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TECHNOLOGIES, POLICIES AND MEASURES FOR MITIGATING CLIMATE CHANGE

IPCC Technical Paper I

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Technologies, Policies and Measures for Mitigating Climate Change

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This is a Technical Paper of the Intergovernmental Panel on Climate Change prepared in response to a request from the United Nations Framework Convention on Climate Change. The material herein has undergone expert and government review, but has not been considered by the Panel for possible acceptance or approval.

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This paper was prepared under the auspices of IPCC Working Group II,
which is co-chaired by Dr Robert T. Watson of the USA and Dr M.C. Zinyowera of Zimbabwe.

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Contents

Preface

This Intergovernmental Panel on Climate Change (IPCC) Technical Paper on Technologies, Policies and Measures for Mitigating Climate Change was produced in response to a request from the Ad Hoc Group on the Berlin Mandate (AGBM) of the Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC).

The Technical Papers are initiated either at the request of the bodies of the COP or by the IPCC. They are based on the material already in the IPCC assessment reports and special reports and are written by Lead Authors chosen for the purpose. They undergo a simultaneous expert and government review and a subsequent final government review. The Bureau of the IPCC acts in the capacity of an editorial board to ensure that the review comments are adequately addressed by the Lead Authors in the finalization of the Technical Paper.

The Bureau met in its Eleventh Session (Geneva, 7-8 November 1996) and considered the major comments received during the final government review. In the light of its observations and request, the Lead Authors finalized the Technical Paper. The Bureau expressed satisfaction that they had followed the agreed Procedures and authorized the release of the Paper to the AGBM and thereafter publicly.

We owe a debt of large gratitude to the Lead Authors who gave of their time very generously and who completed the Paper at short notice and according to schedule. We thank the Co-Chairmen of Working Group II of the IPCC, Drs R.T. Watson and M.C. Zinyowera who oversaw the effort and the Bureau of the Working Group and particularly Dr Richard Moss, the Head of the Technical Support Unit of the Working Group, for their insistence on adhering to quality and timeliness.

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Chairman of the IPCC

N. Sundararaman
Secretary of the IPCC

Technologies, Policies and Measures for Mitigating Climate Change

R.T. Watson, M.C. Zinyowera and R.H. Moss (eds.)

This paper was prepared under the auspices of IPCC Working Group II.

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TECHNICAL SUMMARY

This Technical Paper provides an overview and analysis of technologies and measures to limit and reduce greenhouse gas (GHG) emissions and to enhance GHG sinks under the United Nations Framework Convention on Climate Change (FCCC). The paper focuses on technologies and measures for the countries listed in Annex I of the FCCC, while noting information as appropriate for use by non-Annex I countries. Technologies and measures are examined over three time periods—with a focus on the short term (present to 2010) and the medium term (2010–2020), but also including discussion of longer-term (e.g., 2050) possibilities and opportunities. For this analysis, the authors draw on materials used to prepare the IPCC Second Assessment Report (SAR) and previous IPCC assessments and reports.

The Technical Paper includes discussions of technologies and measures that can be adopted in three energy end-use sectors (commercial/residential/institutional buildings, transportation and industry), as well as in the energy supply sector and the agriculture, forestry and waste management sectors. Broader measures affecting national economies are discussed in a final section on economic instruments. A range of potential measures are analyzed, including market-based programs; voluntary agreements; regulatory measures; research, development and demonstration (RD&D); taxes on GHG emissions; and emissions permits/quotas. It should be noted that the choice of instruments could have economic impacts on other countries.

The paper identifies and evaluates different options on the basis of three criteria. Because of the difficulty of estimating the economic and market potential (see Box 1) of different technologies and the effectiveness of different measures in achieving emission reduction objectives, and because of the danger of double-counting the results achieved by measures that tap the same technical potentials, the paper does not estimate total global emissions reductions. Nor does the paper recommend adoption of any particular approaches.

Residential, Commercial and Institutional Buildings Sector

Global carbon dioxide (CO_2) emissions from residential, commercial, and institutional buildings are projected to grow from 1.9 Gt C/yr in 1990 to 1.9–2.9 Gt C/yr in 2010, 1.9–3.3 Gt C/yr in 2020, and 1.9–5.3 Gt C/yr in 2050. While 75% of the 1990 emissions are attributed to energy use in Annex I countries, only slightly over 50% of global buildings-related emissions are expected to be from Annex I countries by 2050.

Energy-efficiency technologies for building equipment with paybacks to the consumer of five years or less have the economic potential to reduce carbon emissions from both residential and commercial buildings on the order of 20% by 2010, 25% by 2020 and up to 40% by 2050, relative to IS92 baselines in which energy efficiency improves.

Improvements in the building envelope (through reducing heat transfer and use of proper building orientation, energy-efficient windows and climate-appropriate building albedo) have the economic potential to reduce heating and cooling energy in residential buildings with a five-year payback or less by about 25% in 2010, 30% in 2020 and up to 40% in 2050, relative to IS92 baselines in which the thermal integrity of buildings improves through market forces.

The reductions can be realized through use of the following four general measures: (i) market-based programmes in which customers or manufacturers are provided technical support and/or incentives; (ii) mandatory energy-efficiency standards, applied at the point of manufacture or at the time of construction; (iii) voluntary energy-efficiency standards; and (iv) increased emphasis of private or public RD&D programmes to develop more efficient products. Measures need to be carefully tailored to address market barriers. While all of the measures have some administrative and transaction costs, the overall impact on the economy will be favourable to the extent that the energy savings are cost-effective.

Total achievable reductions (market potential), not including reductions due to voluntary energy-efficiency standards, are estimated to be about 10–15% in 2010, 15–20% in 2020 and 20–50% in 2050, relative to the IS92 scenarios. Thus, total achievable global carbon emissions reductions for the buildings sector are estimated to range (based on IS92c, a and e) from about 0.175–0.45 Gt C/yr by 2010, 0.25–0.70 Gt C/yr by 2020 and 0.35–2.5 Gt C/yr by 2050.

Box 1. Technical, Economic and Market Potential

Technical Potential—The amount by which it is possible to reduce GHG emissions or improve energy efficiency by using a technology or practice in all applications in which it could technically be adopted, without consideration of its costs or practical feasibility.

Economic Potential—The portion of the technical potential for GHG emissions reductions or energy efficiency improvements that could be achieved cost-effectively in the absence of market barriers. The achievement of the economic potential requires additional policies and measures to break down market barriers.

Market Potential—The portion of the economic potential for GHG emissions reductions or energy efficiency improvements that currently can be achieved under existing market conditions, assuming no new policies and measures.

Transport Sector

Transport energy use resulted in emissions of 1.3 Gt C in 1990, of which Annex I countries accounted for about three-quarters. Roughly half of global emissions in 1990 came from light-duty vehicles (LDVs), a third from heavy-duty vehicles (HDVs), and most of the remainder from aircraft. In a range of scenarios of traffic growth and energy-intensity reductions, CO_2 emissions increase to 1.3–2.1 Gt C by 2010, 1.4–2.7 Gt C by 2020, and 1.8–5.7 Gt C by 2050. The Annex I share decreases to about 60–70% by 2020 and further thereafter. Trucks and aircraft increase their shares in most scenarios. The transport sector is also a source of other GHGs, including nitrous oxide (N_2O), chlorofluorocarbons (CFCs), and hydrofluorocarbons (HFCs). Aircraft nitrogen oxide (NO_x) emissions contribute to ozone formation that may have as much radiative impact as aircraft CO_2.

Energy-intensity reductions in LDVs that would give users a payback in fuel savings within 3–4 years could reduce their GHG emissions relative to projected levels in 2020 by 10–25%. The economic potential for energy-intensity reductions in HDVs and aircraft might achieve about 10% reductions in GHG emissions where applied relative to projected levels in 2020.

Controls on air-conditioning refrigerant leaks have the technical potential to reduce life-cycle greenhouse forcing due to cars by 10% in 2020. Development of catalytic converters that do not produce N_2O could provide a similar reduction in forcing due to cars. Aircraft engines that produce 30–40% less NO_x than current models might be technically feasible and would also reduce forcing due to air transport, although there might be a trade-off with engine efficiency, hence CO_2 emissions.

Diesel, natural gas and propane, where used in LDVs instead of gasoline, have the technical potential to reduce full-fuel-cycle emissions by 10–30%. Where alternative fuels from renewable sources are used, they have the technical potential to reduce full-fuel-cycle GHG emissions by 80% or more.

New measures would be needed to implement these technical options. Standards, voluntary agreements and financial incentives can help to introduce energy-efficiency improvements, which might be cost-effective for vehicle users. RD&D would be needed to find means of reducing HFC, N_2O and aircraft NO_x emissions, which could then be controlled through standards, although the costs of these are currently unknown.

There are several social and environmental costs associated with road transport at local, regional and global levels. Market instruments such as road-user charges can be used to reflect many of these costs, especially those at local and regional levels. These instruments can also contribute to GHG mitigation by reducing traffic. Fuel taxes are an economically efficient means of GHG mitigation, but may be less efficient for addressing local objectives. Nevertheless, they are administratively simple and can be applied at a national level. Increases in fuel prices to reflect the full social and environmental costs of transport to its users could reduce projected road transport CO_2 emissions by 10–25% by 2020 in most regions, with much larger reductions in countries where prices are currently very low. Alternative fuel incentives might deliver up to 5% reduction in projected LDV emissions in 2020, but the longer term effect might be much greater.

Changes in urban and transport infrastructure, to reduce the need for motorized transport and shift demand to less energy-intensive transport modes, may be among the most important elements of a long-term strategy for GHG mitigation in the transport sector. Packages of measures to bring about such changes would need to be developed on a local basis, in consultation with stakeholders. In some circumstances, the resulting traffic reductions can result in GHG emission reductions of 10% or more by 2020, while obtaining broad social and environmental benefits.

Industrial Sector

During the past two decades, the industrial sector fossil fuel CO_2 emissions of most Annex I countries have declined or remained constant as their economies have grown. The reasons are different for Organisation for Economic Cooperation and Development (OECD) Annex I economies which have been driven more by efficiency gains and a shift towards the service sector, and economies in transition which are undergoing large-scale restructuring and reduction in their heavy industrial sub-sectors. Global industrial emissions (including those related to manufacturing, agriculture, mining and forestry) were 2.8 Gt C (47% of total), to which Annex I countries contributed 75%. Global industrial emissions are projected to grow to 3.2–4.9 Gt C by 2010, to 3.5–6.2 Gt C by 2020 and to 3.1–8.8 Gt C by 2050. Annex I industrial CO_2 emissions are projected to either remain constant then decline by 33%, or increase by 76% by 2050 (see Tables A1–A4 in Appendix A). There are clearly many opportunities for gains in energy efficiency of industrial processes, the elimination of process gases and the use of coordinated systems within and among firms that make more efficient use of materials, combined heat and power, and cascaded heat. Major opportunities also exist for cooperative activities among Annex I countries, and between Annex I countries and developing countries.

While standard setting and regulation have been the traditional approaches to reduce unwanted emissions, the immense range of sectors, firms and individuals affected suggests that these need to be supplemented with market mechanisms, voluntary agreements, tax policy and other non-traditional approaches. It will be politically difficult to implement restrictions on many GHGs, and the administrative enforcement burden and transaction costs need to be kept low. Since many firms have stated their commitment to sustainable practices, developing cooperative agreements might be a first line of approach (SAR II, 20.5; SAR III, Chapter 11).

It is estimated that Annex I countries could lower their industrial sector CO_2 emissions by 25% relative to 1990 levels, by simply replacing existing facilities and processes with the most efficient technological options currently in use (assuming a constant structure for the industrial sector). If this upgraded replacement occurred at the time of normal capital stock turnover, it would be cost-effective (SAR II, SPM 4.1.1).

Energy Supply Sector

Energy consumed in 1990 resulted in the release of 6 Gt C. About 72% of this energy was delivered to end users, accounting for 3.7 Gt C; the remaining 28% was used in energy conversion and distribution, releasing 2.3 Gt C. It is technically possible to realize deep emission reductions in the energy supply sector in step with the normal timing of investments to replace infrastructure and equipment as it wears out or becomes obsolete (SAR II, SPM 4.1.3). Over the next 50–100 years, the entire energy supply system will be replaced at least twice. Promising approaches to reduce future emissions (not ordered according to priority) include more efficient conversion of fossil fuels; switching to low-carbon fossil fuels; decarbonization of flue gases and fuels, and CO_2 storage; switching to nuclear energy; and switching to renewable sources of energy (SAR II, SPM 4.1.3).

The efficiency of electricity generation can be increased from the present world average of about 30% to more than 60% sometime between 2020 and 2050 (SAR II, SPM 4.1.3.1). Presently, the best available coal and natural gas plants have efficiencies of 45 and 52%, respectively (SAR II, 19.2.1). Assuming a typical efficiency of new coal-fired power generation (with de-SO_x and de-NO_x scrubbing equipment) of 40% in Annex I countries, an increase in efficiency of 1% would result in a 2.5% reduction in CO_2 emissions (SAR II, 19.2.1.1). While the cost associated with these efficiencies will be influenced by numerous factors, there are advanced technologies that are cost-effective, comparable to some existing plants and equipment. Switching to low-carbon fossil fuels (e.g., the substitution of coal by natural gas) can achieve specific CO_2 reductions of up to 50%. Decarbonization of flue gases and fuels can yield higher CO_2 emission reductions of up to 85% and more, with typical decarbonization costs ranging from $80–150 per tonne of carbon avoided. Switching to nuclear and renewable sources of energy can eliminate virtually all direct CO_2 emissions as well as reduce other emissions of CO_2 that occur during the life-cycle of energy systems (e.g., mining, plant construction, decommissioning), with the costs of mitigation varying between negligible additional cost to hundreds of dollars per tonne of carbon avoided (SAR II, Chapter 19). Approaches also exist to reduce emissions of methane (CH_4) from coal mining by 30–90%, from venting and flaring of natural gas by more than 50%, and from natural gas distribution systems by up to 80% (SAR II, 22.2.2). Some of these reductions may be economically viable in many regions of the world, providing a range of benefits, including the use of CH_4 as an energy source (SAR II, 19.2.2.1).

The extent to which the potential can be achieved will depend on future cost reductions, the rate of development and implementation of new technologies, financing and technology transfer, as well as measures to overcome a variety of non-technical barriers such as adverse environmental impacts, social acceptability, and other regional, sectoral, and country-specific conditions.

Historically, the energy intensity of the world economy has improved, on average, by 1% per year largely due to technology performance improvements that accompany the natural replacement of depreciated capital stock (SAR II, B.3.1). Improvements beyond this rate are unlikely to occur in the absence of measures. The measures discussed are grouped into five categories (not ordered according to priority): (i) market-based programmes; (ii) regulatory measures; (iii) voluntary agreements; (iv) RD&D; and (v) infrastructural measures. No single measure will be sufficient for the timely development, adoption and diffusion of the mitigation options. Rather, a combination of measures adapted to national, regional and local conditions will be required. Appropriate measures, therefore, reflect the widely differing institutional, social, economic, technical and natural resource endowments in individual countries and regions.

Agricultural Sector

Agriculture accounts for about one-fifth of the projected anthropogenic greenhouse effect, producing about 50 and 70%, respectively, of overall anthropogenic CH_4 and N_2O emissions; agricultural activities (not including forest conversion) account for approximately 5% of anthropogenic emissions of CO_2 (SAR II, Figure 23.1). Estimates of the potential global reduction in radiative forcing through the agricultural sector range from 1.1–3.2 Gt C-equivalents per year. Of the total global reductions, approximately 32% could result from reduction in CO_2 emissions, 42% from carbon offsets by biofuel production on land currently under cultivation, 16% from reduced CH_4 emissions, and 10% from reduced emissions of N_2O.

Emissions reductions by the Annex I countries could make a significant contribution to the global total. Of the total potential CO_2 mitigation, Annex I countries could contribute 40% of the reduction in CO_2 emissions and 32% of the carbon offset from biofuel production on croplands. Of the global total reduction in CH_4 emissions, Annex I countries could contribute 5% of the reduction attributed to improved technologies for rice production and 21% of reductions attributed to improved management of ruminant animals. These countries also could contribute about 30% of the reductions in N_2O emissions attributed to reduced and more efficient use of nitrogen fertilizer, and 21% of the reductions stemming from improved utilization of animal manures. Some technologies, such as no-till farming and strategic fertilizer placement and timing, already are being adopted for reasons other than concern for climate change. Options for reducing emissions, such as improved farm management and increased efficiency of nitrogen fertilizer use, will maintain or increase agricultural production with positive environmental effects.

Forest Sector

High- and mid-latitude forests are currently estimated to be a net carbon sink of about 0.7 ± 0.2 Gt C/yr. Low-latitude forests are estimated to be a net carbon source of 1.6 ± 0.4 Gt C/yr, caused mostly by clearing and degradation of forests (SAR II, 24.2.2). These sinks and sources may be compared with the carbon release from fossil fuel combustion, which was estimated to be 6 Gt C in 1990.

The potential land area available in forests for carbon conservation and sequestration is estimated to be 700 Mha. The total carbon that could be sequestered and conserved globally by 2050 on this land is 60–87 Gt C. The tropics have the potential to conserve and sequester by far the largest quantity of carbon (80%), followed by the temperate zone (17%) and the boreal zone (3%).

Slowing deforestation and assisting regeneration, forestation and agroforestry constitute the primary mitigation measures for carbon conservation and sequestration. Among these, slowing deforestation and assisting regeneration in the tropics (about 22–50 Gt C) and forestation and agroforestry in the tropics (23 Gt C) and temperate zones (13 Gt C) hold the most technical potential of conserving and sequestering carbon. To the extent that forestation schemes yield wood products, which can substitute for fossil fuel-based material and energy, their carbon benefit can be up to four times higher than the carbon sequestered. Excluding the opportunity costs of land and the indirect costs of forestation, the costs of carbon conservation and sequestration average between $3.7–4.6 per ton of carbon, but can vary widely across projects.

Governments in a few developing countries, such as Brazil and India, have instituted measures to halt deforestation. For these to succeed over the long term, enforcement to halt deforestation has to be accompanied by the provision of economic and/or other benefits to deforesters that equal or exceed their current remuneration. National tree planting and reforestation programmes, with varying success rates, exist in many industrialized and developing countries. Here also, adequate provision of benefits to forest dwellers and farmers will be important to ensure their sustainability. The private sector has played an important role in tree planting for dedicated uses, such as paper production. It is expanding its scope in developing countries through mobilizing resources for planting for dispersed uses, such as the building and furniture industries.

Wood residues are used regularly to generate steam and/or electricity in most paper mills and rubber plantations, and in specific instances for utility electricity generation. Making plantation wood a significant fuel for utility electricity generation will require higher biomass yields, as well as thermal efficiency to match those of conventional power plants. Governments can help by removing restrictions on wood supply and the purchase of electricity.

Ongoing jointly implemented projects address all three types of mitigation options discussed above. The lessons learned from these projects will serve as important precursors for future mitigation projects. Without their emulation and replication on a national scale, however, the impact of these projects by themselves on carbon conservation and sequestration is likely to be small. For significant reduction of global carbon emissions, national governments will need to institute measures that provide local and national, economic and other benefits, while conserving and sequestering carbon.

Solid Waste and Wastewater Disposal

An estimated 50–80 Mt CH_4 (290–460 Mt C) was emitted by solid waste disposal facilities (landfills and open dumps) and wastewater treatment facilities in 1990. Although there are large uncertainties in emission estimates for a variety of reasons, overall emissions levels are projected to grow significantly in the future.

Technical options to reduce CH_4 emissions are available and, in many cases, may be profitably implemented. Emissions may be reduced by 30–50% through solid waste source reduction (paper recycling, composting and incineration), and through CH_4 recovery from landfills and wastewater (SAR II, 22.4.4.2). Recovered CH_4 may be used as an energy source, reducing the cost of waste disposal. In some cases, CH_4 produced from landfills and from wastewater can be cost-competitive with other energy alternatives (SAR II, 22.4.4.2). Using the range of emissions estimates in the IS92 scenarios, this implies equivalent carbon reductions of about 55–140 Mt in 2010; 85–170 Mt in 2020; and 110–230 Mt in 2050.

Controlling CH_4 emissions requires a prior commitment to waste management, and the barriers toward this goal may be reduced through four general measures: (i) institution building and technical assistance; (ii) voluntary agreements; (iii) regulatory measures; and (iv) market-based programmes. Of particular importance, in many cases the resulting CH_4 reductions will be viewed as a secondary benefit of these measures, which often may be implemented in order to achieve other environmental and public health benefits.

Economic Instruments

A variety of economic instruments is available to influence emissions from more than one sector. At both the national and international levels, economic instruments are likely to be more cost-effective than other approaches to limit GHG emissions. These instruments include subsidies, taxes and tradable permits/quotas, as well as joint implementation. These instruments will have varying effects depending on regional and national circumstances, including existing policies, institutions, infrastructure, experience and political conditions.

National-level instruments include: (i) changes in the current structure of subsidies, either to reduce subsidies for GHG-emitting activities or to offer subsidies for activities that limit

GHG emissions or enhance sinks; (ii) domestic taxes on GHG emissions; and (iii) tradable permits.

Economic instruments at the international level include: (i) international taxes or harmonized domestic taxes; (ii) tradable quotas; and (iii) joint implementation.

Economic instruments implemented at the national or international level require approaches to addressing concerns related to equity, international competitiveness, "free riding" (i.e., parties sharing the benefits of abatement without bearing their share of the costs) and "leakage" (i.e., abatement actions in participating countries causing emissions in other countries to increase).

With few exceptions, both taxes and tradable permits impose costs on industry and consumers. Sources will experience financial outlays, either through expenditures on emission controls or through cash payments to buy permits or pay taxes.

Permits are more effective than a tax in achieving a specified emission target, but a tax provides greater certainty about control costs than do permits. For a tradable permit system to work well, competitive conditions must exist in the permit (and product) markets. A competitive permit market could lead to the creation of futures contracts which would reduce uncertainty regarding future permit prices.

A system of harmonized domestic taxes on GHG emissions would involve an agreement about compensatory international financial transfers. To be effective, a system of harmonized domestic taxes also requires that participants not be allowed to implement policies that indirectly increase GHG emissions.

A tradable quota scheme allows each participant to decide what domestic policy to use. The initial allocation of quota among countries addresses distributional considerations, but the exact distributional implications cannot be known beforehand, since the quota price will be known only after trading begins, so protection against unfavorable price movements may need to be provided.

In applying economic instruments to limit GHG emissions at the international level, equity across countries is determined by the quota allocations in the case of tradable quota systems, the revenue-sharing agreement negotiated for an international tax, or the transfer payments negotiated as part of harmonized domestic taxes on GHG emissions.

1. INTRODUCTION

1.1 Purpose and Context

The purpose of this Technical Paper is to provide an overview and analysis of technologies and measures to limit and reduce GHG emissions and to enhance GHG sinks under the United Nations Framework Convention on Climate Change. The "Berlin Mandate," which was agreed upon at the first Conference of the Parties (COP) to the Convention (Berlin, March/April 1995), provides the context for the paper. This mandate establishes a process that aims to elaborate policies and measures, and set quantified emission limitation and reduction objectives.

1.2 Scope and Organization[1]

This Technical Paper provides a sectoral analysis of technologies and practices that will reduce growth in GHG emissions and of measures that can stimulate and accelerate the use of these technologies and practices, with separate consideration of broad economic policy instruments. The paper focuses on technologies and measures for the countries listed in Annex I of the FCCC, while noting information as appropriate for use by non-Annex I countries. Analysis of these technologies and measures is provided in terms of a framework of criteria, which was authorized by IPCC-XII (Mexico City, 11–13 September 1996).

Technologies and measures are examined over three time periods, with a focus on the short term (present to 2010) and the medium term (2010–2020), but also including discussion of longer-term (e.g., 2050) possibilities and opportunities. Many of the data in the SAR were summarized as global values; for this report, data for the Annex I countries also are provided to the extent possible, as a group or categorized into OECD countries and countries with economies in transition. All of the information and conclusions contained in this report are consistent with the SAR and with previously published IPCC reports.

The Technical Paper begins with a discussion of three energy end-use sectors—commercial/residential/institutional buildings, transportation and industry. These discussions are followed by a section on the energy supply and transformation sector, which produces and transforms primary energy to supply secondary energy to the energy end-use sectors.[2] Technologies and measures that can be adopted in the agriculture, forestry and waste management sectors are then discussed. Measures that will affect emissions mainly in individual sectors (e.g., fuel taxes in the transportation sector) are covered in the sectoral discussions listed above; broader measures affecting the national economy (e.g., energy or carbon taxes) are discussed in a final section on economic instruments.

The paper identifies and evaluates different options on the basis of three criteria (see Box 2). Because of the difficulty of estimating the economic and market potential of different technologies and the effectiveness of different measures in achieving emission reduction objectives, and because of the danger of double-counting the results achieved by measures that tap the same technical potentials, the paper does not estimate total global emissions reductions. Nor does the paper recommend adoption of any particular approaches. Each Party to the Convention will decide, based on its needs, obligations and national priorities, what is appropriate for its own national circumstances.

1.3 Sources of Information

The Technical Paper has been drafted in a manner consistent with the rules of procedure for IPCC Technical Papers agreed to at IPCC-XI (Rome, 11–15 December 1995) and further interpreted at IPCC-XII. The contributors and participating governments of the IPCC recognize that a simplification of the review process is necessary to enable the Technical Papers to be completed in a time frame that meets the needs of the Parties of the FCCC. Therefore, materials agreed to be appropriate for use in this Technical Paper are restricted to information derived from IPCC reports and relevant portions of references cited in these reports, and models and scenarios used to provide information in IPCC reports. In accordance with these requirements, information and studies that were not referenced or cited in any IPCC report are not included in the discussion. Important information on potential reductions from energy savings or as captured through particular measures is not always available in the literature; in the absence of such information, the authors of this report have in certain instances presented their own estimates and professional judgment in evaluating the performance of these measures.

1.4 Measures Considered

The implementation of technologies and practices to mitigate GHG emissions over and above the normal background rates of improvement in technology and replacement of depreciated capital stock is unlikely to occur in the absence of measures to encourage their use. Because circumstances differ among countries and regions and a variety of barriers presently inhibit the

[1] The scope of this paper was guided by several UNFCCC documents prepared for the Ad Hoc Group on the Berlin Mandate (AGBM), including FCCC/AGBM/1995/4 and FCCC/AGBM/1996/2.

[2] Primary energy is the chemical energy embodied in fossil fuels (coal, oil and natural gas) or biomass, the potential energy of a water reservoir, the electromagnetic energy of solar radiation, and the energy released in nuclear reactors. For the most part, primary energy is transformed into electricity or fuels such as gasoline, jet fuel, heating oil or charcoal—called secondary energy. The end-use sectors of the energy system provide energy services such as cooking, illumination, comfortable indoor climate, refrigerated storage, transportation and consumer goods using primary and secondary energy forms, as appropriate.

development and deployment of these technologies and practices, no one measure will be sufficient for the timely development, adoption and diffusion of mitigation options. Rather, a combination of measures adapted to national, regional and local conditions will be required. These measures must reflect the widely differing institutional, social, cultural, economic, technical and natural resource endowments in individual countries and regions, and the optimal mix will vary from country to country. The combinations of measures should aim to reduce barriers to the commercialization, diffusion and transfer of GHG mitigation technologies; mobilize financial resources; support capacity building in developing countries and countries with economies in transition; and induce behavioral changes. A number of relevant measures may be introduced for reasons other than climate mitigation, such as raising efficiency or addressing local/regional economic and environmental issues.

A range of potential measures are analyzed in this paper, including market-based programmes (carbon or energy taxes, full-cost pricing, use or phaseout of subsidies, tradable emissions permits/quotas); voluntary agreements (energy use and carbon emissions standards, government procurement[3], promotional programmes for energy-efficient products); regulatory measures (mandatory equipment or building standards, product and practices bans, non-tradable emissions permits/quotas); and RD&D. Some of these measures could be applied at the national or the international levels.

1.4.1 Provision of Information and Capacity Building

The provision of information and capacity building are considered to be necessary components of many of the measures and policies discussed in the paper, and generally are not examined as separate types of measures.

In order for successful GHG abatement techniques and technologies to be diffused to a wide range of users, there needs to be a concerted effort to disseminate information about their technical, managerial and economic aspects. In addition to information availability, training programmes are needed to ensure that successful programmes can be implemented. There is relatively little international transfer of knowledge to non-Annex I countries. Including information and training in loan and foreign assistance packages by aid donors and lending institutions could be an effective mechanism. International agencies such as the United Nations Institute for Training and Research (UNITAR) might take on major information and training responsibilities for GHG-related technology transfer. International and national trade organizations might also be effective in providing information and training.

Information and education measures include efforts to provide information to decision makers with the intention of altering behavior. They can help overcome incomplete knowledge of economic, environmental and other characteristics of promising technologies that are currently available or under development. Information measures have aided the development and commercialization of new energy demand-management and supply technologies in national or regional markets. In addition, information and education may be instrumental in shaping socio-economic practices as well as behavioral attitudes toward the way energy services are provided and demanded. The ability of information and education programmes to induce changes in GHG emissions is difficult to quantify.

Training and capacity building may be prerequisites for decision-making related to climate change and for formulating appropriate policies and measures to address this issue. Training and capacity building can promote timely dissemination of information at all levels of society, facilitating acceptance of new regulations or voluntary agreements. Capacity building also can help catalyze and accelerate the development and utilization of sustainable energy supply and use technologies.

1.4.2 International Coordination and Institutions

Equity issues, as well as international economic competitiveness considerations, may require that certain measures be anchored in regional or international agreements, while other policies can be implemented unilaterally. As a result, a key issue is the extent to which any particular measure might require or benefit from “common action” and what form such action might take. The level of common action could range from a group of countries adopting common measures, coordinating the implementation of similar measures or working to achieve common aims, with flexibility in the technologies, measures and policies used. Other forms of common action could include the development of a common menu of useful actions from which each country would select measures best suited to its situation, or the development of coordination protocols for consistent monitoring and accounting of emissions reductions or for the conduct and monitoring of international tradable emissions initiatives.

This paper does not assess levels or types of international coordination; rather, elements of the analysis illustrate potential advantages and disadvantages of actions taken both at the level of individual countries and internationally.

1.5 Criteria for Analysis

In order to provide a structure and basis for comparison of options, the authors developed a framework of criteria for analysing technologies and measures (see Box 2). These criteria focus the discussion on some of the important benefits and drawbacks of a large number of measures.

The authors focus their evaluations on the main criteria (i.e., GHG reductions and other environmental results; economic and social effects; and administrative, institutional and political

[3] Because of its potential effects on market creation, government procurement is counted as a market-based programme in some sections of this paper.

Box 2. Criteria for Evaluation of Technologies and Measures

1. GHG and Other Environmental Considerations
   - GHG reduction potential
     – Tons of carbon equivalent[4]
     – per cent of IS92a baseline and range (IS92c-e)
   - Other environmental considerations
     – Percentage change in emissions of other gases/particulates
     – Biodiversity, soil conservation, watershed management, indoor air quality, etc.

2. Economic and Social Considerations
   - Cost-effectiveness
     – Average and marginal costs
   - Project-level considerations
     – Capital and operating costs, opportunity costs, incremental costs
   - Macro-economic considerations
     – GDP, jobs created or lost, effects on inflation or interest rates, implications for long-term development, foreign exchange and trade, other economic benefits or drawbacks
   - Equity considerations
     – Differential impacts on countries, income groups or future generations

3. Administrative, Institutional and Political Considerations
   - Administrative burden
     – Institutional capabilities to undertake necessary information collection, monitoring, enforcement, permitting, etc.
   - Political considerations
     – Capacity to pass through political and bureaucratic processes and sustain political support
     – Consistency with other public policies
   - Replicability
     – Adaptability to different geographical and socio-economic-cultural settings

issues), and include elements from all three categories in the discussion of each technology and measure (see tables within respective sections). Because of the limited length and broad scope of the paper, every option cannot be evaluated using each detailed criterion listed. In particular, it is difficult to judge precisely the effectiveness of various instruments in achieving emissions reduction objectives, the economic costs at both the project and macro-economic levels, and other factors, such as other types of environmental effects resulting from the implementation of various options. In some instances, the authors were unable to quantify the cost-effectiveness or fully evaluate other cost considerations noted in the criteria for evaluation. Such cost evaluation could not be completed because costs depend on the specific technical option promoted and the means of implementation; evaluation of the costs of measures has not been well-documented by Annex I countries, and is not available in the literature at this time. Assessing the performance of any of the wide range of technologies and measures is further complicated by the need to consider implementation issues that can affect performance, and by the likelihood that the performance of measures will vary when combined into different packages.

The criteria used by governments for assessing technologies and measures—and the priority placed on each criterion—may differ from those listed here. The information provided about the performance of the technologies and measures described in the SAR with respect to these criteria is intended to inform the choice of options by governments.

1.6 Baseline Projections of Energy Use and Carbon Dioxide Emissions

Historically, global energy consumption has grown at an average annual rate of about 2% for almost two centuries, although growth rates vary considerably over time and among regions. The predominant GHG is CO_2, which represents more than half of the increase in radiative forcing from anthropogenic GHG sources. The majority of CO_2 arises from the use of fossil fuels, which in turn account for about 75% of total global energy use.

Energy consumed in 1990 resulted in the release of 6 Gt C as CO_2. About 72% of this energy was delivered to end users, accounting for 3.7 Gt C in CO_2 emissions; the remaining 28% was used in energy conversion and distribution, releasing 2.3

[4] Carbon equivalents of non-CO_2 GHGs are calculated from the CO_2-equivalents, using the 100-year global warming potentials (GWPs): CH_4 = 21, N_2O = 310 (SAR I, 2.5, Table 2.9).

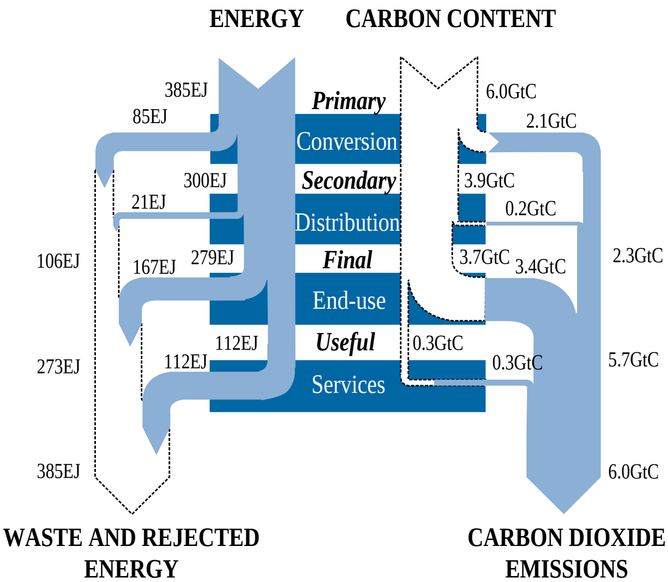

Figure 1: Major energy and carbon flows through the global energy system in 1990, EJ and Gt C (billion tons) elemental carbon. Carbon flows do not include biomass (SAR II, B.2.1, Figure B-2).

Gt C as CO_2 (see Figure 1). In 1990, the three energy end-use sectors accounting for the largest CO_2 releases from direct fuel use were industry (45% of total CO_2 releases), transportation (21%) and residential/commercial/institutional buildings (29%). Transport sector energy use and related CO_2 emissions have grown most rapidly over the past two decades.

As shown in Tables A3 and A4 in Appendix A, Annex I countries are major energy users and fossil fuel CO_2 emitters, although their share of global fossil fuel carbon emissions has been declining. Non-Annex I countries account for a smaller portion of total global CO_2 emissions than Annex I countries, but projections indicate that the share of the non-Annex I countries will increase significantly in all scenarios by 2050.

The mitigation potential of many of the technologies and measures is estimated using a range of baseline projections provided by the IPCC IS92 "a," "c," and "e" scenarios for 2010, 2020 and 2050 (see Tables A1–A4 in Appendix A). The IS92 scenarios (IPCC 1992, 1994) provide a current picture of global energy use and GHG emissions, as well as a range of future projections without mitigation policies, based on assumptions and trend information available in late 1991. By providing common and consistent baselines against which the authors compare percentage reductions in energy use and related GHG emissions, the scenarios make possible rough estimates of the potential emission reduction contributions of different technologies and measures. The rapid changes in national economic trends during the early 1990s for several of the Annex I countries with economies in transition were not captured in these scenarios, hence are not accounted for in quantitative elements of these analyses.

Across the IS92 scenarios, global energy needs are projected to continue to grow, at least through the first half of the next century. Without policy intervention, CO_2 emissions will grow, although this growth will be slower than the expected increase in energy consumption, because of the assumed "normal" rate of decarbonization of energy supply. However, the global decarbonization rate of energy will not fully offset the average annual 2% growth rate of global energy needs.

2. RESIDENTIAL, COMMERCIAL AND INSTITUTIONAL BUILDINGS SECTOR[5]

2.1 Introduction

In 1990, the residential, commercial and institutional buildings sector was responsible for roughly one-third of global energy use and associated carbon emissions both in the Annex I countries and globally. In that year, buildings in Annex I countries used 86 EJ of primary energy and emitted 1.4 Gt C, accounting for about 75% of global buildings energy use (112 EJ, with associated emissions of 1.9 Gt C).[6] However, the share of primary energy use and associated emissions attributable to Annex I countries is projected to drop; the IS92a scenario projects that global buildings-related emissions from Annex I countries will be about 70% in 2020 and slightly over 50% in 2050.

Greater use of available, cost-effective technologies to increase energy efficiency in buildings can lead to sharp reductions in emissions of CO_2 and other GHGs resulting from the production, distribution and use of fossil fuels and electricity needed for all energy-using activities that take place within residential, commercial and institutional buildings. The buildings sector is characterized by a diverse array of energy end uses and varying sizes and types of building shells that are constructed in all climatic regimes. Numerous technologies and measures have been developed and implemented to reduce energy use in buildings, especially during the past two decades in Annex I countries.

Table 1 outlines measures and technical options to mitigate GHG emissions in the buildings sector, and provides a brief description of the climate and environmental benefits as well as economic and social effects (including costs associated with implementation of measures), and administrative, institutional and political issues associated with each measure. Tables 2 and 3 provide estimates of global and Annex I, respectively, emissions reductions associated with both energy-efficient technologies and the energy-efficiency measures.[7] The estimates for the reductions from energy-efficient technologies are based on studies described in the SAR, using expert judgment to extrapolate to the global situation and to estimate reductions in 2020 and 2050, because most of the studies in the SAR estimate energy savings only for 2010. The estimates for the reductions from energy-efficient technologies captured through measures are based on expert judgment regarding policy effectiveness. These two categories of reductions—"potential reductions from energy-efficient technologies" and "potential reductions from energy-efficient technologies captured through measures"—are not additive; rather, the second category represents an estimate of that portion of the first that can be captured by the listed measures.

2.2 Technologies for Reducing GHG Emissions in the Residential, Commercial and Institutional Buildings Sector

A significant means of reducing GHG emissions in the buildings sector involves more rapid deployment of technologies aimed at reducing energy use in building equipment (appliances, heating and cooling systems, lighting and all plug loads, including office equipment) and reducing heating and cooling energy losses through improvements in building thermal integrity (SAR II, 22.4.1, 22.4.2). Other effective methods to reduce emissions include urban design and land-use planning that facilitate lower energy-use patterns and reduce urban heat islands (SAR II, 22.4.3); fuel switching (SAR II, 22.4.1.1, Table 22-1); improving the efficiency of district heating and cooling systems (SAR II, 22.4.1.1.2, 22.4.2.1.2); using more sustainable building techniques (SAR II, 22.4.1.1); ensuring correct installation, operation and equipment sizing; and using building energy management systems (SAR II, 22.4.2.1.2). Improving the combustion of solid biofuels or replacing them with a liquid or gaseous fuel are important means for reducing non-CO_2 GHG emissions. The use of biomass is estimated (with considerable uncertainty) to produce emissions of 100 Mt C/yr in CO_2-equivalent, mainly from products of incomplete combustion that have greenhouse warming potential (SAR II, Executive Summary).

The potential for cost-effective improvement in energy efficiency in the buildings sector is high in all regions and for all major end uses. Projected energy demand growth is generally considerably higher in non-Annex I countries than in Annex I countries due to higher population growth and expected greater increases in energy services *per capita* (SAR II, 22.3.2.2). Although development patterns vary significantly among countries and regions, general trends in Annex I countries with economies in transition and non-Annex I countries include increasing urbanization (SAR II, 22.3.2.2), increased housing area and *per capita* energy use (SAR II, 22.3.2.2, 22.3.2.3), increasing electrification (SAR II, 22.3.2.2), transition from biomass fuels to fossil fuels for cooking (SAR II, 22.4.1.4), increased penetration of appliances (SAR II, 22.3.2.3), and rising use of air conditioning (SAR II, 22.4.1.1). For simplification, the authors assume that by 2020 urban areas in non-Annex I countries will have end-use distributions similar to those now found in Annex I countries, so that energy-saving options and measures for most appliances, lighting, air conditioning and office equipment will be similar for urban areas in both sets of countries. The exception is heating which is likely to be a large energy user only in a few of the non-Annex I countries, such as China (SAR II, 22.2.1, 22.4.1.1.1). In addition, it is assumed that the range of cost-effective energy-savings options will be similar for Annex I and non-Annex I countries by 2020.

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[5] This section is based on SAR II, Chapter 22, *Mitigation Options for Human Settlements* (Lead Authors: M. Levine, H. Akbari, J. Busch, G. Dutt, K. Hogan, P. Komor, S. Meyers, H. Tsuchiya, G. Henderson, L. Price, K. Smith and Lang Siwei).

[6] Global energy use and emissions values are based on IS92 scenarios.

[7] Tables 2 and 3 include only carbon emissions resulting from the use of fuels sold commercially. They do not include the large quantities of biomass fuels used in developing countries for cooking. Fuel switching from biomass fuels for cooking to sustainable, renewable fuels such as biogas or alcohol in developing countries can reduce these emissions (SAR II, 22.4.1.4).

Table 1: *Selected examples of measures and technical options to mitigate GHG emissions in the buildings sector.*

Technical Options	Measures	Climate and Other Environmental Effects[a]	Economic and Social Effects	Administrative, Institutional and Political Considerations
Building Equipment Heating – Condensing furnace – Electric air-source heat pump – Ground-source heat pump Cooling – Efficient air conditioners Water Heating – Efficient water heaters – Air-source heat pump water heater – Exhaust air heat pump water heater Refrigeration – Efficient refrigerators Other Appliances – Horizontal axis clothes washer – Increased clothes washer spin speed – Heat pump clothes dryer Cooking – Biomass stoves Lighting – Compact fluorescent lamps – Halogen IR lamps – Efficient fluorescent lamps – Electromagnetic ballasts – Specular reflective surfaces – Replacement of kerosene lamps – Lighting control systems Office Equipment – Efficient computers – Low-power mode for equipment Motors – Variable speed drives – Efficient motors Energy Management – Building energy management systems – Advanced energy management systems	**Market-based Programmes** – Voluntary agreements – Market pull or market aggregation – Development incentive programmes – Utility demand-side management programmes – Energy service companies	**Climate Benefits** – Reductions of 2.5–4% of emissions due to buildings by 2010 – Reductions of 3–5% of emissions due to buildings by 2020 – Reductions of 5–13% of emissions due to buildings by 2050 **Other Effects** – Qualitatively similar to those from mandatory energy-efficiency standards	– Qualitatively similar to mandatory energy-efficiency standards (see below), except do not have equipment costs for testing laboratories or initial production costs – Monitoring and implementation costs	**Administrative/ Institutional Factors** – Difficulty in improving integrated systems – Need for trained personnel – Landlord/tenant incentive issue – Programme design to address all options – Need for new institutional structures **Political Factors** – Cross-subsidies
	Regulatory Measures – Mandatory energy-efficiency standards	**Climate Benefits** – Reductions of 4–7% of emissions due to buildings by 2010 – Reductions of 6–10% of emissions due to buildings by 2020 – Reductions of 10–25% of emissions due to buildings by 2050 **Other Effects** – Reduced impacts on land, air and water from extraction, transport and transmission, conversion, and use of energy	**Economic Issues** – Carbon reductions are cost-effective with a presumed payback period of <5 years **Macro-economic Issues** – Savings beneficial to the economy **Project-level Effects** – Need for trained personnel – Costs for analysis, testing and training – Equipment costs for testing laboratories – Initial production costs – Need for new institutional structures – Changes in product attributes	**Administrative/ Institutional Factors** – Analysis, testing and rating capability – Testing laboratories – Certification equipment – National, regional or international agreement on test procedures and on standard levels – Raising capital for testing – Reduced future energy-generation requirements **Political Factors** – Opposition from manufacturers – Opposition from other affected groups – Responding to environmental and consumer concerns
	Voluntary Measures – Voluntary energy-efficiency standards	**Climate Benefits** – Global emissions reductions of 10–50% of the reductions achieved with mandatory standards **Other Effects** – Similar to those from mandatory energy-efficiency standards	– Qualitatively similar to mandatory energy-efficiency standards	– Qualitatively similar to mandatory energy-efficiency standards

Table 1 (continued)

Technical Options	Measures	Climate and Other Environmental Effects[a]	Economic and Social Effects	Administrative, Institutional and Political Considerations
Building Thermal Integrity – Improved duct sealing – Proper orientation – Insulation and sealing – Energy-efficient windows	**Market-based Programmes** – Home energy rating systems – Utility DSM assistance to architects/builders – Building procurement programmes	**Climate Benefits** – Reductions of 1.5–2% of emissions from buildings by 2010 – Reductions of 1.5–2.5% of emissions from buildings by 2020 – Reductions of 2–5% of emissions from buildings by 2050 **Other Effects** – Qualitatively similar to those from mandatory energy-efficiency standards	– Qualitatively similar to mandatory energy-efficiency standards for building equipment, except do not have equipment costs for testing laboratories or initial production costs – Monitoring and implementation costs	**Administrative/ Institutional Factors** – Difficulty in improving integrated systems – Need for trained personnel – Landlord/tenant incentive issue – Programme design to address all options – Need for new institutional structures **Political Factors** – Cross-subsidies
	Regulatory Measures – Mandatory energy-efficiency standards	**Climate Benefits** – Reductions of 1.5–2% of emissions from buildings by 2010 – Reductions of 1.5–2% of emissions from buildings by 2020 – Reductions of 2–5% of emissions from buildings by 2050 **Other Effects** – Qualitatively similar to those from mandatory energy-efficiency standards	– Qualitatively similar to mandatory energy-efficiency standards for building equipment, although training and enforcement costs may be higher	**Administrative/ Institutional Factors** – Difficult to enforce – Difficult to verify compliance **Political Factors** – Opposition from builders – Opposition from other affected groups – Responding to environmental and consumer concerns

Note: Percentage values in this table correspond to absolute values in the section of Table 2 entitled “Potential Reductions from Energy-efficient Technologies Captured through Measures.” To match the values, add the emissions reduction percentages for market-based programmes and for mandatory energy-efficiency standards for both buildings equipment and building thermal integrity (e.g., 2010 reductions of 2.5–4% from market-based programmes for building equipment plus reductions of 1.5–2% from market-based programmes for building thermal integrity equals 4–6%, which corresponds to 95–160 Mt C reductions from market-based programmes in Table 2).

2.2.1 Building Equipment

The largest potential energy savings are for building equipment. Cost-effective energy savings for these end uses vary by product and energy prices, but savings in the range of 10–70% (most typically 30–40%) are available by replacing existing technology with such energy-efficient technologies as condensing furnaces, electric air-source heat pumps, ground-source heat pumps, efficient air conditioners, air-source or exhaust air heat pump water heaters, efficient refrigerators, horizontal axis clothes washers, heat pump clothes dryers, kerosene stoves, compact fluorescent lamps, efficient fluorescent lamps, electronic ballasts, lighting control systems, efficient computers, variable speed drives and efficient motors (SAR II, 22.4) (see Table 1).

Residential buildings are expected to account for about 60% of global buildings energy use in 2010, falling to 55% by 2050. Based on this ratio, IS92a scenarios indicate that residential buildings will use energy that produces 1.5 Gt C in 2010, 1.6 Gt C in 2020, and 2.1 Gt C in 2050, while commercial buildings will be responsible for emissions of 1.0 Gt C in 2010, 1.1 Gt C in 2020, and 1.7 Gt C in 2050. Based on information presented in the SAR, the authors estimate that efficiency measures with paybacks to the consumer of five years or less have the potential to reduce global residential and commercial buildings carbon emissions on the order of 20% by 2010, 25% by 2020 and up to 40% by 2050, relative to a baseline in which energy efficiency improves (see section of Table 2 entitled “Potential Reductions from Energy-efficient Technologies”).

2.2.2 Building Thermal Integrity

Heating and cooling of residential buildings is largely needed to make up for heat transfer through the building envelope (walls, roofs and windows). Energy savings of 30–35% between 1990 and 2010 have been estimated for retrofits to U.S. buildings built before 1975, but only half of these are cost-effective. Adoption of Swedish-type building practices in west-

Table 2: *Annual global buildings sector carbon emissions and potential reductions in emissions from technologies and measures to reduce energy use in buildings (Mt C) based on IPCC scenario IS92a.*

	Annual Global Buildings Sector Carbon Emissions (Mt C)			
	1990	2010	2020	2050
Source of Emissions—Base Case[a]				
Residential Buildings	1 200	1 500	1 600	2 100
Commercial Buildings	700	1 000	1 100	1 700
TOTAL	**1 900**	**2 500**	**2 700**	**3 800**
		Annual Global Buildings Sector Carbon Emissions Reductions (Mt C)		
Potential Reductions from Energy-efficient Technologies Assuming Significant RD&D Activities[b] (from SAR)				
Residential Equipment[c]		300	400	840
Residential Thermal Integrity[d]		150	190	335
Commercial Equipment[c]		200	275	680
Commercial Thermal Integrity[d]		65	85	170
TOTAL POTENTIAL REDUCTIONS		**715**	**950**	**2 025**
Potential Reductions from Energy-efficient Technologies Captured through Measures[e] (Based on Expert Judgment)				
Mandatory Energy-efficiency Standards[f]		135–225	210–350	450–1,125
Voluntary Energy-efficiency Standards		*g*	*g*	*g*
Market-based Programmes[h]		95–160	125–210	275–685
TOTAL ACHIEVABLE REDUCTIONS		**230–385**	**335–560**	**725–1 810**

Note: "Potential Reductions from Energy-efficient Technologies" and "Potential Reductions from Energy-efficient Technologies Captured through Measures" are not additive; rather, the second category represents that portion of the first that can be captured by the listed measures.

[a] The breakdown between residential and commercial buildings in 2010, 2020 and 2050 is estimated based on 1990 breakdown of 65% residential and 35% commercial (SAR II, 22.2.1), and on the expectation that the commercial sector will grow in significance over this period to 45% in 2050.

[b] Without significant RD&D activities, some of the reductions in 2010, an important part of the reductions in 2020 and most of the 2050 reductions are impossible. RD&D reductions have not been shown separately, because they are assumed to be captured in the "Potential Reductions from Energy-efficient Technologies." 2050 values include the possibility of major RD&D breakthroughs.

[c] Equipment includes appliances, heating and cooling systems, lighting and all plug loads (including office equipment). Potential carbon reductions for residential and commercial equipment are calculated as 20% of residential and commercial emissions in 2010, 25% in 2020 and 40% in 2050, respectively.

[d] Potential carbon reductions for residential thermal integrity are calculated as 25% of the emissions attributed to heating and cooling energy used in the sector (40% of total residential energy use) in 2010, 30% in 2020 and 40% in 2050. Potential savings for commercial thermal integrity are calculated as 25% of the emissions attributed to heating and cooling energy used in the sector (25% of total commercial energy use) in 2010, 30% in 2020 and 40% in 2050.

[e] Potential carbon reductions from mandatory energy-efficiency standards and from market-based programmes can be added, because estimates are conservative and account for potential interactions and possible double-counting. Potential carbon reductions are presented as a range of 60 to 100% of reductions calculated as explained in footnotes f and h for 2010 and 2020, and a range of 60 to 150% of reductions calculated for 2050. The 60% assumes partial implementation of measures. The 150% in 2050 assumes RD&D breakthroughs.

[f] Potential carbon reductions captured through mandatory energy-efficiency standards are calculated as the sum of 40% of residential equipment reductions, 25% of commercial equipment reductions, and 25% of residential and commercial thermal integrity reductions in 2010, as described in footnotes c and d and shown in this table under "Potential Savings from Energy-efficient Technologies." For 2020 and 2050, reductions are calculated as 50% of residential equipment reductions, 30% of commercial equipment reductions and 25% of residential and commercial thermal integrity reductions.

[g] Carbon reductions range from 10 to 50% of reductions from mandatory standards, depending upon the way in which voluntary standards are carried out and on the participation by manufacturers. Due to the uncertainty, this value is not included in the total achievable savings.

[h] Potential carbon reductions captured through market-based programmes are calculated as the sum of 15% of residential equipment reductions, 30% of commercial equipment reductions and 25% of residential and commercial thermal integrity reductions in 2010. For 2020 and 2050, savings are calculated as 15% of residential equipment, 30% of commercial equipment and 25% of residential and commercial thermal integrity reductions.

ern Europe and North America could reduce space heating requirements by an estimated 25% in new buildings relative to those built in the late 1980s (SAR II, 22.4.1.1.1). Although large commercial buildings tend to be internal load-dominated, important energy savings opportunities also exist in the design of the building envelope (SAR II, 22.4.2.1.1). Considerably larger cost-effective savings are possible for new buildings than for existing ones (SAR II, 22.5.1). Since most of the growth in building energy demand is expected to be in non-Annex I countries and a large percentage of this will be new buildings, there are significant opportunities to capture these larger savings if buildings are designed and built to be energy-efficient in these countries (SAR II, 22.4.1).

Overall, based on information presented in the SAR and on expert judgment, the authors estimate that improvements in the building envelope (through reducing heat transfer and using proper building orientation, energy-efficient windows, and climate-appropriate building albedo) have the potential to reduce carbon emissions from heating and cooling energy use in residential buildings with a five-year payback (or less) by about 25% in 2010, 30% in 2020 and up to 40% in 2050, relative to a baseline in which the thermal integrity of buildings improves. Heating and cooling are about 40% of global residential energy use and are expected to decline somewhat as a proportion of total residential energy. For commercial buildings, improvement in the thermal integrity of windows and walls with paybacks of five years or less have lower potential to reduce global carbon emissions, because only about 25% of energy use is due to heating and cooling, and reductions in these loads are more difficult in commercial than residential buildings (see section of Table 2 entitled "Potential Reductions from Energy-efficient Technologies"). Most of these reductions will occur only in new commercial buildings, as retrofits to the walls and windows of existing buildings are costly.

2.3 Measures for Reducing GHG Emissions in the Residential, Commercial and Institutional Buildings Sector

A myriad of measures has been implemented over the past two decades with the goal of increasing energy efficiency in the

***Table 3:** Annual Annex I buildings sector carbon emissions and potential reductions in emissions from technologies and measures to reduce energy use in buildings (Mt C) based on IPCC scenario IS92a.*

	Annual Annex I Buildings Sector Carbon Emissions (Mt C) 1990	2010	2020	2050
Source of Emissions—Base Case[a]				
Residential Buildings	900	1 000	1 050	1 100
Commercial Buildings	500	700	750	900
TOTAL	**1 400**	**1 700**	**1 800**	**2 000**
		Annual Global Buildings Sector Carbon Emissions Reductions (Mt C)		
Potential Reductions from Energy-efficient Technologies Assuming Significant RD&D Activities[b] (from SAR)				
Residential Equipment[c]		200	260	440
Residential Thermal Integrity[d]		125	160	220
Commercial Equipment[c]		140	190	360
Commercial Thermal Integrity[d]		45	55	90
TOTAL POTENTIAL REDUCTIONS		**510**	**665**	**1 110**
Potential Reductions from Energy-efficient Technologies Captured through Measures[e] (Based on Expert Judgment)				
Mandatory Energy-efficiency Standards[f]		95–160	145–240	245–610
Voluntary Energy-efficiency Standards		*g*	*g*	*g*
Market-based Programmes[h]		70–115	90–150	150–380
TOTAL ACHIEVABLE REDUCTIONS		**165–275**	**235–390**	**395–990**

Note: "Potential Reductions from Energy-efficient Technologies" and "Potential Reductions from Energy-efficient Technologies Captured through Measures" are not additive; rather, the second category represents that portion of the first that can be captured by the listed measures.

Footnotes are the same as those for Table 2, except for:
[d] Potential carbon reductions for residential thermal integrity are calculated as 25% of the emissions attributed to heating and cooling energy used in the sector (50% of total residential energy use) in 2010, 30% in 2020 and 40% in 2050. Potential savings for commercial thermal integrity are calculated as 25% of the emissions attributed to heating and cooling energy used in the sector (25% of total commercial energy use) in 2010, 30% in 2020 and 40% in 2050.

buildings sector. This discussion focuses on four general policy areas: (i) market-based programmes in which customers or manufacturers are provided technical support and/or incentives; (ii) mandatory energy-efficiency standards, applied at the point of manufacture or at the time of construction; (iii) voluntary energy-efficiency standards; and (iv) increased emphasis of private or public research, development and demonstration programmes for the development of more efficient products. Information and training programmes are a necessary prerequisite for most of these measures, but it is difficult to directly estimate savings attributable to such programmes (SAR II, 22.5.1.6). Direct government subsidies and loans will not be covered as a separate policy category but rather treated in the context of other measures as a means to reduce private investment costs.[8]

The measures discussed herein often work best in combination. Mutually reinforcing regulatory, information, incentive and other programmes offer the best means for achieving significant portions of the cost-effective energy-efficiency potential (SAR II, 22.5.1.8). Demand-side projects can be "bundled" in order to provide a larger energy "resource" and attract capital, especially in non-Annex I countries (SAR II, 22.5.1.7). Measures need to be carefully tailored to address specific issues and barriers associated with various building characteristics, including commercial versus residential buildings, new construction versus existing retrofits, and owner- versus renter-occupied buildings (SAR II, 22.5.1).

For all of the measures, environmental benefits associated with the use of more energy-efficient equipment and buildings include reduction of other power plant emissions (especially sulfur oxides, nitrogen oxides and particulates), reduced impacts on land and water resulting from coal mining, reduction of air toxics from fossil fuel combustion, and the whole range of environmental benefits resulting from reduced extraction, transport and transmission, conversion and use of energy (Levine *et al*., 1994).

2.3.1 Market-based Programmes

Market-based programmes, which provide some sort of incentive to promote increased use of energy-efficient technologies and practices, can be divided into the following five types:

- Government or utility programmes that obtain *voluntary agreements* from customers (typically industries or owners/operators of large commercial buildings) that they will implement cost-effective energy-efficiency measures in exchange for technical support and/or marketing assistance (e.g., U.S. Department of Energy and Environmental Protection Agency programmes such as Green Lights, Motor Challenge and Energy Star Computers) (SAR II, 22.5.1.6).
- *Procurement programmes* in which very large purchasers (typically governments) commission large numbers of high-efficiency units (SAR II, 22.5.1.1). Examples include the Swedish NUTEK technology procurement programme and the International Energy Agency's Cooperative Procurement of Innovative Technologies.
- *Manufacturer incentive programmes* in which a competition is held and a substantial reward provided for the development/commercialization of a high-efficiency product [e.g., the U.S. Super Efficient Refrigerator Program (SERP)] (SAR II, 22.5.1.1).
- *Utility demand-side management* (DSM) programmes in which incentives are provided to customers for the purchase of energy-efficient products (SAR II, 22.5.1.4).
- Creation of *energy service companies*, often encouraged by government and utility programmes, that pay the full cost of energy-efficient products in exchange for a portion of future energy cost savings (SAR II, 22.5.1.4).

Market-based programmes can be used in place of, or in addition to, standards. In combination with standards, market-based programmes can be designed to induce the acceptance of new and innovative technologies in the marketplace in advance of when they would otherwise be adopted. When combined with active, ongoing RD&D programmes, such efforts are likely to have significant long-term impacts on the availability and performance of advanced, more efficient technologies. For appliances, lighting and office equipment, such programmes can influence a very large number of purchasers, many of whom have little knowledge of or interest in the energy efficiency of the product. Combining market-based programmes and mandatory standards can help overcome some of the difficulties of imposing standards, and could have an impact greater than standards alone.

Importantly, market-based programmes can be directed toward building systems (as opposed to individual pieces of equipment) to reduce energy consumption resulting from inadequate design, installation, maintenance and operation of heating and cooling systems. There are numerous examples of systems problems, such as mismatches between air-handling systems and chillers, absence or inadequate performance of building control systems, simultaneous heating and cooling of different parts of the same building, and so on.

Based on expert judgment, the authors estimate that market-based programmes will result in global carbon emission reductions of about 5% of projected (IS92 scenarios) buildings-related emissions by 2010, about 5–10% by 2020 and about 10–20% by 2050 (see section of Table 2 entitled "Potential Reductions from Energy-efficient Technologies Captured through Measures"), after allowing for an estimate of the portion of savings that is "taken back" in increased services (usage).

Surveys of the costs and benefits of these programmes as they have been applied in the United States generally indicate that they are cost-effective (SAR II, 22.5.1.4). However, it is not possible to generalize, since there have been limited analyses and the costs and savings depend both on the specific technologies that are promoted and the method of implementation of the programme.

[8] Also see Section 9, Economic Instruments.

The major administrative, institutional and political issues in implementing market-based programmes for residential and commercial building equipment follow:

- Difficulties in improving integrated systems
- The need for, and shortage of, skilled persons capable of diagnosing and rectifying systems problems
- The fact that energy users are often not those responsible for paying energy bills, creating a barrier to increased efficiency (SAR II, 22.5.1)
- The need to structure incentives so that intervention in buildings aims at achieving all cost-effective energy efficiency measures
- The need to create institutional structures for the market-based programmes to work effectively
- Perception (or reality) of cross subsidies and related unfairness of expenditures.

2.3.2 Regulatory Measures

Mandatory energy-efficiency standards—through which the government enacts specific requirements that all products (or an average of all products) manufactured and buildings constructed meet defined energy use criteria—are an important regulatory option for residential and commercial buildings; such standards have the potential to yield the largest savings in this sector (SAR II, 22.5.1.2, 22.5.1.3). Appliances typically have lifetimes of 10–20 years (SAR II, 22.4.1.5), while heating and cooling equipment is replaced over a slightly longer time period. These rapid turnover rates mean that inefficient stock can be relatively rapidly replaced with more efficient stock that meets established standards. Residential and commercial buildings, however, more typically last between 50 and 100 years.

Depending on the stringency of the standard levels, the authors estimate (based on expert judgment) that mandatory standards applied to appliances, other energy-using equipment in the building, and the building envelope could result in global carbon emission reductions of about 5–10% of projected (IS92 scenarios) buildings-related emissions by 2010, about 10–15% by 2020 and about 10–30% by 2050 (see section of Table 2 entitled "Potential Reductions from Energy-efficient Technologies Captured through Measures"), after allowing for an estimate of the portion of savings that is "taken back" in increased services (usage).

Mandatory energy-efficiency standards are typically set at levels that are cost-effective such that the benefits in terms of energy savings outweigh any additional costs associated with the more efficient product or building. Thus, such standards yield reductions in carbon emissions at a net negative cost on average. Using the impact of U.S. National Appliance Energy and Conservation Act (NAECA) residential appliance standards during the period 1990–2015 as an example, the cumulative net present costs of appliance standards that have already been implemented in the United States are projected to be $32 000 million and the net present savings are estimated to be $78 000 million (in US$ 1987) (Levine *et al*., 1994).

Project-level costs associated with mandatory standards include programme costs for analysis, testing and rating of the products. Testing laboratories and equipment to certify the performance of the appliances will be needed for a country or group of countries without such facilities but with a growing demand for appliances. Other major costs are the investment costs for initial production of the more efficient products, the need for trained personnel and the need for new institutional structures.

Administrative, institutional and political issues associated with implementing mandatory energy-efficiency standards include the following:

- Opposition from industry for a variety of reasons (perceived loss of profitability, government requirements for increased investments, potential for putting companies out of business and reducing competition)
- Opposition from other groups that could be adversely affected (e.g., electric utilities for some standards)
- Difficulty in obtaining agreement among different countries for uniform test procedures and comparable standards, where this proves desirable
- Difficulty in raising investment money for testing laboratories and for the costs of performing the required tests (especially acute in non-Annex I countries in spite of the fact that the net benefits are much greater than these costs).

Overcoming these difficulties will require substantial effort. Because many appliances are designed, licensed, manufactured and sold in different countries with varying energy costs and consumer use patterns, regional initiatives coupled with financing to set up standards and testing laboratories, especially in Annex I countries with economies in transition and non-Annex I countries, may be needed to overcome many institutional barriers.

There also are administrative, institutional and political benefits associated with mandatory energy-efficiency standards, including responding to consumer and environmental concerns, reducing future generating capacity requirements, and providing credibility to manufacturers that take the lead in introducing energy-efficient products through uniform test procedures. Harmonization of test procedures and standards could reduce manufacturing costs associated with meeting various requirements.

2.3.3 Voluntary Standards

Voluntary energy-efficiency standards, where manufacturers and builders agree (without government-mandated legislation) to generate products or construct buildings that meet defined energy use criteria, can serve as a precursor or alternative to mandatory standards (SAR II, 22.5.1.2). For products covered by these standards, there must be agreement on test procedures, adequate testing equipment and laboratories to certify equipment and product labeling—thus satisfying the prerequisites of mandatory standards. Voluntary standards have been more successful in the commercial sector than in the residential sector, presumably because commercial customers are more knowledgeable about energy use and efficiency of equipment than residential consumers.

Energy use and carbon emissions reductions for voluntary standards vary greatly, depending upon the way in which they are carried out and the participation by manufacturers. Based on expert judgment, the authors estimate that global carbon emissions reductions from these standards could range from 10–50% (or even more if combined with strong incentives) of the reductions from mandatory standards.

Project-level costs associated with voluntary standards (costs of testing equipment and laboratories, and the initial investment costs) are the same as those for mandatory standards. The increased investment for more efficient products, however, will be lower than that for mandatory standards, as voluntary standards are expected to affect the market less.

The administrative, institutional and political issues surrounding the achievement of voluntary standards are similar to those for mandatory standards but of smaller magnitude, proportionate to their ability to affect energy efficiency gains in appliances, other equipment and buildings.

2.3.4 Research, Development and Demonstration

RD&D programmes foster the creation of new technologies that enable measures to have impacts over the longer term. In general, only large industries and governments have the resources and interest to conduct RD&D. The building industry, in contrast, is highly fragmented, which makes it difficult for the industry to pool its resources to conduct RD&D. Government-supported RD&D has played a key role in developing and commercializing a number of energy-efficient technologies, such as low-emissivity windows, electronic ballasts and high-efficiency refrigerator compressors. While Annex I RD&D results can often be transferred to non-Annex I countries, there are conditions specific to these countries that require special attention, such as building design and construction for hot, humid climates. For this reason, it is essential to develop a collaborative RD&D infrastructure between researchers based in non-Annex I countries and both Annex I and non-Annex I country RD&D specialists (SAR II, 22.5.1.5).

A specific carbon emissions reduction estimate is not assigned to RD&D in Table 2; rather, it is noted that vigorous RD&D on measures to use energy more efficiently in buildings—encompassing improvements in equipment, insulation, windows, exterior surfaces and especially building systems—is essential if substantial energy savings are to be achieved in the period after 2010. It is essential to note that the emissions reductions potentials for the residential, commercial and institutional buildings sector will not be realized without significant RD&D activities.

2.4 Global Carbon Emissions Reductions through Technologies and Measures in the Residential, Commercial and Institutional Buildings Sector

A range of total achievable emissions reductions for global residential, commercial and institutional buildings is provided in Tables 1 and 2. These reductions are estimated to be about 10–15% of projected emissions in 2010, 15–20% in 2020 and 20–50% in 2050, based on IS92 scenarios. Thus, total achievable carbon emissions reductions for the buildings sector are estimated to range (based on IS92 scenarios) from about 0.175–0.45 Gt C/yr by 2010, 0.25–0.70 Gt C/yr by 2020 and 0.35–2.5 Gt C/yr by 2050.

The measures described can be differentiated based on their potential for carbon emissions reductions, cost-effectiveness and difficulty of implementation. All of the measures will have favorable impacts on an overall economy, to the extent that the energy savings are cost-effective. Environmental benefits are approximately proportional to the reductions in energy demand, thus to carbon savings. The administrative and transaction costs of the different measures can vary markedly. While building codes and standards can be difficult to administer, many countries now require some minimum level of energy efficiency in new construction. Many of the market programmes introduce some complexity, but they often can be designed to obtain savings that are otherwise very difficult to capture. The appliance standards programmes are, in principle, the least difficult to administer, but political consensus on these programmes can be difficult to achieve.

3. TRANSPORT SECTOR[9]

3.1 Introduction

In 1990, CO_2 emissions from transport sector energy use amounted to about 1.25 Gt C—one-fifth of CO_2 emissions from fossil fuel use (SAR II, 21.2.1). Other important GHG emissions from the sector include N_2O from tailpipe emissions from cars with catalytic converters; CFCs and HFCs, which are leaked and vented from air-conditioning systems; and NO_x emitted by aircraft near the tropopause (at this height, the ozone generated by NO_x is a very potent GHG). World transport energy use grew faster than that in any other sector, at an average of 2.4% per year, between 1973 and 1990 (SAR II, 21.2.1).

GHG mitigation in the transport sector presents a particular challenge because of the unique role that travel and goods movement play in enabling people to meet personal, social, economic and developmental needs (SAR II, 21.2.3). The sector may also offer a particular opportunity because of the commonality of vehicle design and fuel characteristics. Transport has many stakeholders, including private and commercial transport users, manufacturers of vehicles, suppliers of fuels, builders of roads, planners and transport service providers. Measures to reduce transport GHG emissions often challenge the interests of one or another of these stakeholders. Mitigation strategies in this sector run the risk of failure unless they take account of stakeholder concerns and offer better means of meeting the needs that transport addresses. The choice of strategy will depend on the economic and technical capabilities of the country or region under consideration (SAR II, 21.4.7).

3.2 Global Carbon Emission Trends and Projections

Table 4 shows energy use by different transport modes in 1990, and two possible scenarios of CO_2 emissions to 2050 (SAR II, 21.2). These two scenarios are used in this section as the basis for evaluating the effects of measures on GHG emissions. Energy intensity fell by 0.5–1% per year in road transport between 1970 and 1990, and by 3–3.5% per year in air transport between 1976 and 1990. Ranges of future traffic growth and energy-intensity reduction shown in the table are expected to be slower than in the past (SAR II, 21.2.5). Most scenarios in the literature foresee a continuing reduction in growth rates for energy use whereas these two scenarios are based on constant growth rates; thus, the HIGH estimates in this table are much higher than IS92e for 2050. The LOW scenario in 2050 is about 10% below IS92c, and would be unlikely to occur without some change in market conditions (such as a sharp rise in oil prices) or new policies, for example to reduce air pollution and traffic congestion in cities.

The largest transport sector sources of GHG through to 2050 are likely to be cars and other light-duty vehicles (LDVs), heavy-duty vehicles (HDVs) and aircraft. Current annual percentage growth in all of these is particularly high in southeast Asia, while some central and eastern European countries are seeing a very rapid increase in car ownership. Two-wheelers,

[9] This section is based on SAR II, Chapter 21, *Mitigation Options in the Transportation Sector* (Lead Authors: L. Michaelis, D. Bleviss, J.-P. Orfeuil, R. Pischinger, J. Crayston, O. Davidson, T. Kram, N. Nakicenovic and L. Schipper).

Table 4: *Global transport energy use to 2050—LOW and HIGH scenarios.*[a]

Transport Mode	1990 Energy[b] (EJ)	1990 CO_2 Emitted[c] (Mt C)	Traffic Growth[d] (%)	Energy Intensity[e] (%)	CO_2 Emissions (Mt C) 2010 LOW	2010 HIGH	2020 LOW	2020 HIGH	2050 LOW	2050 HIGH
Car, Other Personal and Light Goods Vehicles	30–35	555–648	1.4–2.1	–1.0–0.0	592	989	612	1 223	674	2 310
Heavy Goods Vehicles and Buses	20–23	370–426	1.9–2.7	–0.6–0.0	470	718	530	933	758	2 047
Air	8	148	3.2–4.0	–2.0– -0.6	187	308	210	444	297	1 330
Other (rail, inland waterway)	4	74	0	–0.3–0.3	70	78	68	80	62	87
TOTAL RANGE	63–71	1 166–1 314			1 318	2 094	1 418	2 680	1 791	5 774

[a] Based on SAR II, 21.2.5 and 21.3.1, unless otherwise noted.
[b] Based on SAR II, 21.2.1.
[c] CO_2 emissions in this table are calculated from energy consumption using a constant emission factor for all modes of 18.5 Mt C/EJ.
[d] Based on SAR II, 21.2.4.
[e] Energy use per vehicle kilometre in the case of cars; energy use per ton kilometre for goods vehicles and rail, marine and air freight; and energy per passenger kilometre for buses, air and rail transport.

especially mopeds with two-stroke engines, are one of the fastest growing means of personal transport in parts of south and east Asia and Latin America, but account for only 2–3% of global transport energy use (SAR II, 21.2.4). These vehicles have very high emissions of local pollutants.

Annex I countries accounted for about three-quarters of global transport sector CO_2 emissions in 1990. This share is likely to decline to about 60–70% by 2020 (SAR II, 21.2.2) and further by 2050, assuming continuing rapid growth in non-Annex I countries.

3.3 Technologies for Reducing GHG Emissions in the Transport Sector

Transport systems and technology are evolving rapidly. Although in the past this evolution has included reductions in energy intensity for most vehicle types, relatively little reduction occurred during the decade prior to 1996. Instead, recent technical advances mainly have been used to enhance performance, safety and accessories (SAR II, 21.2.5). There is little or no evidence for any saturation of transport energy demand as marginal income continues to be used for a more transport-intensive lifestyle, while increasing value-added in production involves more movement of intermediate goods and faster, more flexible freight transport systems.

A number of technological and infrastructural mitigation options are discussed in the SAR (II, 21.3). Several are already cost-effective in some circumstances (i.e., their use reduces private transport costs, taking into account energy savings, improvements in performance, etc.). These options include energy-efficiency improvements; alternative energy sources; and infrastructure changes, modal shifts and fleet management. The cost-effectiveness of these technical options varies widely among individual users and among countries, depending on availability of resources, know-how, institutional capacity and technology, as well as on local market conditions.

3.3.1 Energy-efficiency Improvements

Some energy-intensity reductions are cost-effective for vehicle operators, because fuel savings will compensate for the additional cost of more energy-efficient vehicles (SAR II, 21.3.1). Several studies have indicated that these potential savings are not achieved for a variety of reasons, in particular their low importance for vehicle manufacturers and purchasers relative to other priorities, such as reliability, safety and performance. Many vehicle users also budget for vehicle operation separately from vehicle purchase, especially where the latter depends on obtaining a loan, so that they do not trade off the vehicle price directly against operating costs. Although fuel savings may not justify the time, effort and risk involved for the individual or corporate vehicle purchaser, they could be achieved through measures that minimize or bypass these barriers. In cars and other personal vehicles, savings that are cost-effective for users in 2020 might amount to 10–25% of projected energy use, with vehicle price increases in the range $500–1 500. Larger savings in energy are possible at higher cost, but these would not be cost-effective (NRC, 1992; ETSU, 1994; DeCicco and Ross, 1993; Greene and Duleep, 1993).

The potential for cost-effective energy savings in commercial vehicles has been studied less than that in cars, and is estimated to be smaller—perhaps 10% for buses, trains, medium and heavy trucks and aircraft—because commercial operators already have stronger incentives to use cost-effective technology (SAR II, 21.3.1.5).

Energy-intensity reductions are possible beyond the level that is cost-effective for users; however, vehicle design changes that offer large reductions in energy intensity also are likely to affect various aspects of vehicle performance (SAR II, 21.3.1.5). Achieving these changes would thus depend either on a shift in the priorities of vehicle manufacturers and purchasers, or on breakthroughs in technology performance and cost.

Where energy-intensity reductions result from improved vehicle body design, GHG mitigation may be accompanied by a reduction in emissions of other air pollutants, where these are not controlled by standards that effectively require the use of catalytic converters. On the other hand, some energy-efficient engine designs (e.g., direct fuel injection and lean-burn engines) have relatively high emissions of NO_x or particulate matter (SAR II, 21.3.1.1).

Changes in vehicle technology can require very large investments in new designs, techniques and production lines. These short-term costs can be minimized if energy-efficiency improvements are integrated into the normal product cycle of vehicle manufacturers. For cars and trucks, this means that there might be a ten-year delay between a shift in priorities or incentives in the vehicle market, and the full results of that shift being seen in all the vehicles being produced. For aircraft, the delay is longer because of the long service life of aircraft, and because new technology is only approved for general use after its safe performance has been demonstrated through years of testing.

3.3.2 Alternative Energy Sources

On a full-fuel-cycle basis, alternative fuels from renewable energy sources have the potential to reduce GHG emissions from vehicle operation (i.e., excluding those from vehicle manufacture) by 80% or more (SAR II, 21.3.3.1). At present, these fuels are more expensive than petroleum products under most circumstances, although vehicles operating on liquid biofuels can perform as well as conventional vehicles and manufacturing costs need be no higher in mass production. Widespread use of these fuels depends on overcoming various barriers, including the costs of transition to new vehicle types, fuel production and distribution technology, concerns about safety and toxicity, and possible performance problems in some climates. The widespread use of hydrogen and electricity in road vehicles poses technical and cost challenges that remain to be overcome.

Fossil fuel alternatives to gasoline [e.g., diesel, liquefied petroleum gas (LPG), compressed natural gas (CNG)] can offer 10–30% emission reductions per kilometre, and are already cost-effective for niche markets such as high-mileage and fleet vehicles, including small urban buses and delivery vans (SAR II, 21.3.3.1). Several governments are encouraging the use of LPG and CNG because they have lower emissions of conventional pollutants than gasoline or diesel, but switching from gasoline to diesel can result in higher emissions of particulates and NO_x. The use of hybrid and flexible-fuel vehicles may allow alternative fuels and electric vehicles to meet the mobility needs of a larger segment of vehicle users, but at a higher cost and with smaller GHG reductions than single-fuel vehicles (SAR II, 21.3.4). Alternatives to diesel are unlikely to be cost-effective for users of heavy-duty vehicles, and many will result in increased GHG emissions (SAR II, 21.3.3.2). Nevertheless, a small but increasing number of urban buses and delivery vehicles are being fueled with CNG, LPG, or liquid natural gas (LNG) to reduce urban emissions of NO_x and particulates. Alternatives to kerosene in aircraft are being tested, but are unlikely to be cost-effective in the near term (SAR II, 21.3.3.3). Much of the political impetus for the use of alternative fuels has objectives other than GHG mitigation, such as improving urban air quality, maintaining agricultural employment, and ensuring energy security.

3.3.3 Infrastructure and System Changes

Urban density, urban and transport infrastructure, and the design of transport systems can all affect the distance people travel to meet their needs and their choice of transport modes (SAR II, 21.4.2). These factors also influence the volume of freight transport and the modes used. The extent of these various effects is controversial, and it should be noted that urban and transport infrastructure is usually designed predominantly for objectives other than GHG mitigation.

Traffic and fleet management systems have the potential to achieve energy savings on the order of 10% or more in urban areas (SAR II, 21.4.2). Energy use for freight transport might be reduced substantially through changes in the management of truck fleets. Modal shifts from road to rail may result in energy savings of 0–50%, often resulting in commensurate or greater GHG emission reductions, especially where trains are powered by electricity from non-fossil fuel sources (SAR II, 21.3.4, 21.4.2). The cost-effectiveness and practicality of freight transport by rail varies widely among regions and commodities (SAR II, 21.2.5). The long-term potential for rail freight may depend on the development of rail and intermodal technologies that can cope with a growing emphasis on flexibility and responsiveness.

3.4 Measures for Reducing GHG Emissions in the Transport Sector

A first step toward meeting climate objectives in the transport sector is to introduce GHG mitigation measures that are fully justified by other policy objectives. Such measures may increase the competitiveness of industry, promote energy security, improve citizens' quality of life, or protect the environment (SAR II, 21.4). In principle, the most economically efficient way to address all of these issues is by removing the subsidies that exist in some countries for road transport, and by introducing pricing mechanisms that reflect the full social and environmental cost of transport (SAR II, 21.4.5).

In practice, economically efficient measures such as road-user charges may be difficult to implement for technical and political reasons. Local circumstances demand local solutions, and the success of strategies may depend on their being designed:

- With an understanding of the current system and its evolution
- Including consideration of a wide range of measures
- In consultation with stakeholders
- Including monitoring and adjustment mechanisms (SAR II, 21.4.7).

This analysis cannot provide a global assessment, but considers ranges of possible effects of measures. It focuses on the three vehicle groups expected to be the largest sources of GHGs in 2020 (i.e., LDVs, HDVs and aircraft).

Annex I countries account for the vast majority of the world's vehicle fleets; developing countries in 1990 accounted for about a tenth of the world's cars. Meanwhile, almost all of the vehicles produced worldwide are either manufactured in Annex I countries or made to designs originating in those countries (SAR II, 21.2.4). Policies introduced in Annex I countries that affect vehicle technology are thus likely to have worldwide effects.

3.4.1 Measures Affecting Light-duty Road Vehicles and Urban Traffic

Long-term management of GHG emissions from light-duty vehicles is likely to depend on implementing wide-ranging strategies involving several areas of policymaking and levels of government (SAR II, 21.4.1). These strategies might involve a variety of measures, including fuel economy standards (SAR II, 21.4.3), fuel taxes (SAR II, 21.4.5.2), incentives for alternative fuel use (SAR II, 21.3.3), measures to reduce vehicle use (SAR II, 21.4.2), and RD&D into vehicle and transport system technology (SAR II, 21.3.6), some of which are evaluated in Table 5. The relative effectiveness of policies depends on national circumstances, including existing institutions and policies, and on underlying technology trends. Measures to reduce GHG emissions from cars are normally appropriate for other light-duty vehicles such as light trucks, vans, minibuses and sports utility vehicles. These vehicle types increasingly are being used as personal vehicles, leading to higher GHG emissions.

Table 5: *Selected examples of measures to mitigate GHG emissions from light-duty vehicles.*[a]

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Vehicle Energy Intensity – Change vehicle body design – Change engine design – Changes in engine combustion chamber design – Changes in fuel/air mixing – Computer technology to improve vehicle and engine management – Encourage vehicle downsizing (reduced weight and power) [Estimated effects based on SAR II, 21.4.3; SAR II, 21.4.5.1; NRC, 1992; DeCicco and Ross, 1993; OTA, 1991; ETSU, 1994; Goodwin, 1992]	**Market-based Instruments** – Feebates: New car taxes increase US$400 for every L/100 km (no change in average car tax)	**Climate Benefits in 2020** – 10–20% of LDV CO_2 for all scenarios **Other Effects** – Up to 6% increase in traffic and its environmental effects, unless reduced by other measures	**Cost-effectiveness** – Average new car cost increase of 1–9% paid back in fuel savings **Macro-economic Issues** – Implementation costs may decrease car sales in short run – As feebates, but economic boost likely to be smaller **Equity Issues** – For consumers, positive for owners of small cars; negative for non-car-owners and owners of large cars – Can change manufacturing industry competitiveness, but should in an economically efficient way	**Administrative/ Institutional Factors** – Moderate administration costs for government – Less government expertise required than for standards **Political Factors** – Opposition from vehicle manufacturers – Concern about safety effects
	Regulatory Instruments – Fuel Economy Standards or Voluntary Agreements: 30% reduction in new LDV energy intensity in 2010, relative to 1995 levels; reduction relative to trend depends on scenario	**Climate Benefits in 2020** – 3–5% of LDV CO_2 relative to LOW – 22–28% of LDV CO_2 relative to HIGH **Other Effects** – 3–10% traffic increase with local environmental effects in HIGH, unless reduced by other measures	**Cost-effectiveness** – Average new car cost increase of <0.5% in LOW and 5–15% in HIGH paid back in fuel savings – Possible high short-run costs for car industry, but reduces life-cycle cost of car use **Macro-economic Issues** – Reduced oil imports and car running cost may increase car sales and traffic in long run, hence boosting the economy **Equity Issues** – Effects on consumers as feebates – Can affect industry competitiveness in an economically inefficient way	**Administrative/ Institutional Factors** – Government requires expertise to determine standards – Moderate administration costs for government **Political Factors** – Opposition from vehicle manufacturers – Concern about safety effects

Table 5 (continued)

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Vehicle Energy Intensity (see above); Reduce Speed or Improve Speed Management; Improve Fleet Management to Increase Vehicle Load Factor; Switch to Public and Non-motorized Transport; Switch to Alternative Energy Sources (see below) [SAR II, 21.4.5; Goodwin, 1992]	**Market-based Instruments** – Road Fuel Taxes: Locally defined to include social and environmental costs in fuel price • \$0.2–0.5/L where taxes already high • \$0.3–0.8/L where taxes currently low	**Climate Benefits in 2020** – 10–25%[b] of LDV CO_2 in countries where taxes are already high – 40–60%[b] of LDV CO_2 in countries where taxes are very low **Other Effects** – Half or more of GHG impact is through reduced traffic, with proportionate environmental benefits	**Cost-effectiveness** – Higher cost for road-users **Macro-economic Issues** – Reduced car sales; wider effects depend on use of revenue [SAR III, 11.3.2] **Equity Issues** – Gasoline taxes found by some studies to be regressive in North America and progressive in western Europe [SAR III, 11.5.6]	**Administrative/ Institutional Factors** – Difficult to assess social and environmental cost – Revenue source for government, with negligible additional administration cost **Political Factors** – Opposition from fuel producers and suppliers – Opposition from motorists' organizations and other interest groups
Switch to Alternative Energy Sources – Diesel, CNG, LPG as alternatives to gasoline – Synthetic fuels from biomass sources – Hydrogen or electricity from renewable power sources – Hybrid vehicle drive-trains [SAR II, 21.3.3.1; IEA, 1993]	**Economic Instruments** – Fiscal incentives or subsidies for alternative fuels and electric vehicles **Regulatory Instruments** – Alternative fuel/electric vehicle mandates	**Climate Benefits in 2020** – 10-30% where CNG or LPG used; cost-effective potential up to 5% of overall LDV emissions – 80% or more with biofuels and EVs using renewable-derived electricity **Other Effects** – Local air pollution reduced with some alternative fuels, but increased with others; possible increased environmental effects of intensive agriculture where biofuels promoted	**Cost-effectiveness** – User-financed costs lower than gasoline for LPG, CNG and diesel in some applications – User costs higher for biofuel, EV and hydrogen; costs can be very high (up to \$1 000 per ton of CO_2 avoided) **Macro-economic Issues** – Replacing oil with domestically produced fuels can boost employment **Equity Issues** – Biomass use can increase rural employment	**Administrative/ Institutional Factors** – Low administration cost for government – May require new safety and technical standards – International cooperation helpful **Political Factors** – Car manufacturers' cooperation important – Support from producers of alternative fuels, including farmers in case of biofuels
Reduced Refrigerant Leakage in Air Conditioning and Other Cooling Circuits [SAR II, 21.3.1.6]	**Regulatory Instruments** – Refrigerant Leakage Standards: For example, limit HFC leaks to 5% of total charge per year	**Climate Benefits in 2020** – Reduce HFC emissions by 70–80% (equivalent to 7–8% of LDV life-cycle emissions	**Cost-effectiveness** – Not assessed	**Administrative/ Institutional Factors** – International cooperation important **Political Factors** – Manufacturers may oppose standards
Reduce Non-CO_2 Exhaust Emissions – Low-N_2O catalyst	**R&D** – Aim at eliminating N_2O production in catalytic converters	**Climate Benefits** – Equivalent to about 10% of tailpipe GHG emissions	**Cost-effectiveness** – Not assessed	**Administrative/ Institutional Factors** – International cooperation important

Table 5 (continued)

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Use of Motorized Vehicles; Reduce Transport Energy Intensity (mode shifts, changing driving behavior); Use Information Technology to Improve Vehicle, Fleet and Traffic Management; Change Settlement and Transport Systems, including Improved Non-motorized Transport Infrastructure; Telecommunications (home-working, virtual reality systems, etc.) [SAR II, 21.4.6]	**Transport and Urban Planning/Infrastructure** – Local Transport Initiatives: Locally defined; can include fees and taxes, regulations, planning, service provision, education and information	**Climate Benefits in 2020** – 10% or more of LDV emissions in long term, perhaps more where infrastructure is developing rapidly **Other Effects** – Potentially very large benefits	**Cost-effectiveness** – Measures are usually adopted mainly for reasons other than GHG mitigation, so GHG mitigation has small or negative cost **Macro-economic Issues** – Positive or negative depending on local circumstances and design of measures **Equity Issues** – Positive or negative depending on local circumstances and design of measures	**Administrative/ Institutional Factors** – Local decision-making processes important – Cooperation between different levels of government and different policy interests important **Political Factors** – Opposition from road construction industry – Local businesses may oppose access restrictions
All Options [SAR II, 21.3.6, 21.3.1.5, 21.3.3.1]	**RD&D and Information**	**Climate Benefits** – More than 20% of LDV GHGs by 2020, but can be 80% or more in long term (2050+) **Other Effects** – Potentially very large benefits	**Cost-effectiveness** – Inherently unpredictable, but potential for negative-cost emission reductions **Macro-economic Issues** – Inherently unpredictable, but potentially large benefits **Equity Issues** – Unpredictable	**Administrative/ Institutional Factors** – Local/independent initiatives need encouragement – International cooperation helpful

[a] GHG effects calculated for 2020 relative to two scenarios: "LOW" (rapid energy intensity reduction, slow traffic growth) and "HIGH" (slow energy intensity reduction, rapid traffic growth), in which emissions roughly correspond to those in IS92c and IS92e, respectively (see Table 4). Ranges in costs and effects of measures reflect differences among literature sources and ranges of uncertainty; scenarios and national differences are explicitly mentioned.

[b] Based on a fuel own-price elasticity of –0.7. Goodwin (1992) suggests a range of –0.7 to –1.0, so effects could be larger than shown here.

This increasing use could be encouraged if such vehicles are not subject to the same measures as cars.

Many of the measures in Table 5 might be justified wholly or partly by objectives other than GHG mitigation. Fuel economy standards and feebates may be justified as means of overcoming market barriers that inhibit the uptake of cost-effective, energy-efficient technology. Increased fuel taxes also can have a range of social and environmental benefits, while generating revenue that can be recycled to meet priority needs in the transport sector or elsewhere, although they may also impose a welfare loss on some transport users.

Governments are most likely to adopt some combination of measures. For example, fuel economy standards and incentives can result in a lower cost of driving—hence more traffic, unless implemented in conjunction with fuel taxes, road pricing, or other measures to discourage driving. Renewable energy supplies are more likely to be able to meet future transport energy needs if energy intensity and traffic levels are kept low. Thus, the effectiveness of incentives to purchase alternative- fuel vehicles may be enhanced by taxes on conventional fuels, which provide incentives both to use alternative fuels and to reduce energy use.

Policies developed at a local level, aimed at efficiently addressing the full range of local economic, social and environmental priorities, may be among the most important elements of a long-term strategy for GHG mitigation in the transport sector (SAR II, 21.4.2). Measures include computerized traffic control;

parking restrictions and charges; use of tolls, road pricing and vehicle access restrictions; changing road layouts to reduce traffic speed; and improved facilities and priority in traffic for pedestrians, cyclists, and public transport.

Infrastructure development is very expensive, and this cost is likely to be committed for a broad range of economic, social, environmental and other reasons. There may be institutional barriers to integration of GHG mitigation objectives into decision-making processes, but doing so could have a range of benefits, perhaps leading to lower costs where non-motorized transport receives a higher priority than before, relative to motorized transport. Designing cities for non-motorized and public transport can lead to long-term economic benefits as the improved urban environment stimulates local business (SAR II, 21.4.2).

Some of the best-known examples of strategies that have succeeded in reducing traffic and its environmental effects, including GHG emissions, have been implemented by the city-state of Singapore, the city of Curitiba in Brazil and a number of European cities (SAR II, 21.4.6). These cities illustrate the importance of local initiative and integrated planning and market-based approaches in developing appropriate combinations of measures.

A wide range of environmental and social benefits may come from local transport strategies to reduce traffic and improve non-motorized access (SAR II, 21.4.6), although such strategies may also result in welfare losses for some transport users.

In the long term, changes in travel culture and lifestyle, combined with changes in urban layout, might lead to substantial reductions in motorized travel in North American and Australian cities. The potential reduction in west European cities is smaller (SAR II, 21.4.2). Some of the most important short-term opportunities for urban planning to affect long-term transport energy use is in countries with economies in transition and fast-developing countries, where the car is still a minority transport mode but is rapidly increasing in importance (SAR II, 21.4.2).

3.4.2 Measures Affecting Heavy-duty Vehicles and Freight Traffic

Table 6 summarizes some possible effects of measures to reduce heavy-duty vehicle GHG emissions. Measures differ from those for light-duty vehicles because trucks vary more than cars in design and purpose, making it harder to design energy-intensity standards for them, although compulsory fitting of speed limiters and power-to-weight ratios can reduce energy use (SAR II, 21.2.4.3). Meanwhile, commercial vehicle operators are relatively responsive to fuel prices in both their management of existing vehicles and their choice of new vehicles. A combination of fuel taxes and voluntary agreements, publicity and incentives (e.g., in license fees) for the purchase of energy-efficient vehicles may be sufficient to encourage the uptake of technology improvements (SAR II, 21.2.4.3).

Studies in some countries have found that HDVs are subsidized more than LDVs, considering the high share of road repair costs allocable to HDVs. Efficient measures to reflect these costs to freight operators could increase the costs of road freight by 10–30% (SAR II, 21.4.5) and would achieve 10–30% reductions in freight traffic and associated GHG emissions (based on price elasticities in Oum *et al*., 1990).

Table 6: *Selected examples of measures to mitigate GHG emissions from heavy-duty vehicles.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Vehicle Energy Intensity (see Table 4); Reduce Speed or Improve Speed Management; Improve Fleet Management to Increase Vehicle Load Factor; Switch to Public and Non-motorized Transport; Switch to Alternative Energy Sources (see below) [SAR II, 21.4.5; Oum *et al*., 1990]	**Market-based Instruments** – Diesel Tax Increase: Locally defined to include social and environmental costs in fuel price – 50% to 200% fuel price increase	**Climate Benefits** – 10–40% reduction in HDV emissions[a] **Other Effects** – Reduction in traffic and associated environmental impacts	**Cost-effectiveness** – Increased cost for vehicle operators justified by social/environmental costs **Macro-economic Issues** – Broader economic effects depend on use of revenue [SAR III, 11.3.2] **Equity Issues** – International competitiveness effects in haulage and other industry	**Administrative/ Institutional Factors** – Significant revenue source for governments, with negligible additional administration cost – International coordination could help **Political Factors** – Haulage industry likely to oppose

Table 6 (continued)

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Vehicle Energy Intensity (see Table 4) [SAR II, 21.3.1.5]	**Economic Instruments** – Incentives for reduced energy intensity through vehicle taxes, license fees, accelerated depreciation, etc. **Voluntary Agreements** – With fleet operators and vehicle manufacturers to reduce energy intensity	**Climate Benefits** – Up to 10% of HDV emissions **Other Effects** – Possible lower emission of NO_x and particulates – Reduced operating costs can increase traffic and other environmental effects	**Cost-effectiveness** – Increased vehicle cost may be paid back in fuel savings within 3 years **Macro-economic Issues** – Reduced haulage costs likely to boost economy	**Administrative/ Institutional Factors** – Requires high level of government expertise and contact to achieve agreement with manufacturers and users **Political Factors** – Haulage industry might oppose tax changes
Switch to Alternative Energy Sources – Synthetic fuels from biomass sources – Hydrogen or electricity from renewable power sources – Hybrid vehicle drive-trains [SAR II, 21.3.3.2; IEA, 1993, 1994; CEC, 1992]	**Market-based Instruments** – Alternative fuel/EV subsidies and tax incentives	**Climate Benefits** – More than 80% reduction in emissions per ton-km for some biofuels; typically 50% for "biodiesel" – Overall effect depends on resource availability and cost **Other Effects** – Reduced local air pollution – Possible increased environmental effects from biofuels production	**Cost-effectiveness** – Cost of subsidies and foregone tax revenue can be very high (up to $1 000 per ton of CO_2 avoided), but may be justified by agricultural or other policy – Administrative costs low **Macro-economic Issues** – Replacing oil with domestically produced fuels can boost employment **Equity Issues** – Biomass use can increase rural employment	**Administrative/ Institutional Factors** – Supported by alternative fuel producers – May require new safety and technical standards – International cooperation can help **Political Factors** – Supported by alternative fuel producers
Reduce Transport Energy Intensity (fleet management) and Reduce Traffic [SAR II, 21.3.2]	**Planning/Infrastructure/ Information** – Freight transport management systems (e.g., GPS) – Intermodal freight systems with disincentives for use of roads	**Climate Benefits** – Increased truck load factors could reduce GHG/ton-km by 10–30% – Transfer to rail could reduce energy use by 80%, but only for long hauls and low speeds **Other Effects** – Reduction in traffic brings broad environmental benefits	**Cost-effectiveness** – Cost justified by non-GHG environmental benefits	**Administrative/ Institutional Factors** – Local decision-making processes important – Cooperation between different levels of government and different policy interests important – International cooperation helpful **Political Factors** – Road construction industry likely to oppose
All Types of Technical Measures [SAR II, 21.3.6, 21.3.1.5, 21.3.3.2]	**RD&D and Information**	**Climate Benefits** – More than 10% of HDV GHGs by 2020, but can be 80% or more in long term (2050+), with broad environmental benefits	**Cost-effectiveness** – Unpredictable **Macro-economic Issues** – Unpredictable **Equity Issues** – Unpredictable	**Administrative/ Institutional Factors** – Local/independent initiatives need encouragement – International cooperation helpful **Political Factors** – Supported by industry

[a] Based on a fuel own-price elasticity of –0.2. Oum *et al*. (1990) give a wide range of freight own-price elasticities, depending on commodity, type of haul and other factors.

Table 7: *Selected examples of measures to mitigate GHG emissions from aircraft.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Traffic; Reduce Energy Intensity (aircraft design operation) – Improve maintenance – Change airframe design – Change engine design – Improve flight management – Increase aircraft load factor	**Market-based Instruments** – Aviation Fuel Taxes: 10% on fuel price (2¢/L tax) [SAR II, 21.4.5.2]	**Climate Benefits** – 1% short-term reduction in traffic – Larger percentage long-term reduction in aviation GHG	**Macro-economic Issues** – Depend on revenue use	**Administrative/ Institutional Factors** – Need regional or international agreement **Political Factors** – Opposition from airlines
Emission Controls	**Regulatory Instruments** – Aircraft Engine NO_x Standards [SAR II, 21.3.1.6, 21.4.1]	**Climate Benefits** – Possibly 30–40% reduction in NO_x emission factor during cruise – Longer-term target might be 80% reduction **Other Effects** – Reduces NO_x around airports – Higher particulate emissions possible		**Administrative/ Institutional Factors** – Could be based on existing international standards – Need broad international agreement **Political Factors** – Aircraft engine manufacturers might oppose tight standards
Reduce Energy Intensity (operational) – Reduce delays – Optimize flight patterns	**Planning/Infrastructure** – Improve air traffic control – Improve fleet management and routing [SAR II 21.3.2; ETSU, 1994]	**Climate Benefits** – 3–5% reduction in GHG emissions **Other Effects** – Reduced noise and air pollution	**Cost-effectiveness** – Economic benefits for industry **Macro-economic Issues** – High government costs	**Administrative/ Institutional Factors** – Need regional or international cooperation **Political Factors** – Supported by airlines
Reduce Energy Intensity and Traffic, and Switch to Alternative Fuels	**RD&D and Information** [SAR II, 21.3.1.3, 21.3.1.5, 21.3.6, 21.3.3.3, 21.3.1.6]	**Climate Benefits** – 10% by 2020, but can be 80% GHG mitigation in long term (2050+) **Other Effects** – Unpredictable	**Cost-effectiveness** – Unpredictable **Macro-economic Issues** – Unpredictable **Equity Issues** – Unpredictable	**Administrative/ Institutional Factors** – International cooperation helpful **Political Factors** – Supported by airlines and aircraft manufacturers

Other policies, such as the development of intermodal facilities to encourage the use of rail, often are advocated. Enhancing rail infrastructure may indeed be able to contribute to GHG mitigation, when combined with constraints on the use of road freight, and disincentives such as tolls (SAR II, 21.4.3). High use of rail is most practical for long hauls, so that such policies would be most effective in large countries or when internationally coordinated in regions with large numbers of small countries (SAR II, 21.2.4).

3.4.3 Measures Affecting Aircraft[10]

Table 7 summarizes the effects of a range of policies to reduce GHG emissions from aircraft. Large reductions in NO_x emissions might be more politically feasible through aircraft engine standards (SAR II, 21.3.1.6) and RD&D funding, although the radiative impact of aircraft NO_x is short-lived and highly uncertain and there could be tradeoffs between reduced NO_x and fuel efficiency (SAR II, 21.3.1.6).

The Council of the International Civil Aviation Organization (ICAO) recommends that fuel used for international aviation

[10]In cooperation with ICAO and the international ozone assessment process under the Montreal Protocol, the IPCC has agreed to conduct an assessment of the global atmospheric effects of aircraft emissions, including evaluation of technologies and measures for reducing emissions. This assessment will be available in 1998.

should be tax-exempt (SAR II, 21.4.5.2), but does not preclude "charges" for environmental purposes. Some airports have landing fees related to aircraft noise levels, and environmental charges could extend to cover aircraft GHG emissions (e.g., through a fuel surcharge). International cooperation, at least at a regional level, could discourage airlines from selecting airports for refueling or as long-haul hubs on the basis of relative fuel prices.

In the long term, substantial reductions in CO_2 and NO_x emissions from aircraft may depend on RD&D along with market incentives to develop and introduce technologies and practices with lower energy intensity (SAR II, 21.3.1.3) and fuels based on renewable sources (SAR II, 21.3.3.3). At present, there are substantial institutional and technical barriers, including safety concerns, to the introduction of such technologies.

4. INDUSTRIAL SECTOR[11]

4.1 Introduction

In 1990, the global industrial sector[12] directly consumed an estimated 91 EJ of end-use energy (including biomass) to produce \$6.7 x 10^{12} of added economic value, which resulted in emissions of an estimated 1.80 Gt C. When industrial uses of electricity are added, primary energy attributable to the industrial sector was 161 EJ and 2.8 Gt C, or 47% of global CO_2 releases (SAR II, 20.1; Tables A1–A4). In addition to energy-related GHG emissions, the industrial sector is responsible for a number of process-related GHG emissions, although estimates vary in their reliability. Industrial process-related gases include the following (SAR II, 20.2.2):

- CO_2 from the production of lime and cement (calcination process), steel (coke and pig-iron production), aluminum (oxidation of electrodes), hydrogen (refineries and the chemical industry) and ammonia (fertilizers and chemicals)
- CFCs, HFCs and hydrochlorofluorocarbons (HCFCs) produced as solvents, aerosol propellants, refrigerants and foam expanders
- CH_4 from miscellaneous industrial processes (iron and steel, oil refining, ammonia and hydrogen)
- N_2O from nitric acid and adipic acid (nylon) production; perfluorocarbons (PFCs) such as carbon tetrafluoride (CF_4) and hexafluoroethylene (C_2F_6) from aluminum production (electrolysis), and used in manufacturing processes of the semiconductor industry; and sulfur hexafluoride (SF_6) from magnesium production.

The industrial sector typically represents 25–30% of total energy use for OECD Annex I countries. The industrial share of total energy use for the non-Annex I countries averaged 35–45%, but was as high as 60% in China in 1988. The Annex I countries with economies in transition have experienced declines in industrial energy use, which are not expected to reverse until the latter half of the 1990s. It is clear that different countries have followed very different fossil-fuel trajectories to arrive at their present economic status. The variation in industry's energy share among countries reflects not only differences in energy intensity but also the more rapid growth of the industrial sectors of non-Annex I countries, the transition of OECD Annex I country economies away from manufacturing and toward services, improved energy efficiency in manufacturing, and the transfer of some energy-intensive industries from OECD Annex I countries to non-Annex I countries (SAR II, 20.2.1).

During the first half of the 1990s, industrial sector carbon emissions from the European Union and the United States remained below their peak levels of 10–15 years earlier, while Japan's emissions remained relatively constant. The CO_2 emissions of the industrial sector of non-Annex I countries continue to grow as the sector expands, even though energy intensity is dropping in some countries such as China. If energy-intensity improvements continue in non-Annex I countries, and if decarbonization of energy use follows the pattern of OECD Annex I countries, total GHG emissions from the developing world could grow more slowly than projected in the IPCC IS92 scenarios. Figure 2 shows industrial sector CO_2 emissions relative to *per capita* gross domestic product (GDP), illustrating that, for some countries, industrial sector emissions have fallen or remain constant even with substantial economic growth as a result of energy-intensity improvements, decarbonization of energy, or industrial structural changes.

4.2 Technologies for Reducing GHG Emissions in the Industrial Sector

Future reductions in CO_2 emissions of 25% are technically possible for the industrial sector of OECD Annex I countries if technologies comparable to present-generation, efficient manufacturing facilities are adopted during natural capital stock turnover (SAR II, SPM 4.1.1). For Annex I countries with economies in transition, GHG reducing industrial options are intimately tied to economic redevelopment choices and the form that industrial restructuring will take.

4.2.1 Introducing New Technologies and Processes

Although the efficiency of industrial processes has increased greatly during the past two decades, energy-efficiency improvements remain the major opportunity for reducing CO_2 emissions. The greatest potential lies in Annex I countries with economies in transition and non-Annex I countries, where industrial energy intensity (either as EJ/ton of product or EJ/economic value) is typically two to four times greater than in OECD Annex I countries. Even so, many opportunities remain for additional gains in OECD Annex I countries. For example, the most efficient industrial processes today utilize three or four times the thermodynamic energy requirement for processes in the chemical and primary metals industry (SAR II, 20.3). The greatest gains in efficiency for OECD Annex I countries have occurred in chemicals, steel, aluminum, paper and petroleum refining, suggesting that it should be relatively easy to achieve even larger gains in these industries in non-Annex I and transitional economies.

4.2.2 Fuel Switching

Switching to less carbon-intensive industrial fuels such as natural gas can reduce GHG emissions in a cost-effective manner, and such transitions are already underway in many regions.

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[11] This section is based on SAR II, Chapter 20, *Industry* (Lead Authors: T. Kashiwagi, J. Bruggink, P.-N. Giraud, P. Khanna and W. Moomaw).

[12] In the IS92 scenarios, hence in this paper, the global industrial sector includes industrial activities related to manufacturing, agriculture, mining and forestry.

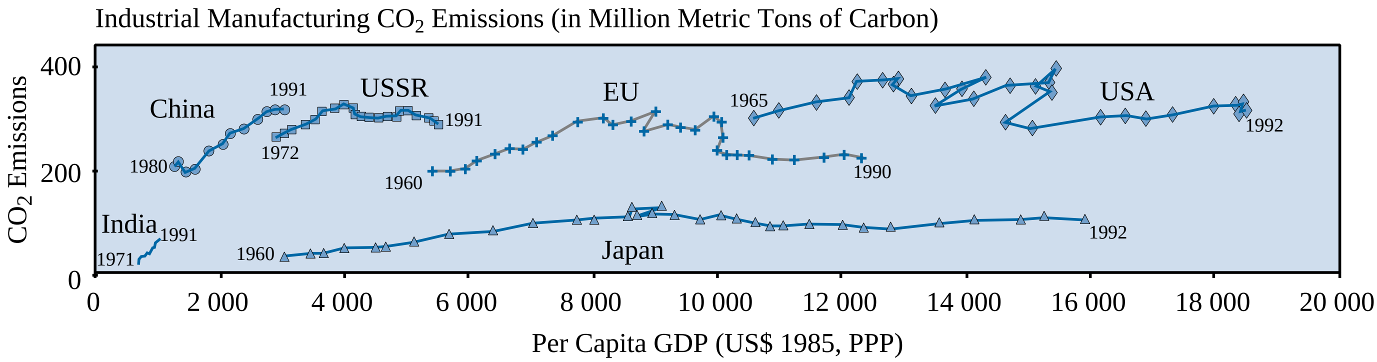

Figure 2: Fossil fuel CO_2 development path for the industrial manufacturing sectors of the United States of America, the 15 nations that now comprise the European Union (except the former East Germany), Japan, China, India and the former Soviet Union (USSR). The industrial sector is as defined by OECD, plus CO_2 associated with refineries and the fraction of electricity that is used by industry (SAR II, 20.2.3, Figure 20-1). The manufacturing sector is a subsector of all industrial activities described in this paper.

However, care must be exercised to ensure that increased emissions from natural gas leakage do not offset these gains. The efficient use of biomass in steam and gas turbine cogeneration systems also can contribute to emissions reductions, as has been demonstrated in the pulp and paper, forest products and some agricultural industries (such as sugar cane) (SAR II, 20.4).

4.2.3 *Cogeneration and Thermal Cascading*

Increasing industrial cogeneration and thermal cascading of waste heat have significant GHG reduction potential for fossil and biofuels. In many cases, combined heat and power or thermal cascading is economically cost-effective, as has been demonstrated in several Annex I countries. For example, coal-intensive industry has the potential to reduce its CO_2 emissions by half, without switching fuels, through cogeneration. Thermal cascading, which involves the sequential capture and reuse of lower temperature heat for appropriate purposes, requires an industrial ecology approach that links several industrial processes and space and water conditioning needs, and may require inter-company cooperation and joint capital investment to realize the greatest gains (SAR II, 20.4).

4.2.4 *Process Improvements*

Industrial feedstocks account for an estimated 16% of industrial sector energy, most of which eventually ends up as CO_2. Replacing natural gas as the source of industrial hydrogen with biomass hydrogen or with water electrolysis using carbon-free energy sources would reduce carbon emissions in the manufacture of ammonia and other chemicals, and, if inexpensive enough, might ultimately replace coking coal in the production of iron. Efforts to produce cheap hydrogen for feedstocks need to be coordinated with efforts to produce hydrogen as a transportation fuel (SAR II, 20.4; SAR III, 9.4).

Industrial process alterations can reduce all process-related GHGs significantly or even eliminate them entirely. Cost-effective reductions of 50% of PFC emissions from aluminum production, and over 90% of NO_x from nylon production have been achieved in the United States and Germany through voluntary programmes (SAR II, 20.3).

4.2.5 *Material Substitution*

Replacing materials associated with high GHG emissions with alternatives that perform the same function can have significant benefits. For example, cement produces 0.34 t C per ton of cement (60% from energy used in production and 40% as a process gas). Shifting away from coal to natural gas or oil would lower the energy-related CO_2 emissions for cement production, and additional CO_2 reductions from other techniques (e.g., the fly-ash substitution and the use of waste fuels) are possible. Shifting to other construction materials could yield even greater improvements. A concrete floor has 21 times the embedded energy of a comparable wooden one, and generates CO_2 emissions in the calcination process as well. Denser materials also extract a GHG penalty when they are transported. The use of plants as a source of chemical feedstock can also reduce CO_2 emissions. Many large wood-products companies already produce chemicals in association with their primary timber or pulp and paper production. In India, a major effort to develop a "phytochemical" feedstock base has been underway. Lightweight packaging, for example, will cause lower transport-related emissions than heavier materials. Material substitution is not always straightforward, however, and depends on identifying substitutes with the qualities needed to critical specifications (SAR II, 20.3.4).

4.2.6 *Material Recycling*

When goods are made of materials whose manufacture consumes a considerable amount of energy, the recycling and reuse of these goods can save not only energy but GHGs released to the atmosphere. Primary materials release about four times the CO_2 of secondary (recycled) materials in steel, copper, glass and paper production. For aluminum, this figure is substantially higher. Carbon savings of 29 Mt are estimated for a 10% increase in OECD recycling of these materials. Recycling can involve restoring the material to its original use or "cascading" the material by successively downgrading its use into applications requiring lower quality materials. Emphasis is needed on technological innovation to upgrade the quality of recycled materials (SAR II, 20.4.2.4).

4.3 Measures for Reducing GHG Emissions in the Industrial Sector

A variety of potential sector-specific measures, discussed briefly below and in Table 8, could encourage improvements in energy efficiency and reductions in process-related emissions (SAR II, 20.5; SAR III, 11). In addition, economy-wide instruments (e.g., phaseout of energy subsidies and adoption of carbon taxes) could affect emissions in the sector by encouraging processes that are less energy- or fossil fuel-intensive. These economy-wide instruments are not discussed here, because they are covered in Section 9, Economic Instruments.

4.3.1 Market-based Programmes

4.3.1.1 Incentives

Tax incentives could be designed for OECD Annex I country firms to encourage continued innovation in energy-efficient and low GHG-emitting processes. Most industrial processes have a relatively short lifetime, on the order of a decade or less, while facilities are used for several decades. Hence, there are large opportunities to rapidly introduce low-emitting technology into the manufacturing process as part of normal capital-stock turnover. Under present circumstances, where GHGs are uncosted externalities, there are no compelling reasons beyond profit maximization for companies to choose a lower GHG-emission strategy over a higher one when they are planning new processes or products. Even when it is cost-effective to introduce low GHG-emitting technologies, there may be barriers to doing so. Hence, there is a need for additional incentives to encourage firms in OECD Annex I countries to utilize the natural cycle of capital stock replacement to introduce less GHG-intensive technology and production facilities to achieve further reductions. Perhaps accelerating depreciation taxes might encourage such a shift.

In addition, financial incentives that encourage industry to adopt combined heat and power facilities, use more renewables, or use more secondary materials could accelerate a further lowering of emissions. Even if incentives are not provided, removing impediments to industrial cogeneration of electricity and heat would be effective.

4.3.1.2 Government Procurement Programmes

Governments could establish procurement requirements for products that minimize GHG emissions in their manufacture and use. If drawn flexibly, government purchasing criteria would stimulate suppliers to develop low GHG-emitting products that met both governmental and larger market needs.

4.3.2 Regulatory Programmes

4.3.2.1 Emissions Standards and Offsets

Setting industry- and product-specific GHG emission standards, like the energy-efficiency standards for appliances or vehicles, can bring about more certain compliance. Efficiency or performance standards can help to overcome a variety of barriers and shift production to lower GHG-emitting industrial practices. These barriers can include lack of information about high-efficiency products, financial analyses or investment criteria that overemphasize investment costs and de-emphasize operating costs, or difficulty in obtaining more efficient products through suppliers. However, reaching agreement about the appropriate standards for different types of equipment in different applications can be difficult, while monitoring and enforcement costs may be high and may raise the price to consumers. Moreover, use of regulations could run counter to the recent emphasis on use of flexible approaches.

A government might encourage the manufacture of more efficient products by allowing companies to receive some credit for reducing emissions during product use as an offset to manufacturing emissions standards. Many manufactured products, including computers, automobiles and light bulbs, consume far more energy and release more GHGs during their use than in their manufacture. For automobiles, the ratio may be more than 10 to 1.

4.3.3 Voluntary Agreements

Voluntary agreements in the United States and Europe have been effective in achieving energy and GHG reductions in industries that have been encouraged to manufacture or install efficient lighting, computers, office equipment and building shells. These include negotiated but voluntary targets for achieving emissions reductions, voluntary adoption of high-efficiency products or processes, cooperative RD&D efforts, and agreements to monitor and report emissions reductions based on voluntary actions. Voluntary agreements with industry groups to improve general environmental quality could be expanded to include GHG reduction (e.g., expansion of government-industry environmental covenants in The Netherlands), as could the ISO 14000 process.[13] Domestic and international supplier requirements that specify low GHG content also could be developed. These private

[13]ISO 14000 is an independently certifiable environmental management system established by the non-governmental International Standards Organization.

Table 8: Selected examples of measures to mitigate GHG emissions in the industrial sector.

Technical Options	Measures	Climate and Other Environmental Effects[a]	Economic and Social Effects	Administrative, Institutional and Political Considerations
New Technologies and Processes – Hydrogen reduction of metal oxide ores – Carbon-free hydrogen and ammonia production – Non-reactive electrodes for aluminum production – Non-fluorine-based aluminum production	**RD&D** – Develop low-cost, carbon-free hydrogen-production technology – Develop electrodes – Develop production process	**Climate Benefits** – Savings of 4% CO_2/yr by 2050 **Other Effects** – Reduction in air pollution from coke	**Cost-effectiveness** – Expensive in near term **Macro-economic Issues** – Would transform industrial feedstocks from coal base	**Administrative/ Institutional Factors** – Modest at research stage – Government, university and industry labs **Political Factors** – Obtaining government funding
Energy Efficiency Gains – More efficient lights, motors and pumps – Improved heat capture – Thermal cascading (i.e., match lower temperature waste heat to appropriate task)	**Market Mechanisms** – Tax incentives for energy efficiency, fuel switching, and reduced GHG releases – Phase out subsidies for GHG-releasing products and fuels – GHG emission taxes – Government procure-ment programmes – Tradable Permits: Domestic and int'l **International Initiatives** – Activities implemented jointly among Annex I countries – Multilateral lending incentives – Technology sharing and transfer	**Climate Benefits** – Savings of 25% CO_2/yr for industrial sector of Annex I countries – Larger savings in developing and Eastern European economies **Other Effects** – Reduction in air pollution **Climate Benefits** – Reductions in CO_2 in Eastern Europe (AIJ), and in developing coun-tries through lending and tech. transfer **Other Effects** – Lower air pollution in Eastern Europe and developing countries	**Cost-effectiveness** – High **Macro-economic Issues** – Restructure tax system to lower tax on income and capital **Equity Issues** – Means of providing technology to develop-ing and Eastern European countries – Higher consumer prices may need off-set for low-income consumers	**Administrative/ Institutional Factors** – Some government effort to change tax codes – Major effort comes from within industry – Some government coordination of district heating systems **Political Factors** – May be opposition from energy supply industries **Administrative/ Institutional Factors** – Complex record-keeping for AIJ – Current institutions are adequate **Political Factors** – Need to assure host country of control over sinks
Fuel Switching – To natural gas – To biomass (especially for forest, paper and agricultural products) – To renewables (solar drying) – To electricity substitution when it reduces GHG emissions	**Regulatory Measures** – GHG emission standards – Manufacturing/product use emissions tradeoffs and credits – Eliminate regulatory, trade and treaty impediments	**Climate Benefits** – Savings of 20% CO_2/yr by 2020 for industrial sector **Other Effects** – Reduction in air pollution	**Cost-effectiveness** – High **Macro-economic Issues** – Internalizing costs of all fuels will hasten shift **Equity Issues** – Trade-off between food and fuel crops	**Administrative/ Institutional Factors** – Modest; most effort comes from industry **Political Factors** – Opposition from producers of fuels being displaced
Cogeneration – Combined heat and power (new industrial facilities, retrofit old facilities) – Gas turbines/combined cycle – Fuel cells	**Regulatory Measures** – Assure market for industry-generated heat and power	**Climate Benefits** – Savings of 15% CO_2/yr by 2020 for industrial sector **Other Effects** – Reduction in air pollution	**Cost-effectiveness** – High **Macro-economic Issues** – Some industry restructuring	**Administrative/ Institutional Factors** – Modest; most effort comes from industry **Political Factors** – May be difficult to site district heating system

Table 8 (continued)

Technical Options	Measures	Climate and Other Environmental Effects[a]	Economic and Social Effects	Administrative, Institutional and Political Considerations
Process Improvements – N_2O reduction for nylon production – CF_4 reduction in aluminum production – HCFC elimination	**Voluntary Agreements** – Joint industry/ government initiatives **Regulatory Measures** – Treaty and domestic law requirements	**Climate Benefits** – Savings of 2–5% CO_2-equivalent/yr by 2010 **Other Effects** – N_2O and HCFC reduction will protect ozone layer	**Cost-effectiveness** – High	**Administrative/ Institutional Factors** – Modest; most effort comes from industry **Political Factors** – Generates good will among government, industry and public
Material Substitution – Replace metals with plastic – Replace concrete with wood or plastic – Lighter materials lower transport-related CO_2 – Use chemicals made from plant materials	**Voluntary Agreements** – GHG reduction goals – GHG sink enhancement – Energy efficiency goals **Market Mechanisms** – Taxes and incentives – Government procurement **Regulatory Measures** – Specify content	**Climate Benefits** – Has not been determined **Other Effects** – Reduction in air pollution	**Cost-effectiveness** – Has not been determined **Macro-economic Issues** – Dislocations in existing industries **Equity Issues** – Some job dislocations	**Administrative/ Institutional Factors** – Modest; most effort comes from industry **Political Factors** – Objection to regulations by industry
Material Recycling/Reuse – Design for disassembly – Design materials for reuse – Material quality cascading	**Market Mechanisms** – Tax incentives – Remove market barriers **Regulatory Measures** – Public/private collection of used materials – Specify recycled content	**Climate Benefits** – Savings of 29 Mt C/yr by OECD countries for a 10% increase in recycling **Other Effects** – Less solid waste and lower resource use	**Cost-effectiveness** – High **Macro-economic Issues** – Decreased use of primary materials **Equity Issues** – Regional job creation near product-use site	**Administrative/ Institutional Factors** – Modest; most effort comes from industry **Political Factors** – Directly engages public in problem solving – Objection to regulations by industry

[a] Estimated reductions assume a 1990 industry manufacturing sector structure. Reductions by different technical options may not be additive.

agreements could be modeled on the no-CFC specifications of many electronics firms prior to the 1995 phaseout. The potential for emissions reductions has been estimated with reasonable certainty by the U.S. Environmental Protection Agency for HFC- and aluminum-related GHGs, and for the “Green Lights” and Energy Star Programs. Public relations or other economic benefits (such as potential for manufacture and sale of new products) accrue to participating companies and are essential in promoting voluntary actions by firms.

4.3.4 Research, Development and Demonstration

RD&D is needed in the near term in order to create and commercialize new industrial technology and to reach future emissions goals in the 2020 to 2050 time frame. For example, if hydrogen is to become a zero-carbon feedstock and fuel, work needs to begin now to ensure that the technology to produce it, and the infrastructure to deliver it, are available and affordable in the future. Systematic evaluation of the effectiveness of policies that are either already in use in different countries or that have been proposed is also needed to determine which will encourage the greatest GHG reductions at the lowest cost.

4.3.5 International Initiatives

4.3.5.1 Special Opportunities for Annex I Countries with Economies in Transition and Non-Annex I Countries

The reindustrialization process in countries with economies in transition provides major opportunities to replace inefficient, high-carbon industries with efficient low-carbon manufacturing processes. Much of this change will involve restructuring these economies, as heavy industry is replaced by alternative manufacturing. In addition, since most of the growth in industrial energy use is likely to be in the non-Annex I countries in the coming decades, the greatest reductions in the growth rate of future GHG emissions can be achieved by introducing new technology and industrial processes early in these emerging industrial economies.

Tradable permits and joint implementation[14] could be useful mechanisms to achieve GHG reductions within the industrial sector by providing investment capital in energy-efficient manufacturing and process technology. These measures are discussed more fully in Section 9.

Opportunities also exist for companies in OECD Annex I countries to create GHG reducing joint ventures with companies and governments in Annex I countries with economies in transition, as well as in non-Annex I countries.

4.3.5.2 Barriers to International Initiatives

Technology transfer of modern industrial capacity to non-Annex I countries and Annex I countries with economies in transition is being impeded by disagreements over intellectual property rights and a lack of available capital and hard currency. Other barriers include a lack of capacity and basic environmental legislation, and institutional factors in the host countries. There are currently legal and treaty impediments to implementing cooperative actions among firms to reduce greenhouse gases. Many countries have anti-trust laws to prevent price collusion and monopolistic behavior by firms. Within the World Trade Organization, there is concern about environmental protection as a potential restraint on free trade. These restrictions need to be examined to determine how environmental benefits, like GHG reductions, can be achieved by firms without compromising the intended goals of these rules. As the private sector takes on a larger role in addressing GHG emissions from industry, there will need to be greater transparency of these actions through reporting and verification mechanisms involving third parties such as non-governmental organizations, and governmental and international agencies.

4.4 Global Carbon Emissions Reductions through Technologies and Measures in the Industrial Sector

The IPCC IS92 scenarios indicate that total energy and CO_2 for the industrial sector of Annex I countries are projected to rise from approximately 122 EJ and 2.1 Gt C in 1990 to 165 EJ (141–181 EJ) and 2.7 Gt C (2.1–3.1 Gt C) in 2010, and to 186 EJ (154–211 EJ) and 2.9 Gt C (2.1–3.5 Gt C) in 2020, reaching 196 EJ (140–242 EJ) and 2.6 Gt C (1.4–3.7 Gt C) by 2050. Projected average annual growth in both energy use and emissions is close to 1% per year greater for the world as a whole, indicating the growing importance of the industrial sector in non-Annex I countries.

Annex I countries could lower their industrial sector CO_2 emissions by 25% relative to 1990 levels, by simply replacing existing facilities and processes with the most efficient technological options currently in use (assuming a constant structure for the industrial sector). This upgraded replacement would be cost-effective if it occurred at the time of normal capital stock replacement. This seems within the realm of both technological and economic feasibility (SAR II, SPM 4.1.1). It is difficult to estimate potential emissions reductions compared to the IS92 scenarios for Annex I countries with economies in transition and non-Annex I countries; however, such reductions are likely to be significant due to the existing energy-intensive facilities and the potential to implement more efficient practices and technologies as growth occurs in these regions.

[14] Chapter 11 of SAR III uses the term "joint implementation" to include "activities implemented jointly" and that usage is continued here.

5. ENERGY SUPPLY SECTOR[15]

5.1 Introduction

The energy supply sector consists of a sequence of elaborate and complex processes for extracting energy resources, converting these into more desirable and suitable forms of energy, and delivering energy to places where the demand exists. Global energy consumption has grown at an average annual rate of approximately 2% for almost two centuries, although energy growth varies considerably over time and among regions (SAR II, SPM 4.1). If past trends continue, energy-related GHG emissions are likely to grow more slowly than energy consumption in general and energy sector requirements in particular, due to a gradual trend toward the decarbonization of energy supply. Across the range of the IPCC IS92 scenarios, energy-related CO_2 emissions are projected to increase from 6 Gt C in 1990 to 7–12 Gt C by 2020 and to 6–19 Gt C by 2050, of which the energy sector accounts for 2.3–4.1 Gt C (1.4–2.9 Gt C in Annex I) by 2020 and 1.6–6.4 Gt C (1.0–3.1 Gt C in Annex I) by 2050, respectively.

The availability of fossil reserves and resources as well as renewable potentials is unlikely to pose a major constraint to long-term energy supply (SAR II, B.3.3). Similarly, the availability of uranium and thorium is unlikely to place a major constraint on the future development of nuclear power. There is also a large long-term potential for renewable energy resources, although the costs of achieving a significant portion of this potential are uncertain and depend on many factors ranging from RD&D activities and early technology adoption in niche markets to suitable geographic locations (SAR II, B.5.3.1). Table 9 summarizes global energy reserves and resources in terms of both their energy and carbon content as well as renewable potentials (SAR II, B.3.3.1).

Energy supply technologies and energy infrastructures have inherently long economic lifetimes, and fundamental transitions in the energy supply sector take many decades. This means that technical measures and policies will take considerable time to implement. However, within a period of 50–100 years, the entire energy supply system will be replaced at least twice. It is technically possible to realize deep emission reductions in the energy supply sector in step with the normal timing of investments to replace infrastructure and equipment as it wears out or becomes obsolete (SAR II, SPM 4.1.3).

The mitigation potentials of the individual options identified in this assessment are not additive, because the realization of some options is mutually exclusive or may involve double-counting. Thus, a systematic approach is required to assess the potential impacts and feasibility of combinations of individual mitigation measures and policies at the energy system level, while ensuring regional and global balance between demands and supplies. To assess the long-term technical potential of combinations of measures at the energy systems level, in contrast to the level of individual technologies, numerous scenarios of potential energy system futures have been constructed. In one such exercise, variants of a Low CO_2-Emitting Energy Supply System (LESS) were analyzed in the SAR (SAR II, SPM 4.1.4). The LESS constructions are “thought experiments” exploring many combinations of technical possibilities of reducing global CO_2 emissions to about 4 Gt C by 2050 and to about 2 Gt C by 2100 (SAR Syn.Rpt., 5.8). The literature provides strong support for the feasibility of achieving the performance and cost characteristics assumed for energy technologies in the LESS constructions, although uncertainties will exist until more RD&D has been carried out and the technologies have been tested in the market (SAR II, SPM 4.1.4; SAR Syn.Rpt., 5.9). In another scenario exercise conducted in 1993, the World Energy Council presented an “ecologically driven” scenario, in which similar emissions reductions were obtained (SAR II, 19.3.1.4). These exercises are, by their nature, speculative and involve assumptions about mitigation potentials, short- and long-term costs of technologies, and their full socio-economic and environmental consequences. Additional scenario development and analysis are required to establish the internal consistency of various assumptions over time, including possible interactions between such assumptions as those that might relate the evolution of systems for energy use, economic growth, land use and population (IPCC 1994, II, SPM).

5.2 Technologies for Reducing GHG Emissions in the Energy Supply Sector

Promising approaches to reduce future emissions, not ordered according to priority, include more efficient conversion of fossil fuels; switching to low-carbon fossil fuels; decarbonization of flue gases and fuels and CO_2 storage; switching to nuclear energy; and switching to renewable sources of energy (SAR II, SPM 4.1.3). Each of these options has its unique characteristics that determine cost-effectiveness, as well as social and political acceptability. Both the costs and the environmental impacts should be evaluated on the basis of full life-cycle analyses. The technical potential for CO_2 emission reductions of selected mitigation technologies is explored in Box 3.

5.2.1 More Efficient Conversion of Fossil Fuels

Generally, new technologies promise higher conversion efficiencies from fossil fuels. For example, the efficiency of power

[15]This section is based primarily on SAR II, Chapter 19, *Energy Supply Mitigation Options* (Lead Authors: H. Ishitani, T. Johansson, S. Al-Khouli, H. Audus, E. Bertel, E. Bravo, J. Edmonds, S. Frandsen, D. Hall, K. Heinloth, M. Jefferson, P. de Laquil III, J.R. Moreira, N. Nakicenovic, Y. Ogawa, R. Pachauri, A. Riedacker, H.-H. Rogner, K. Saviharju, B. Sorensen, G. Stevens, W.C. Turkenburg, R.H.Williams and F. Zhou); SAR II, Chapter B, *Energy Primer* (Lead Authors: N. Nakicenovic, A. Grubler, H. Ishitani, T. Johansson, G. Marland, J.R. Moreira and H-H. Rogner); and SAR III, Chapter 11, *An Economic Assessment of Policy Instruments for Combatting Climate Change*. It also draws to a lesser extent on the SAR II and III SPMs.

Table 9: *Global energy reserves and resources, their carbon content, energy potentials by 2020–2025, and maximum technical potential.*[a]

	Consumption (1860–1990)		Consumption (1990)		Reserves Identified/ Potentials by 2020–2025		Resource Base/ Maximum Potentials	
	EJ	Gt C	EJ	Gt C	EJ	Gt C	EJ	Gt C
Oil								
Conventional	3 343	61	128	2.3	6 000	110	8 500	156
Unconventional	–	–	–	–	7 100	130	16 100	296
Gas								
Conventional	1 703	26	71	1.1	4 800	72	9 200	138
Unconventional	–	–	–	–	6 900	103	26 900	403
Coal	5 203	131	91	2.3	25 200	638	125 500	3 173
Total Fossil	10 249	218	290	5.7	50 000	1 053	>186 200	4 166
Nuclear[b]	212	–	19	–	1 800	–	>14 200	–
					EJ/yr		EJ/yr	
Hydro	560	–	21	–	35–55	–	>130	–
Geothermal	–	–	<1	–	4	–	>20	–
Wind	–	–	–	–	7–10	–	>130	–
Ocean	–	–	–	–	2	–	>20	–
Solar	–	–	–	–	16–22	–	>2 600	–
Biomass	1 150	–	55	–	72–137	–	>1 300	–
Total Renewables	1 710	–	76	–	130–230	–	>4 200	–

[a]Table based on SAR II, B.3.3.1, Tables B-3 and B-4.
[b]Natural uranium reserves and resources are effectively 60 times larger if fast breeder reactors are used.
– = negligible or not applicable

production can be increased from the present world average of about 30% to more than 60% in the longer term. Also, the use of combined heat and power production where it is applicable—whether for process heat or space heating or cooling—offers a significant increase in fuel utilization efficiencies (SAR II, SPM 4.1.3.1). Integration of energy conversion from very high to very low temperatures—sometimes called energy cascading—offers additional efficiency improvements (SAR II, 20.4.2.3).

While the cost associated with these efficiency improvements will be influenced by numerous factors—including the rate of capital replacement, the discount rate, and the effect of research and development—there are advanced technologies that are cost-effective compared to some existing plants and equipment that are less efficient or emit larger amounts of GHGs. Some technology options (e.g., combined-cycle power generation) can penetrate the current marketplace. To realize other options, governments would have to take integrated action which may include eliminating permanent subsidies for energy, internalizing external costs, providing funding for additional RD&D of low- and zero-CO_2 emission technologies, and providing temporary incentives for early market introduction of these technologies as they approach commercialization (SAR II, Chapter 19, Executive Summary). Therefore, while the efficiency of power production can be improved globally, this could incur additional costs and may not occur in the absence of appropriate GHG policies.

The theoretical potential for efficiency improvements is very large and current energy systems are nowhere near the maximum theoretical (ideal) levels suggested by the second law of thermodynamics. Many studies indicate low current values for most conversion processes based on second law (or exergy) efficiencies. Much inertia must be overcome before even a fraction of this potential can be realized, along with numerous barriers, such as social behavior, vintage structures, costs, lack of information and know-how, and insufficient policy incentives. For fossil fuels, the magnitude of the efficiency improvement potentials suggests, irrespective of costs, the areas that have the highest emission mitigation potentials (SAR II, B.2.2).

In general, the introduction of new vintages of efficient technologies is governed by the energy system's natural capacity retirement process and future demand growth prospects. In the short term, the efficiency improvement rate based on the natural turnover of capital may be largest in countries with rapid economic growth (SAR II, 19.1). Therefore, those Annex I countries that are undergoing the process of transition to a market economy and presently have inefficient energy conversion systems have high potentials for efficiency improvements.

The global average efficiency of fossil-fueled power generation is about 30%; the average efficiency in the OECD countries is about 35%. Assuming a typical efficiency of new coal-fired power generation (with de-SO_x and de-NO_x equipment) of 40%

in Annex I countries, an increase of 1% in efficiency would result in a 2.5% reduction in CO_2 emissions (SAR II, 19.2.1.1). In the longer run, new electricity generation technologies based on coal with higher efficiencies include supercritical steam cycles, pressurized fluidized bed combustion and integrated gasification combined cycles. Some of these technologies are commercial, while others require further RD&D.

Natural gas in combined-cycle power plants has the highest conversion efficiencies of all fossil fuels—presently 45% in the short term and 55% and more in the longer term. Combined-cycle plants have approximately 30% lower investment costs than a conventional gas steam counterpart, although specific electricity costs will depend on the usually higher fuel costs of natural gas compared to coal. On the other hand, combined-cycle plants are more costly than simple combustion turbines, which are less efficient but have shorter installation times (SAR II, 19.2.1.1).

GHG reduction potential is approximately proportional to realized efficiency improvements. For improved technologies that use the same fossil fuel, the efficiency gains translate to lower fuel costs, which often can offset the somewhat higher capital needs. The technology improvements can result in significant secondary benefits, such as reductions of other pollutants [e.g., sulfur dioxide (SO_2), NO_x and particulates]. Additional costs are often negligible because efficiency improvements do not require radical technology changes. Energy-efficiency improvements also have the advantage of being replicable.

Combined heat and power production (CHP) offers a significant rise in fuel utilization, of up to 80–90%, which is much higher than separate electricity and heat production (SAR II, 19.2.1.4). The economics of CHP are closely linked to the availability or development of district heating and cooling networks and sufficient demand densities.

5.2.2 Switching to Low-carbon Fossil Fuels

Switching to fuels with a lower carbon-to-hydrogen ratio, such as from coal to oil or natural gas, and from oil to natural gas, can reduce emissions. Natural gas has the lowest CO_2 emissions per unit of energy of all fossil fuels, at about 15 kg C/GJ, compared to oil with about 20 kg C/GJ and coal with about 25 kg C/GJ (all based on low heating values). The lower carbon-containing fuels can, in general, be converted with higher efficiency than coal. Large resources of natural gas exist in many areas (SAR II, SPM 4.1.3.1). New, low capital cost, highly efficient combined-cycle technology can reduce electricity costs considerably in some areas where natural gas prices are relatively low compared to coal.

Switching from coal to natural gas while maintaining the same fuel-to-electricity conversion efficiency would reduce emissions by 40%. Accounting for the conversion efficiency of natural gas, which is generally higher than that of coal (SAR II, 19.2.1), the overall emissions reduction per unit of electricity generated might be in the range of 50%.

Although natural gas is abundant, it is not available as a domestic energy source in some parts of the world. Thus, a wider shift to natural gas would lead to changes in energy import dependencies, which raises a number of policy issues. Initial investment and administrative costs may be substantial, due to the need to develop new transport, distribution and end-use infrastructures. Hence, the actually achievable reduction potentials may differ significantly among regions, depending on local conditions such as relative fuel prices or gas availability.

A wider use of natural gas could lead to additional leakages of CH_4, the main component of natural gas. Approaches exist to reduce emissions of CH_4 from coal mining by 30–90%, from venting and flaring of natural gas by more than 50%, and from natural gas distribution systems by up to 80% (SAR II, 22.2.2). Some of these reductions may be economically viable in many regions of the world, providing a range of benefits, including the use of CH_4 as an energy source (SAR II, 19.2.2.1).

5.2.3 Decarbonization of Flue Gases and Fuels, and CO_2 Storage and Sequestering

The removal and storage of CO_2 from fossil fuel power-station stack gases is feasible, but reduces the conversion efficiency and significantly increases the production cost of electricity. Another approach to decarbonization uses fossil fuel as a feedstock to make hydrogen-rich fuels—for example, hydrogen itself, methanol, ethanol or CH_4 converted from coal. Both approaches generate a stream of CO_2 that could be stored, for example, in depleted natural gas fields or in the oceans (SAR II, SPM 4.1.3.1). Because of its costs and the need to develop the technology, this option has only limited opportunities for near- and medium-term application (e.g., as a source of CO_2 to be used in enhanced oil recovery) (SAR II, 19.2.3.1). For some longer term CO_2 storage options (e.g., in the oceans), the costs, environmental effects, and efficacy remain largely unknown (SAR II, SPM 4.1.3.1).

For a conventional coal power plant with 40% efficiency, removing 87% of CO_2 emissions from flue gases (from 230 to 30 g C/kWh$_e$) would reduce the efficiency to 30% and increase electricity costs by about 80%, which is equivalent to $150/t C avoided (SAR II, 19.2.3.1).

For a natural gas combined-cycle plant with 52% efficiency, reducing CO_2 emissions by about 82% (from 110 to 20 g C/kWh$_e$) would reduce the efficiency to 45% and increase electricity costs by about 50%, which is equivalent to $210/t C avoided (SAR II, 19.2.3.1). Although the specific abatement costs per tonne of carbon avoided are higher for natural gas than for coal, this translates into lower incremental cost per kilowatt-hour of electricity because of the lower specific carbon content of natural gas.

Another process for decarbonization of fuels is the gasification of coal and CO_2 removal by reforming synthesis gas. For an original integrated gasification combined cycle (IGCC) coal power plant with 44% efficiency, reducing CO_2 emissions by about 85% (from 200 to 25 g C/kWh$_e$) would reduce the efficiency to about 37% and increase electricity costs by 30–40%, which is equivalent to less than $80/t C avoided (SAR II, 19.2.3.2).

One future option to reduce costs that is under investigation is the use of oxygen rather than air for combustion to obtain a flue gas that is essentially CO_2 and water vapor.

Another related option would be to produce hydrogen-rich gases for electricity generation and other applications. For the recovery of CO_2 by steam reforming natural gas, the costs of capture and storage in a nearby natural gas field are estimated to be less than $30/t C avoided (SAR II, 19.2.3.2). The future availability of conversion technologies, such as fuel cells that can efficiently use hydrogen, would increase this option's relative attractiveness. Delivery of electricity and hydrogen as final energy would practically eliminate emissions at the point of end use, and allow carbon removal and storage from the energy sector itself.

Storage of recovered CO_2 in exhausted oil and gas wells is another option (SAR II, 19.2.3.3). The estimated global storage capacity of oil and gas fields is in the range of 130–500 Gt C, which translates into a large mitigation potential. Storage costs in onshore natural gas fields are estimated to be less than $11/t C, while transport costs are about $8/t C for a 250-km pipeline with a capacity of 5.5 Mt C/yr (SAR II, 19.2.3.3). Another option is CO_2 storage in saline aquifers, which can be found at different depths around the world.

The deep ocean is the largest potential repository for CO_2 (SAR II, 19.2.3.3). CO_2 could be directly transferred to the oceans, ideally at depths of 3 000 m or perhaps more; the deposited CO_2 would be isolated from the atmosphere for at least several centuries. Concerns over potential environmental impacts as well as the development of appropriate disposal technologies and the assessment of their costs require further research.

5.2.4 *Switching to Nuclear Energy*

Nuclear energy could replace baseload fossil fuel electricity generation in many parts of the world if generally acceptable responses can be found to concerns such as reactor safety, radioactive-waste transport and disposal, and nuclear proliferation (SAR II, SPM 4.1.3.2). A review of opinion surveys concludes that public concerns about nuclear energy focus on doubt about economic necessity, fear of large-scale catastrophes, storage of nuclear waste and the misuse of fissile material (SAR II, 19.2.4).

Nuclear electricity generation costs vary across a number of countries from 2.5–6¢/kWh$_e$; costs for new plants, including waste disposal and decommissioning plants, range from 2.9–5.4¢/kWh$_e$ using a 5% discount rate, and 4.0–7.7¢/kWh$_e$ using a 10% discount rate (SAR II, 19.2.4). Projected levelized costs of baseload electricity by the turn of the century indicate that nuclear power will remain an option in several countries with plants in operation and under construction. Since these nuclear generating costs are comparable to those of coal, the specific mitigation costs would range from $120/t C avoided to negligible additional costs (assuming conventional coal electricity costs of 5¢/kWh$_e$, nuclear costs between 5.0 and 7.7¢/kWh$_e$ and emissions avoided of 230 g C/kWh$_e$) (SAR II, 19.2.1.1).

New designs, such as modular high-temperature gas-cooled reactors are being developed to provide increased safety and improved economic performance through reduced construction lead times and reduced operation and maintenance costs. Interest in liquid metal-cooled reactors and other new designs, such as high-energy accelerator devices, has been revived in view of their potential use in management and disposal of fissile materials. Other concepts are being developed with the objective of enhancing the use of nuclear power for non-electrical applications, such as process and district heat, and, in the longer term, nuclear energy could be deployed for hydrogen production (SAR II, 19.2.4).

5.2.5 *Switching to Renewable Sources of Energy*

Technological advances offer new opportunities and declining costs for energy from renewable sources. In the longer term, renewables can meet a major part of the world's demand for energy. Power systems, with the addition of fast-responding backup and storage units, can accommodate increasing amounts of intermittent generation (SAR II, SPM 4.1.3.2). Renewable sources of energy used sustainably have low or no GHG emissions. There are some emissions associated with the unsustainable use of biomass—for example, from reducing the amount of standing biomass and from decomposition of biomass associated with flooded reservoirs (SAR II, 19.2.5). If the development of biomass energy can be carried out in ways that effectively address concerns about other environmental issues (e.g., impacts on biodiversity) and competition with other land uses, biomass could make major contributions in both the electricity and fuels markets (SAR II, SPM 4.1.3.2). By and large, renewable sources of energy could offer substantial reductions of GHG emissions compared to the use of fossil fuels (SAR II, 19.2.5), provided their economic performance continues to improve and no siting problems arise.

5.2.5.1 Hydropower

The technical potential has been estimated at 14 000 TWh$_e$/yr, of which 6 000–9 000 TWh$_e$/yr are economically exploitable in the long run after considering social, environmental, geological and cost factors (SAR II, 19.2.5.1). The market potential for reducing GHG emissions depends on which fossil fuel hydropower replaces. The long-term economic potential for replacing coal is 0.9–1.7 Gt C avoided annually (depending on technology and efficiency); for natural gas, the potential is 0.4–0.9 Gt C avoided annually.

The investment costs for hydro projects in 70 developing countries for the 1990s suggest that, on average, the cost of new hydroelectricity delivered to final use is 7.8¢/kWh_e. The actual investment cost can be high, with financing likely to become a barrier due to the long amortization horizons involved (SAR II, 19.2.5.1). Replacing modern coal-fired electricity as presented in the SAR II (19.2.1.1) would result in average CO_2 reduction costs of $120/t C avoided (assuming conventional coal electricity costs of 5¢/kWh_e and emissions avoided of 230 g C/kWh_e) (SAR II, 19.2.1.1).

Small-scale hydro can be regionally important especially where cost-effective. On the other hand, the construction phase of larger hydroelectric plants has social consequences and direct and indirect environmental impacts, such as water diversion, slope alteration, reservoir preparation, creation of infrastructure for the large workforce, or disturbing aquatic ecosystems, with adverse human health impacts. The social consequences include the relocation of people as well as a boom and bust effect on the local economy. The associated infrastructure stimulates regional economic development and also provides additional benefits for agriculture as a water reservoir (SAR II, 19.2.5.1).

5.2.5.2 Biomass

Potential biomass energy supplies include municipal solid waste, industrial and agricultural residues, existing forests, and energy plantations (SAR II, 19.2.5.2.1).

Yields and costs of biomass energy depend on local conditions, such as land and biomass waste availability and production technology. Typically, the energy output-input ratio for high-quality food crops is low compared to the ratio for energy crops, which often exceeds the former ratio by a factor of 10. Biomass production cost estimates vary over a large range. On the basis of commercial experience in Brazil, an estimated 13 EJ/yr of biomass could be produced at an average cost for delivered woodchips of $1.7/GJ. Costs are higher in Annex I countries. For electricity generation in the Annex I countries, future biomass inputs are expected to cost around $2/GJ (SAR II, 19.2.5.2.1).

The mitigation cost range for biomass-derived energy forms such as electricity, heat, biogas or transportation fuels not only depends on the biomass production cost but also on the economics of the specific fuel conversion technologies. Assuming biomass costs of $2/GJ and small-scale production, electricity can be generated for 10–15 ¢/kWh_e. For lower cost biomass ($0.85/GJ), electricity can be generated for less than 10 ¢/kWh (SAR II, 19.2.5.2.2). On the basis of replacing coal with biomass, the mitigation costs would range between $200–400/t C avoided. A future biomass-integrated gasifier/gas turbine cycle with an expected efficiency of 40–45% and biomass costs of $2/GJ could produce electricity at costs comparable to coal and/or coal prices in the range of $1.4–1.7/GJ (SAR II, 19.2.5.2.2). In this case, the specific mitigation costs could well become negligible.

Advanced biofuels from woody feedstocks offer the potential of higher energy yields at lower costs and lower environmental impacts than most traditional biofuels. In addition to ethanol, methanol and hydrogen are promising biofuel candidates.

Modern biomass energy also offers the potential for generating income in rural areas. This income could allow developing-country farmers to modernize their farming techniques and reduce the need to expand output by bringing more marginal lands into production. In industrialized countries, biomass production on excess agricultural lands could allow governments eventually to phase out agricultural subsidies (SAR II, 19.2.5.2).

At present, advanced biomass conversion technologies as well as biomass plantations are in their infancy and require further RD&D to become technically mature and economically viable. Concerns about future food supplies have raised the issue that land will not be available for biomass production for energy in Africa and other non-Annex I countries (SAR II, 19.2.5.2.1). The potential competition for land use will depend on the degree to which agriculture can be modernized in these countries to achieve yields equivalent to those obtained in the Annex I countries, and whether intensified agricultural production will occur in an environmentally and economically acceptable way.

5.2.5.3 Wind

Intermittent wind power on a large grid can contribute an estimated 15–20% of annual electricity production without special arrangements for storage, backup and load management (SAR II, 19.2.5.3.2, 19.2.6.1). In a fossil-dominated utility system, the mitigation effect of wind technologies corresponds to the reduction in fossil fuel use. The wind potential by 2020 is projected to range from 700–1 000 TWh_e (SAR II, B.3.3.2); if utilized to replace fossil fuels and irrespective of costs, this translates into CO_2 emission reductions of 0.1–0.2 Gt C/yr.

The present stock average cost of energy from wind power is approximately 10¢/kWh, although the range is wide. By 2005 to 2010, wind power may be competitive with fossil and nuclear power in more than small niche markets. For average new technology, investment costs of $1 200/kW and electricity production costs of 6¢/kWh have been estimated. Costs could be significantly lower for large wind farms. In the future, costs as low as 3.2¢/kWh have been calculated for favorable locations at a discount rate of 6% (SAR II, 19.2.5.3.3). In this case, the specific CO_2 mitigation costs are negligible, if not zero or negative, where electricity from coal is more expensive. Countries with large numbers of operating wind turbines sometimes experience public resistance to such factors as the noise of turbines, the visual impact on the landscape and the disturbance of wildlife (SAR II, 19.2.5.3.5).

5.2.5.4 Solar Energy

Direct conversion of sunlight to electricity and heat can be achieved by photovoltaic (PV) and solar thermal electric technologies. PV is already competitive as a stand-alone power source remote from electric utility grids. However, it has not been competitive in bulk electric grid-connected applications. Although module capital costs have decreased drastically over recent years, system capital costs are

Box 3. Technical Potential of CO_2 Emission Reductions based on the IPCC IS92 Scenarios for Different Mitigation Technologies by the Year 2020

In preparing these calculations of technical potential, it is assumed that 50% of the new installed energy conversion capacities in Annex I countries between 1990 and 2020 would employ the mitigation technologies described in this paper, irrespective of costs which would vary for different technologies. Six different mitigation technologies are considered: replacing coal with natural gas, flue gas decarbonization for coal and natural gas, CO_2 removal from coal, and replacement of coal and natural gas with nuclear power, or with biomass, respectively. This calculation does not attempt to present a comprehensive assessment of mitigation options in the energy sector. Only six examples are presented due to the limitations imposed by the IS92 scenarios. The mitigation potential of each individual technology option is based on a sensitivity analysis of the IS92a scenario and the range between IS92e and IS92c. Some of these mitigation options may be mutually exclusive and are not additive.

Each calculation includes a number of steps. First, new capacity additions between 1990 and 2020 in the IS92 scenarios are inferred; second, the profiles of new capacities that are to be partially replaced in Annex I countries by mitigation technologies are also inferred with the assumption that 50% of these capacities would consist of new technologies; third, the implied CO_2 emissions reductions are determined for all three IS92 scenarios using technology characteristics from SAR II, Chapter 19, and emissions coefficients from SAR II, Chapter B; and finally, percentage emissions reductions are evaluated for each of the three scenarios.

The extent to which the technical potential can be achieved will depend on future cost reductions, the rate of development and implementation of new technologies, financing and technology transfer, as well as measures to overcome a variety of non-technical barriers such as adverse environmental impacts, social acceptability, and other regional, sectoral and country-specific conditions.

Mitigation Technology	Technical CO_2 Reduction Potential Based on IS92a Scenario (and Range for IS92e to IS92c)		
	Gt C	% of Annex I	% of World
Replacing Coal with Natural Gas for Electricity Generation in Annex I Countries	0.25 (0.01–0.4)	4.0 (2.0–6.0)	2.5 (1.0–4.0)
Flue Gas Decarbonization (with de-NO_x and de-SO_x) for Coal in Electricity Generation in Annex I Countries	0.35 (0.1–0.6)	6.0 (3.0–8.0)	3.5 (1.5–5.0)
Flue Gas Decarbonization (with de-NO_x) for Natural Gas Electricity Generation in Annex I Countries	0.015 (0.0–0.05)	0.5 (0.0–0.5)	0.15 (0.0–0.45)
CO_2 Removal from Coal Before Combustion for Electricity Generation in Annex I Countries	0.35 (0.1–0.6)	6.0 (3.0–8.0)	3.5 (1.5–5.0)
Replacing Natural Gas and Coal with Nuclear Power for Electricity Generation in Annex I Countries	0.4 (0.15–0.65)	7.0 (3.0–9.5)	4.0 (2.0–5.5)
Replacing Coal with Biomass (in Electricity Generation, Synfuel Production and Direct End Use) in Annex I Countries[a]	0.55 (0.25–0.85)	9.5 (5.5–12.0)	5.5 (3.0–7.0)

[a] The biomass requirements would amount to 9–34 EJ/yr, which is less than the range of 72–187 EJ for the biomass potential by 2020 to 2025 (SAR II, B.3.3.2). These figures are higher than those assessed in the SAR chapter on agriculture (SAR II, 23), and can be achieved only through actions which go beyond agricultural measures.

$7 000–10 000/kW; the corresponding electricity cost is 23–33¢/kWh, even in areas of high insulation (2 400 kWh/m²/yr). However, the cost of PV systems is expected to improve significantly through RD&D, as well as with economies of scale. Because of its modularity, PV technology is a good candidate for cost-cutting through learning-by-doing, as well as technological innovation (SAR II, 19.2.5.4.1). Although PV devices emit no pollution in normal operation, some systems involve the use of toxic materials, which can pose risks in manufacture, use and disposal.

By 2020 to 2025, the annual economic potential of solar energy in well-defined niche markets is assessed to be 16–22 EJ (SAR II, B.3.3.2). Realization of this potential will depend on the cost and performance improvements of solar electric technologies. If fully realized, irrespective of costs, the CO_2 reduction could amount to 0.3–0.4 Gt C annually. A 50-MW power plant based on 1995 technology with installed costs of $2 300/kW would have generating costs of about 8–9¢/kWh_e in areas with good insulation (SAR II, 19.2.5.4.1). The mitigation cost versus coal-fired electricity generation of approximately 5¢/kWh then would range from $130–170/t C avoided; compared to gas-fired electricity with similar costs, the range would be from $270–350/t C avoided. These costs do not account for energy system considerations such as storage requirements, or benefits of replacing more expensive peak electricity where the PV output is well-correlated with peak electrical demand.

Optimistic assessments of future PV costs indicate values as low as $700–800/kW by 2020–2030 and electricity costs of 2.2–4.4¢/kWh, depending on the level of insulation (SAR II, 19.2.5.4.1; Table 19-6). Ignoring energy system considerations, use of PV generation at these costs would reduce both generation costs and emissions relative to conventional coal technologies at today's costs. Other estimates of PV generation costs in 2030 are between 50 and 100% higher than these values, depending on whether or not there is accelerated RD&D.

Solar thermal-electric systems have the long-term potential to provide a significant fraction of the world's electricity and energy needs. This technology generates high-temperature heat, thus may realize conversion efficiencies of about 30% (SAR II, 19.2.5.4.2). Parabolic-trough technology has achieved significant cost reductions and current plants have energy costs of 9–13¢/kWh in the hybrid mode. Power towers have significantly lower projected energy costs of 4–6¢/kWh (SAR II, 19.2.5.4.2).

In addition to electricity production, solar thermal systems can provide high-temperature process heat, and central receivers can be used to process advanced fuels such as hydrogen and chemicals (SAR II, 19.2.5.4.2). Local solar thermal systems can provide heating and hot water for domestic, commercial or industrial uses (SAR II, 19.2.5.5).

5.2.5.5 Geothermal and Ocean Energy

Electricity is generated from geothermal energy in 21 countries. The cost of electric generation from this source is estimated to be around 4¢/kWh_e and heat is generated at 2¢/kWh_{th}. Direct use of geothermal water occurs in about 40 countries; 14 countries have an installed capacity of more than 100 MW_{th} (SAR II, 19.2.5.6.1).

Various emissions are associated with geothermal energy, including CO_2, hydrogen sulfide and mercury. Advanced technologies are almost closed-loop and have very low emissions (SAR II, 19.2.5.6.1). The geothermal energy potential by 2020–2025 is estimated to be 4 EJ (SAR II, B.3.3.2). Hot dry rock and other non-hydrothermal reservoirs offer new supply resources. Despite its importance at the level of the local economy, the carbon reduction potential is small.

Although the total energy flux of tides, waves, and thermal and salinity gradients of the world's oceans is large, only a small fraction is likely to be exploited in the next 100 years (SAR II, 19.2.5.6.2).

5.3 Measures for Reducing GHG Emissions in the Energy Supply Sector

Refer to Table 10 for examples of measures and technical options to mitigate GHG emissions in electricity generation.

5.3.1 Market-based Programmes

Market-based programmes directly change the relative price of energy-related activities. In a perfectly competitive marketplace, under an emission tax or tradable quota scheme, emitters would reduce emissions up to the point where the marginal cost of control equals the emission tax rate or the equilibrium price of an emission quota. Both instruments would promote dynamic efficiency (cost minimization over the long term, when factors of production are variable and technological change may be stimulated), as each provides a continuous incentive for RD&D in emission abatement technologies to avoid the tax or quota purchases (SAR III, 11.5). As such, the costs of emission taxes are known, but the magnitude of emission reductions is uncertain. This situation reverses for emission quotas.

5.3.1.1 Phasing Out Permanent Subsidies

Permanent energy sector subsidies provide incorrect market signals to producers and consumers alike, and may lead to energy prices below actual cost; resource allocation is thus distorted and inherently suboptimal. Subsidies to established technologies create artificial market barriers to the entry of new technologies. For this reason, the adoption of marginal cost pricing and the minimization, if not elimination, of long-term, permanent subsidies that increase GHG emissions have been proposed as means for improving market entry opportunities

Table 10: *Selected examples of measures and technical options to mitigate GHG emissions in electricity generation.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Efficiency Improvements – Power generation thermal efficiency improvement potential from present average of 30% to 60% in the longer run – Power transmission – Refineries – Synfuel production – Gas transmission	**Market-based Programmes** – GHG taxes – Energy taxes – Tradable emission permits **Regulatory Measures** – Mandatory efficiency standards **Voluntary Agreements** – Voluntary arrangement with customers – Reduced own-use energy	**Climate Effects** – Reduction of all GHG and other pollutants; an increase in thermal conversion efficiency from 35 to 40% reduces CO_2 emissions by 12.5% – Long-term potential up to 50% emission reduction **Other Effects** – Improved local air quality and lower regional pollution	**Cost-effectiveness** – Evolutionary changes can be achievable at no or low additional costs **Macro-economic Issues** – Energy import reduction **Equity Issues** – Tend to be highly equitable and replicable	**Administrative/ Institutional Factors** – A fair share of the improvement potential may be realized even in the absence of direct GHG mitigation policies and measures – Information dissemination **Political Factors** – Create platforms and incentives for voluntary agreements
Switching to Low-carbon Fuels – From coal to natural gas – From oil to natural gas	**Market-based Programmes** – GHG taxes – Fuel-specific energy taxes – Tradable emission permits **Regulatory Measures** – Mandatory fuel use **Voluntary Agreements** – Voluntary fuel switching	**Climate Effects** – Reduction of CO_2 and other pollutants, *ceteris paribus* by 40% (from coal and 20% from oil) – In addition. natural gas often offers higher conversion efficiencies which provides further GHG reductions – Potential disbenefit of higher CH_4 emissions **Other Effects** – Improved local air quality and lower regional pollution	**Cost-effectiveness** – Cost-effective where gas available, but high gas infrastructure costs – Uncertain gas prices in the longer run **Macro-economic Issues** – In the short- to medium-term, potential for low-cost electricity supply – For countries without sufficient domestic gas availability, increasing gas-import dependence **Equity Issues** – International competition for low-cost natural gas	**Administrative/ Institutional Factors** – Need for long-term gas trade arrangements – Compatible with decentralization and deregulation of energy industries – Encourage cogeneration and independent power production **Political Factors** – Supply security concerns, geopolitics
Decarbonization of Flue Gases – CO_2 abatement (scrubbing) – Coal gasification and reforming of synthesis gas – Production of hydrogen-rich gases	**Market-based Programmes** – Carbon taxes – Tradable emission permits **Regulatory Measures** – Emission standards – Regulation of underground storage sites – International conventions on ocean storage **Voluntary Agreements** – CO_2 cascading when applicable	**Climate Effects** – Specific CO_2 reduction by up to 85%, per kWh_e – Disposal/storage with uncertain prospects of ocean storage **Other Effects** – Effective decarbonization presumes large-scale de-SO_x and de-NO_x, hence improved local and regional air quality	**Cost-effectiveness** – Involves least changes in energy sector – High scrubbing costs between $80–150/t C and more – Additional storage costs – Loss of efficiency in electricity generation **Macro-economic Issues** – No major energy sector restructuring – Higher domestic fossil extraction and/or fuel imports **Equity Issues** – Access to CO_2 disposal sites	**Administrative/ Institutional Factors** – RD&D on disposal and ocean storage – Access to depleted oil and gas fields **Political Factors** – International agreements on large-scale ocean disposal

Table 10 (continued)

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Nuclear – Increased use of nuclear energy	**Market-based Programmes** – Carbon taxes – Tradable emission permits **Regulatory Measures** – Standards and codes – Non-proliferation **Voluntary Agreements** – Agreements among nuclear industry, operators and the concerned public **RD&D** – RD&D on waste disposal and safety	**Climate Effects** – Reduction of all GHG and other pollutants, such as SO_x, NO_x and particulates **Other Effects** – Local air quality improvements – Accidental radioactivity release and nuclear waste disposal	**Cost-effectiveness** – Under special conditions, cost-effective mitigation option – High up-front, large and increasing cost range – Limited to baseload operation **Macro-economic Issues** – Lower expenditures for fuel imports; uncertainty about economic feasibility – Lack of public acceptance **Equity Issues** – Limited technology access due to risks of proliferation	**Administrative/ Institutional Factors** – Lack of public support – Concerns include proliferation, waste disposal and safety standards **Political Factors** – Stable regulatory and policy climate – International agreements on large-scale nuclear waste disposal
Biomass – Energy plantation and forestry – Biomass conversion for electricity and heat generation – Biomass gasification and liquid fuel production – Hydrogen from biomass	**Market-based Programmes** – Change structure of subsidies to agriculture – Carbon taxes – Tradable emission permits **Regulatory Measures** – Emission regulation – Agricultural zoning **Voluntary Agreements** – Utilize marginal lands for energy plantation – Support of local biofuel or bio-conversion initiatives **RD&D** – RD&D support to reduce costs of advanced conversion plants	**Climate Effects** – Can result in no net carbon emissions – Could be a sequestration option **Other Effects** – Reduction of other pollutants – Concerns about biodiversity and monocultures	**Cost-effectiveness** – Advanced conversion plants not commercially available, but possible with accelerated RD&D **Macro-economic Issues** – Restructure of agriculture and perhaps forestry – Economic development in rural areas **Equity Issues** – Accessible land	**Administrative/ Institutional Factors** – Land-use conflict – Energy plantation cooperatives – Independent power production arrangements – Compatible with decentralization and deregulation of energy industries – Information dissemination **Political Factors** – Stable agricultural and rural development policy
Wind (an example of intermittent renewables) – Utilization of wind turbines at favorable sites – Remote from grid – Integrated with grid	**Market-based Programmes** – Carbon taxes – Tradable emission permits **Regulatory Measures** – Emission regulation – Zoning appropriate sites **Voluntary Agreements** – Early adopters with utilities **RD&D** – RD&D support to reduce costs	**Climate Effects** – Reduction of all GHG and other pollutants, such as SO_x, NO_x and particulates **Other Effects** – Possible impacts on landscape, noise and wildlife	**Cost-effectiveness** – Cost-effective at favorable sites – Cost range large, hence uncertain economics **Macro-economic Issues** – Economic development in rural areas	**Administrative/ Institutional Factors** – Compatible with decentralization and deregulation of energy industries – Information dissemination – Zoning for wind farms – Access to utility grids **Political Factors** – Stable energy policy

for modern technologies with lower GHG emissions (SAR II, SPM 4.4). These subsidies absorb large amounts of capital, reducing the financing possibilities of investments in energy efficiency, RD&D in low CO_2-emitting technologies or other economic activities. Conventional energy technologies benefit from direct subsidies of more than $300 billion per year worldwide (SAR II, 19.4).

The argument for eliminating permanent subsidies, however, does not mean that some temporary, short-term subsidies could not be used as measures to support the market entry of GHG mitigating options such as renewables, nuclear power or clean coal technologies. For example, price guarantees for independent producers utilizing low-carbon technologies would help reduce the economic risk of technologies that are not fully matured.

5.3.1.2 Full-cost Pricing of Energy Services

The literature on full-cost pricing is controversial. No consensus exists on how to monetize the external (true social) costs of energy production and use (SAR III, SPM 6). If consensus were possible to attain, then the practice of full-cost pricing would contribute to a level playing field for all energy technologies. External costs include those costs usually not reflected in market prices in the absence of policies. Examples in the literature include morbidity, mortality, environmental damage, or the potential adverse consequences of the impacts of climate change, job opportunities, competitiveness and other opportunity costs.

The inclusion of energy externalities would improve the competitiveness of low-emission energy uses (SAR II, 19.4). Because the external costs of existing and new technologies are unknown but are expected to vary greatly among countries and regions, unilateral national adoption of full-cost pricing may, in the short run, adversely affect international economic competitiveness. International agreements may be needed to overcome this competitiveness concern.

5.3.1.3 Tradable Emission Quotas and Permits

Other possible measures include setting emission quotas and issuing tradable emission permits. At the international level, fulfilment of quotas can enhance activities implemented jointly, which could simultaneously bring technology and finance to non-Annex I countries and to some Annex I countries undergoing economic transition, and help implement least-cost strategies internationally.[16]

5.3.1.4 Financing Assistance

Capital shortage, especially in the developing world and some Annex I countries undergoing economic transition, is a major barrier to the implementation of GHG mitigation options. If a project has lower life-cycle costs and emissions but higher capital requirements than its alternative, it may not attract the necessary finance. In addition, energy supply technologies compete with other development needs for limited capital. However, many mitigation and other energy options could involve indigenous technology production, creating new local infrastructure and employment. Especially in rural areas, decentralized technologies may aid development goals (SAR II, 19.Executive Summary).

Even in the industrialized countries, the capital required for financing energy supply system-related GHG reduction may yield lower returns than other investment opportunities. Measures that make supply and conversion technologies more attractive in the marketplace would help resolve some of the financing difficulties by reducing risk, uncertainty and upfront capital requirements. Other measures include accelerated depreciation, start-up loans and concessional grants (SAR II, SPM 4.4).

5.3.2 Regulatory Measures

The conventional approach to environmental policy in many countries has used uniform standards (based on technology or performance) and direct government expenditures on projects that are designed to improve the environment. Like market-based incentives, the first of these strategies requires that polluters undertake pollution abatement activities; under the second strategy, the government itself expends resources on environmental quality. Both of these strategies figure prominently in current and proposed measures to address global climate change (SAR III, 11.4).

Standards and codes have the advantage that the effect on GHG emissions can, in general, be assessed *a priori*. The disadvantage, however, is that the costs incurred are often unknown and can be higher than market-based instruments. Under some circumstances, however, a performance standard may provide greater incentives but under other circumstances also lower incentives for technological adoption than a marketable permit system (SAR III, 11.4.1).

An example of a regulatory measure in the United States is the Public Utilities Regulatory Policy Act (PURPA), enacted in 1978, which required electric utilities to buy power from independent producers at the long-term avoided cost and led to the creation of a competitive, decentralized market. Small- to medium-scale cogeneration fueled by natural gas and biomass became a popular technology approach. PURPA is largely responsible for the introduction of more than 10 000 MW_e of renewable electric capacity (SAR II, 19.4). According to some assessments, such regulatory measures could lead to higher electricity costs.

5.3.3 Voluntary Agreements

[16] Chapter 11 of SAR III uses the term "joint implementation" to include "activities implemented jointly" and that usage is continued here.

Voluntary agreements generally refer to actions undertaken in the participants' self-interest and endorsed by a government with the objective of reducing GHG emissions. Such agreements are considered in many Annex I countries to constitute a flexible measure. The agreements can take on many different forms at both national and international levels, and can include target- and performance-based agreements, cooperative RD&D, general information exchange, and activities implemented jointly.

Forward-looking firms may take steps to control GHG emissions if they fear more costly mandatory controls in the absence of voluntary reductions. This could explain why some voluntary agreements for domestic energy management have arisen. The vast majority of GHG reductions from the actions announced or expanded through the U.S. Climate Change Action Plan, for example, come from voluntary initiatives aimed at increasing energy efficiency (SAR III, 11.4.3).

5.3.4 Research, Development and Demonstration

High rates of innovation in the energy sector are a prerequisite for meeting the most ambitious GHG mitigation objectives and significantly lowering the costs of many technology options below present levels. The trend in recent years, however, has been one of declining investment in energy RD&D on the part of both the private sector and the public sector (see Table 11; SAR II, 19.4). Over the last decade, public-sector support for energy RD&D has declined absolutely by one-third, and by half a percentage of GDP (SAR II, 19.4). In the past, over half of government-supported RD&D in the International Energy Agency (IEA) member countries was allocated to nuclear energy and less than 10% was allocated for renewables. Together with energy conservation, more than 80% of RD&D is devoted to low- or zero-GHG emitting measures.
Although many energy sector mitigation options require further RD&D support, it is important to have a government strategy that does not attempt to pick individual technology winners. Fortunately, many of the promising technologies for reducing emissions, such as many renewable and other low- or zero-GHG emitting energy technologies, require relatively modest investments in RD&D. This is a reflection largely of the small scale and the modularity of these technologies (SAR II, 19.4). As a result, it should be feasible to support a diversified portfolio of options, even with limited resources for RD&D. It has been estimated that research and development of a range of renewable energy technologies would require on the order of $15–20 billion distributed over a couple of decades (SAR II, 19.4).

RD&D programmes are necessary but not sufficient to establish new technologies in the marketplace. Commercial demonstration projects and programmes located in realistic economic and organizational contexts to stimulate markets for new technologies also are needed. For a wide range of small-scale, modular technologies, such as most renewable energy technologies and fuel cells, energy production costs can be expected to decline with the cumulative volume of production, as a result of learning by doing.

5.3.5 Infrastructural Measures

5.3.5.1 Removal of Institutional Barriers

In some circumstances, the removal of institutional barriers can attract private-sector interest in advanced renewable technologies. Regulatory reform and deregulation (breaking-up of producer monopolies, transmission and distribution networks) have allowed small and independent power producers access to the grid and improved their competitiveness. Standardization of equipment to facilitate connection to the grid also would improve technology adoption. In the case of adoption of advanced renewable technologies, these measures can reduce

Table 11: *Total reported IEA government R&D budgets (columns 1–7; US$ billion at 1994 prices and exchange rates) and GDP (column 8; US$ trillion at 1993 prices).*

Year	(1) Fossil Energy	(2) Nuclear Fission	(3) Nuclear Fusion	(4) Energy Conservation	(5) Renewable Energy	(6) Other	(7) Total	(8) GDP	(9) % of GDP
1983	1.70	6.38	1.43	0.79	1.05	1.08	12.40	10.68	0.12
1984	1.60	6.12	1.44	0.70	1.02	0.99	11.88	11.20	0.11
1985	1.51	6.26	1.42	0.70	0.85	1.04	11.77	11.58	0.10
1986	1.51	5.72	1.31	0.59	0.66	0.94	10.74	11.90	0.09
1987	1.37	4.36	1.23	0.65	0.62	1.04	9.27	12.29	0.08
1988	1.46	3.64	1.13	0.53	0.62	1.19	8.58	12.82	0.07
1989	1.30	4.42	1.07	0.45	0.57	1.33	9.13	13.23	0.07
1990	1.75	4.48	1.09	0.55	0.61	1.15	9.62	13.52	0.07
1991	1.52	4.45	0.99	0.59	0.64	1.39	9.57	13.58	0.07
1992	1.07	3.90	0.96	0.56	0.70	1.28	8.48	13.82	0.06
1993	1.07	3.81	1.05	0.65	0.71	1.38	8.66		
1994	0.98	3.74	1.05	0.94	0.70	1.30	8.72		

GHG emissions.

5.3.5.2 Energy System Planning

Traditionally, the domain of energy sector industries has been the production and sale of kWh_e, litres of gasoline, or tonnes of coal. The focus was on growth of demand for energy supplies and the efficient expansion of capital to meet that demand, not on the most efficient way to meet the growing and widening demand for energy services.

Some regulatory commissions are requiring energy sector industries to adopt a wider business concept, which extends to include the provision of energy services rather than the sale of energy units. Most importantly, end-use efficiency and technologies become an integral part of the energy industry capital allocation process. Energy planning would extend beyond the traditional energy sector boundaries and adopt a full energy system perspective.

However, the energy utility sectors in Annex I countries currently are undergoing privatization and deregulation. These changes may also provide opportunities for GHG mitigation, such as independent power production and CHP. These changes also mean that governments may have to modify the policy levers used to achieve environmental objectives. For example, demand-side management and integrated resource planning may need to be reexamined.

5.3.5.3 Local and Regional Environment Measures

Energy supply and end use lead to a number of local and regional environmental impacts. Local impacts include indoor and urban pollution. Regional impacts include acidification and possible land-use conflicts. Policies and measures for mitigating local and regional environmental impacts can affect and interact with policies for mitigating climate change. For example, more efficient conversion and end use of energy brings multiple benefits as it reduces environmental impacts on all scales. In contrast, other policies might involve complex trade-offs. Some measures that improve regional environmental conditions may lead to higher GHG emissions; for example, flue gas scrubbers for the abatement of sulfur emissions from coal-fired power plants decrease the overall conversion efficiency, resulting in higher carbon emissions. Additionally, some GHGs may have adverse effects on local and regional air quality (e.g., small CHP might not include full de-SO_x and de-NO_x abatement equipment). Because the adverse regional impacts are more certain than the impacts of global climate change, action to combat this type of pollution is likely to occur in many parts of the world in the short to medium term.

Thus, integration of policies and measures is needed to reduce the overall environmental impacts at the national, regional and local levels. In particular, policies and measures addressing local and regional environmental impacts should be assessed for their potential conflict with goals and policies for reduction of GHG emission.

6. AGRICULTURE SECTOR[17]

6.1 Introduction

Agriculture accounts for about one-fifth of the projected anthropogenic greenhouse effect, producing about 50 and 70%, respectively, of overall anthropogenic CH_4 and N_2O emissions; agricultural activities (not including forest conversion) account for approximately 5% of anthropogenic emissions of CO_2 (SAR II, Figure 23.1). Total global land under cultivation is estimated to be approximately 1 700 Mha (SAR II, 23.2.2, Table 23-3).

The agriculture sector is characterized by large regional differences in both management practices and the rate at which it would be possible to implement mitigation measures. The effectiveness of various mitigation measures needs to be gauged against the base emission levels and changes in different regions. In non-Annex I countries where rapid increases in fertilizer use and crop production are occurring, substantial increases in emissions of N_2O and CH_4 are projected. Even full implementation of mitigation measures will not balance these increases. Comprehensive analyses of land use, cropping systems and management practices are needed at regional and global levels to evaluate changes in emissions and mitigation requirements.

6.2 Technologies for Reducing GHG Emissions in the Agriculture Sector

Technologies for mitigation of GHGs in agriculture and the potential decreases in emissions of CO_2, CH_4 and N_2O are shown in Table 12. Also shown in Table 12 are the equivalent carbon emission reductions for CH_4 and N_2O based on their respective ratios of global warming potential (SAR I, Table 2.9). Of the total possible reduction in radiation forcing (shown as C-equivalents), approximately 32% could result from reduction in CO_2 emissions, 42% from carbon offsets by biofuel production on existing croplands, 16% from reduced CH_4 emissions and 10% from reduced emissions of N_2O.

Emissions reductions by the Annex I countries could make a significant contribution to the global total. Of the total potential CO_2 mitigation, Annex I countries could contribute 40% of the reduction in CO_2 emissions, and 32% of the carbon offset from biofuel production on croplands. Of the global total reduction in CH_4 emissions, Annex I countries could contribute 5% of the reduction attributed to improved technologies for rice production, and 21% of reductions attributed to improved management of ruminant animals. These countries also could contribute about 30% of the reductions in N_2O emissions attributed to reduced and more efficient use of nitrogen fertilizer, and 21% of the reductions stemming from improved utilization of animal manures.[18]

Estimates of potential reductions range widely, reflecting uncertainty in the effectiveness of recommended technologies and the degree of future implementation globally. To satisfy global food requirements and acceptability by farmers, technologies and practices should meet the following general guidelines: (i) sustainable agricultural production will be achieved or enhanced; (ii) additional benefits will accrue to the farmer; and (iii) agricultural products will be accepted by consumers. Farmers have no incentive to adopt GHG mitigation techniques unless they improve profitability. Some technologies, such as no-till agriculture or strategic fertilizer placement and timing, already are being adopted for reasons other than concern for climate change. Options for reducing emissions, such as improved farm management and increased efficiency of nitrogen fertilizer use, will maintain or increase agricultural production with positive environmental effects.

These multiple benefits will result in high cost-effectiveness of available technologies. Practices that recover investment cost and generate a profit in the short term are preferred over practices that require a long term to recover investment costs; practices that have a high probability associated with expected profits are desired over practices that have less certainty about their returns. When human resource constraints or knowledge of the practice prevent adoption, public education programmes can improve the knowledge and skills of the work force and managers to help advance adoption. Comprehensive national and international programmes of research, education and technology transfer will be required to develop and diffuse knowledge of improved technologies. Crop insurance or other programmes to share the risk of failure due to natural disaster are needed to aid the adoption of improved practices.

6.2.1 *Mitigation of Carbon Dioxide Emissions (SAR II, 23.2)*

Options to mitigate CO_2 emissions from agriculture include reducing emissions from present sources, and creating and strengthening carbon sinks. Options for increasing the role of agricultural land as a sink for CO_2 include carbon storage in managed soils and carbon sequestration after reversion of surplus farm lands to natural ecosystems. However, soil carbon sequestration has a finite capacity over a period of 50–100 years, as new equilibrium levels of soil organic matter are established. Efforts to increase soil carbon levels have additional benefits in terms of improving the productivity and sustainability of agricultural production systems. Soils of croplands taken

[17]This section is based on SAR II, Chapter 23, *Agricultural Options for Mitigation of Greenhouse Gas Emissions* (Lead Authors: V. Cole, C. Cerri, K. Minami, A. Mosier, N. Rosenberg, D. Sauerbeck, J. Dumanski, J. Duxbury, J. Freney, R. Gupta, O. Heinemeyer, T. Kolchugina, J. Lee, K. Paustian, D. Powlson, N. Sampson, H. Tiessen, M. van Noordwijk and Q. Zhao).

[18]Annex I countries' share of emission reductions is based on production data in the Food and Agriculture Organization (FAO) 1994 Production Yearbook, Vol. 48, FAO Statistics Series. Rome, Italy.

Table 12: Agricultural technologies for mitigation of GHG emissions and potential reductions of annual emissions of carbon dioxide, methane and nitrous oxide (based on SAR II, Tables 23-4, 23-5, 23-6, 23-10 and 23-11).

Net Carbon Dioxide Emissions	**Mt C/yr**	
Reducing CO_2 Emissions		
– Reduction in fossil energy use by agriculture in industrialized countries (reductions expected in expanded use of minimum and no tillage, irrigation scheduling, solar drying of crops and improved fertilizer management[a])	10–50	
Increasing C Sinks		
– Increasing soil C through better management of existing agricultural soils[b]	400–600	
– Increasing soil C through permanent set-aside of surplus agricultural land in temperate regions[c]	21–42	
– Restoration of soil C on degraded lands[d]	24–240	
Biomass Production as a C Offset		
– Biofuel production from dedicated crops on existing croplands[e]		
• Temperate regions	85–490	
• Tropical regions	160–510	
• Temperate shelter belts	10–60	
• Tropical agroforestry	46–200	
– Biofuel production from crop residues[f]	100–200	
TOTAL POTENTIAL CO_2 MITIGATION	855–2 390	
Reducing Methane Emissions	**Mt CH_4/yr**	**Mt C-Equiv[g]**
Improved Management of Ruminant Livestock		
– Improved diet quality and nutrient balance	10–35	57–202
– Increased feed digestibility	1–3	6–18
– Improved animal genetics and reproduction	1–6	6–36
Improved Management of Livestock Manures		
– Covered lagoons	2–6.8	12–39
– Digesters	0.6–1.9	3–12
Improved Rice Production Practices		
– Irrigation management[e]	3.3–9.9	19–52
– Nutrient management	2.5–15	14–87
– New cultivars and other practices	2.5–10	14–58
TOTAL POTENTIAL DECREASE IN METHANE EMISSIONS	23–88	131–504
Reducing Nitrous Oxide Emissions	**Mt N_2O-N/yr**	**Mt C-Equiv[h]**
Increase N Fertilizer Use Efficiency		
– Reduce use of nitrogen fertilizers (apply improved technology for nitrogen application, match N supply with crop demand, integrate production systems to maximize manure reuse in plant production, conserve plant residue N on the production site, and optimize tillage, irrigation and drainage)	0.3–0.9	85–245
– Decrease forest conversion	0.06–0.17	21–47
TOTAL POTENTIAL DECREASE IN NITROUS OXIDE EMISSIONS	0.4–1.1	106–292

[a] Based on current use of 3–4.5% of the total fossil C emission (2.8 Gt C/yr; OECD, 1991) by industrialized countries and an arbitrary reduction range of 10–50%.
[b] Assuming a recovery of one-half to two-thirds of the estimated historic loss (44 Gt) of C from currently cultivated soils (excluding wetland soils) over a 50-year period.
[c] Based on an estimated C sequestration of 1.5–3 Gt over a 100-year period, from a 15% set-aside of cultivated soils (~640 Mha), in industrialized countries with current or potential production surpluses; annual and cumulative rates given as 1 and 50%, respectively. Based on restoration of 10–20% of former wetland area (8 Mha) now under cultivation in temperate regions.
[d] Assuming potential C sequestration of 1–2 kg C/m^2 over a 50-year period, on an arbitrary 10-50% of moderately to highly degraded land (1.2x10^9 ha globally).
[e] Assuming about 10–15% of world cultivated lands to be available for biofuels.
[f] Based on 25% recovery of crop residues and assumptions on energy conversion and substitution.
[g] C-equivalent of CH_4 emissions based on 100-year GWP (SAR I, Table 2.9).
[h] C-equivalent of N_2O emissions based on 100-year GWP (SAR I, Table 2.9).

out of production in permanent set-asides and allowed to revert to native vegetation eventually could reach carbon levels comparable to their precultivation condition. Considering the 640 Mha of land currently under cultivation in the United States, Canada, the former Soviet Union, Europe, Australia and Argentina, and assuming recovery of the soil carbon originally lost to cultivation, a permanent set-aside of 15% of the land area could sequester 1.5–3 Gt C (over 50–100 years).

A large-scale reversion or afforestation of agricultural land is only possible if adequate supplies of food, fibre and energy can be obtained from the remaining area. This is currently possible in the European Union and United States through intensive farming systems. However, if farming intensity changes because of environmental concerns or changes in policy, this mitigation option may no longer be available.

Currently, only half of the conversion of tropical forests to agriculture contributes to an increase in productive cropland. The only way to break out of this cycle is through more sustainable use, improved productivity of existing farmland and better protection of native ecosystems. These practices could help reduce agricultural expansion (hence deforestation) in humid zones, especially in Latin America and Africa.

Management practices to increase soil carbon stocks include reduced tillage, crop residue return, perennial crops (including agroforestry), and reduced bare fallow frequency. However, there are economic, educational and sociological constraints to improved soil management in much of the tropics. Many tropical farmers cannot afford or have limited access to purchased inputs such as fertilizer and herbicides. Crop residues are often needed for livestock feed, fuel or other household uses, which reduces carbon inputs to soil. To the extent that improved management is based on significantly increased fossil fuel consumption, benefits for CO_2 mitigation will be decreased.

Energy use by agriculture, per unit of farm production, has decreased since the 1970s. Fossil fuel use by agriculture in industrialized Annex I countries, constituting 3–4% of overall consumption, can be reduced through the use of minimum tillage, irrigation scheduling, solar drying of crops and improved fertilizer management.

Both conventional food and fibre crops and dedicated biofuel crops, such as short-rotation woody crops and perennial herbaceous energy crops, produce biomass that is valuable as a feedstock for energy supply. Dedicated biofuel crops require similar soils and management practices as conventional agricultural crops, and would compete with food production for limited resources (SAR II, 23.2.4). The extent to which their production will be expanded depends on the development of new technologies, their economic competitiveness with traditional food and fibre crops, and social and political pressures. Dedicated energy plants, including short-rotation woody crops, perennial herbaceous energy crops, and annuals such as whole-plant cereal crops or kenaf, could be sustainably grown on 8–11% of the marginal to good cropland in the temperate zone. For example, in the European Union it has been estimated that 15–20 Mha of good agricultural land will be surplus to food production needs by the year 2010. This would be equivalent to 20–30% of the current cropland area.

Due to increasing agricultural demand in the tropics, a lower percentage of land is likely to be dedicated to energy crops, so a reasonable estimate may be 5–7%. In total, however, there could be a significant amount of land available for biofuel production, especially from marginal land and land in need of rehabilitation. The CO_2 mitigation potential of a large-scale global agricultural biofuel programme could be significant. Assuming that 10–15% of the world's cropland area could be made available, fossil fuel substitutions in the range of 300–1300 Mt C have been estimated. This does not include the indirect effects of biofuel production through increasing carbon storage in standing woody biomass or through increasing soil carbon sequestration. Recovery and conversion of 25% of total crop residues (leaving 75% for return to the soil) could substitute for an additional 100–200 Mt fossil fuel C/yr. However, the possible offsets by increased N_2O emissions need to be considered. Generally, crops from which only the oil, starch or sugar are used are of limited value in reducing CO_2 emissions, due to the low net energy produced and the relatively high fossil fuel inputs required. The burning of whole plant biomass as an alternative to fossil fuel results in the most significant CO_2 mitigation.

Ranges in estimates of potential mitigation reflect uncertainty about the effectiveness of management options and about the degree of future implementation globally. A primary issue in evaluating these options is whether the world can continue to support an increasing population with its growing needs for food and fibre and, at the same time, expand the amount of land used for production of biomass for energy (SAR II, 23.2.5, 25.3.3).

6.2.2 Mitigation of Methane Emissions (SAR II, 23.3.1.1)

The largest agricultural sources of CH_4 are managed ruminant animals and rice production. Rice cultivation will continue to increase at its current rate to meet food requirements. Flooded rice fields produce CH_4 emissions, which can be reduced by improved management measures. The ranges of potential reductions shown indicate uncertainty about the effectiveness of mitigation measures and the degree of additivity of effects as, for example, in rice production. Successful implementation of available mitigation technologies will depend on demonstration that: (i) grain yield will not decrease or may increase; (ii) there will be savings in labour, water and other production costs; and (iii) rice cultivars that produce lower CH_4 emissions are acceptable to local consumers.

Emissions of CH_4 from domestic ruminant animals can be reduced as producers use improved grazing systems with higher quality forage, since animals grazing on poor-quality rangelands

Table 13: *Selected examples of technical options to mitigate GHG emissions in the agricultural sector.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Reduce Fossil Energy Use – Reduce tillage – Reduce fertilizer use – Irrigation scheduling – Solar crop drying	**Market-based Programmes** – Agricultural fuel taxes **Voluntary Agreements** – Technology transfer	**Climate Benefits** – Reduced CO_2 emissions of 10–50 Mt C/yr	**Macro-economic Issues** – Reduced costs for fuel and fertilizers	**Administrative/ Institutional Factors** – Cooperation of government agencies and integration of farm programmes essential **Political Factors** – Determining taxes
Increase C Storage in Agricultural Soils – Reduce tillage – Improve residue management – Restore productivity of degraded soils – Increase permanent set-aside in temperate regions	**Voluntary Agreements** – Change commodity programmes to allow more flexibility and support of best management practices – Technology transfer	**Climate Benefits** – Increased C storage of 440–880 Mt C/yr **Other Effects** – Reduced soil erosion – Increased food production on balance of options	**Cost-effectiveness** – Increased costs for herbicides offset by reduced labour needs **Macro-economic Issues** – Reduced fuel costs	**Administrative/ Institutional Factors** – Cooperation of government agencies and integration of farm programmes essential – Credit availability may constrain
Expand Biofuel Production as C Offset – Dedicated short-rotation woody crops and herbaceous energy crops on existing croplands – Biofuels from crop residues	**Market-based Programmes** – Energy pricing – Removal of market barriers	**Climate Benefits** – Fossil C offset of 400–1 460 Mt C/yr – Increased soil C storage	**Macro-economic Issues** – Higher costs of electricity – Competition for limited croplands will increase land prices and potentially food prices	**Political Factors** – Generally opposed by traditional agricultural interests – Possible negative impact on food production politically sensitive
Improve Management of Ruminant Animals – Increase feed digestibility – Improve animal genetics and fertility	**Regulatory Measures** – Regulation of animal density	**Climate Benefits** – Reduced CH_4 emissions of 12–44 Mt CH_4/yr **Other Effects** – Less nutrient pollution	**Macro-economic Issues** – Need for trained managers and technology transfer	**Political Factors** – Special concern in areas of high animal density, as in Annex I countries
Adopt Manure Management Practices for CH_4 Collection – Covered lagoons and biogas generators	**Voluntary Agreements** – Technology transfer	**Climate Benefits** – Reduced CH_4 emissions of 3–9 Mt CH_4/yr	**Cost-effectiveness** – Costs reduced by local energy availability	**Administrative/ Institutional Factors** – International technology transfer needed
Improve Rice Production Practices – Water management – Nutrient management – New low methane cultivars	**Voluntary Agreements** – Technology transfer	**Climate Benefits** – Reduced CH_4 emissions of 8–35 Mt CH_4/yr	**Equity Issues** – Seasonal water allocation difficult	**Administrative/ Institutional Factors** – Requires regional coordination of water scheduling
Increase N Fertilizer Use Efficiency – Better application methods – Match N supply with crop needs – Maximize manure use – Optimize tillage, irrigation and drainage	**Market-based Programmes** – Taxes on N fertilizer use **Regulatory Measures** – Limits on N fertilizer use	**Climate Benefits** – Reduced N_2O emissions of 0.4–1.1 Mt N_2O-N/yr **Other Effects** – Improved water quality	**Cost-effectiveness** – Costs offset by reduced N requirement	**Political Factors** – Possible negative impact on food production politically sensitive

produce more CH_4 per unit of feed consumed. Confined feeding operations utilizing balanced rations that properly manage digestion of high-energy feeds also can reduce direct emissions, but can increase indirect emissions from feed production and transportation. CH_4 produced in animal waste disposal systems can provide an on-farm energy supply, and the CH_4 utilized in this manner is not emitted to the atmosphere. Overall, potential global reduction of CH_4 emissions amounts to about 35% (15–56%) of emissions from agriculture.

6.2.3 Mitigation of Nitrous Oxide Emissions (SAR II, 23.3.1.2)

Nitrogen is an essential plant nutrient; however, it is also a component of some of the most mobile compounds in the soil-plant-atmosphere system. Since nitrogen is the major component of mineral fertilizer, there is mounting concern over the extent to which high-input agriculture loads nitrogen compounds into the environment. Nitrogen budgeting, or an input/output balance approach, provides a basis for policies to improve nitrogen management in farming and livestock systems, and for mitigating its environmental impact. Management systems can decrease the amount of nitrogen lost to the environment through gaseous losses of ammonia or N_2O, or through leaching of nitrate into the subsoil. In some cases, improved efficiency is achieved by using less fertilizer; in other cases, it can be achieved by increasing yields at the same nitrogen levels.

The primary sources of N_2O from agriculture are mineral fertilizers, legume cropping, and animal waste. These losses often are accelerated by poor soil physical conditions. Some N_2O also is emitted from biomass burning. Improvements in farm technology, such as use of controlled-release fertilizers, nitrification inhibitors, the timing of nitrogen application and water management should lead to improvements in nitrogen use efficiency and further limit N_2O formation. The underlying concept in reducing N_2O emissions is that if fertilizer nitrogen (including manure nitrogen) is better used by the crop, less N_2O will be produced and less nitrogen will leak from the system. By better matching nitrogen supply to crop demand and more closely integrating animal waste and crop residue management with crop production, N_2O emissions could be decreased by about 0.36 Mt N_2O-N or about 17% (9–26%) of the current emission rate in agriculture.

6.3 Measures for Reducing GHG Emissions in the Agriculture Sector

Measures that can have significant effects on the mitigation of GHGs in the agriculture sector include the following (see Table 13 for sample technical options):

- Market-based programmes (e.g., reduction and reform of agricultural support policies; taxes on use of nitrogen fertilizers; subsidization of production and use of biomass energy)
- Regulatory measures (e.g., limits on use of nitrogen fertilizers; cross-compliance of agricultural support to environmental objectives)
- Voluntary agreements (e.g., soil management practices that enhance carbon sequestration in agricultural soils)
- International programmes (e.g., support of technology transfer in agriculture).

The primary objectives of many of these measures are usually not related solely to climate change issues, but rather to such aims as reducing environmental pollution and natural resource degradation. Governments could promote more efficient fertilizer use by changing commodity programmes to allow more flexibility and to encourage farmers to grow crops and adopt practices that rely less on commercial fertilizers. Support and encouragement of the best management practices to reduce soil degradation and environmental pollution would be consistent with mitigation measures for reduction of GHGs.

Measures to encourage improved land-use practices can increase carbon storage. These could include permanent set-aside provisions for marginal and degraded lands. Incentives could be provided for managing existing croplands in a sustainable and environmentally sound manner. Government programmes can support the development of practices that maintain or increase crop yields and reduce emissions per unit of crop yield.

7. FOREST SECTOR[19]

7.1 Introduction

Forests constitute both a sink and a source of atmospheric CO_2. Forests absorb carbon through photosynthesis, but emit carbon through decomposition and when trees are burned due to anthropogenic and natural causes. Managing forests in order to retain and increase their stored carbon will help to reduce the rate of increase in atmospheric CO_2 and stabilize atmospheric concentrations. Even though some degraded lands are unsuitable for forestry, there is considerable potential for mitigation through improved management of forest lands for carbon conservation, storage and substitution, in balance with other objectives. This section describes national forest practices and measures and international projects and programmes that may be successfully pursued to achieve this goal.[20]

Forests currently cover about 3.4 Gha worldwide, with 52% of the forests in the low latitudes (approximately 0–25°N and °S latitude), 30% in the high latitudes (approximately 50–75°N and °S latitude), and 18% in the mid-latitudes (approximately 25–50°N and °S latitude) (SAR II, 24.2.1). The world's forests store large quantities of carbon, with an estimated 330 Gt C in live and dead above- and below-ground vegetation, and 660 Gt C in soil (mineral soil plus organic horizon) (SAR II, 24.2.2). An unknown quantity of carbon also is stored in products such as wood products, buildings, furniture and paper.

High- and mid-latitude forests are currently estimated to be a net carbon sink of about 0.7 ± 0.2 Gt C/yr. Low-latitude forests are estimated to be a net carbon source of 1.6 ± 0.4 Gt C/yr, caused mostly by clearing and degradation of forests (SAR II, 24.2.2). These sinks and sources may be compared with the carbon release from fossil fuel combustion, which was estimated to be 6 Gt C in 1990.

7.2 Technologies for Reducing GHG Emissions in the Forest Sector

Forest management practices that can restrain the rate of increase in atmospheric CO_2 can be grouped into three categories: (i) management for carbon conservation; (ii) management for carbon sequestration and storage; and (iii) management for carbon substitution. *Conservation* practices include options such as controlling deforestation, protecting forests in reserves, changing harvesting regimes, and controlling other anthropogenic disturbances, such as fire and pest outbreaks. *Sequestration and storage* practices include expanding forest ecosystems by increasing the area and/or biomass and soil carbon density of natural and plantation forests, and increasing storage in durable wood products. *Substitution* practices aim at increasing the transfer of forest biomass carbon into products rather than using fossil fuel-based energy and products, cement-based products and other non-wood building materials.

The potential land area available for the implementation of forest management options for carbon conservation and sequestration is a function of the technical suitability of the land to grow trees and the actual availability as constrained by socio-economic circumstances. The literature reviewed for the SAR (SAR II, 24.4.2.2) suggests that globally 700 Mha of land might be available for carbon conservation and sequestration (345 Mha for plantations and forestry, 138 Mha for slowed tropical deforestation, and 217 Mha for natural and assisted regeneration). Table 14 provides an estimate of global potential to conserve and sequester carbon, based on the above studies. The tropics have the potential to conserve and sequester the largest quantity of carbon (80% of the total potential), followed by the temperate (17%) and the boreal zones (3%). Natural and assisted regeneration and slowing deforestation account for more than half of the amount in the tropics. Forestation and agroforestry contribute the remaining tropical sink, and without these efforts regeneration and slowing deforestation would be highly unlikely.

Scenarios show that annual rates of carbon conservation and sequestration from all of the practices mentioned increase over time (SAR II, 24.4.2.2). Carbon savings from slowed deforestation and regeneration initially are the highest, but from 2020 onwards plantations sequester practically identical amounts as they reach maximum carbon accretion (see Figure 3). On a global scale, forests turn from a global source to a sink by about 2010, as tropical deforestation is offset by carbon conserved and sequestered in all zones.

Using the mean cost of establishment or first costs for individual options by latitudinal region, the cumulative cost (undiscounted) for conserving and sequestering the quantity of carbon shown in Table 14 ranges from about $250–300 billion at an average unit cost ranging from $3.7–4.6/t C (SAR II, 24.5.4). Average unit cost decreases with more carbon conserved by slowing deforestation and assisting regeneration, as these are the lowest cost options. Assuming an annual discount rate of 3%, these costs fall to $77–99 billion and the average unit cost falls to $1.2–1.4/t C. Land costs and the costs of establishing infrastructure, protective fencing, education and training are not included in these cost estimates.

While the uncertainty in the above estimates is likely to be high, the trends across options and latitudes appear to be sound. The factors causing uncertainty are the estimated land availability for forestation projects and regeneration programmes, the rate at which tropical deforestation can actually be reduced, and the

[19]This section is based on SAR II, Chapter 24, *Management of Forests for Mitigation of Greenhouse Gas Emissions* (Lead Authors: S. Brown, J. Sathaye, M. Cannell and P. Kauppi).

[20]Mitigation technologies, policies and measures to reduce GHG emissions from grasslands, deserts and tundra are still in their infancy, and mitigation options in these sectors have yet to be evaluated in depth; hence, these are not addressed in this report.

Table 14: Global carbon that could be sequestered and conserved, and related costs (1995–2050).

(1) Latitudinal Zone	(2) Measure	(3) C Sequestered or Conserved (Gt C)[a]	(4) Cost (US$/t C)[b]	(5) Total Cost (10^9 US$)[c]
High	Forestation	2.4	8 (3–27)	17
Mid	Forestation	11.8	6 (1–29)	60
	Agroforestry	0.7	5	3
Low	Forestation	16.4	7 (3–26)	97
	Agroforestry	6.3	5 (2–12)	27
	Regeneration	11.5–28.7	2 (1–2)	
	Slowing Deforestation	10.8–20.8	2 (0.5–15)	44-97[d]
	TOTAL	60–87	3.7–4.6 (1–29)	250–300

Source: SAR II, Tables 24-5, 24-8 and 24-9.

[a] Includes above- and below-ground vegetation, soil and litter C.

[b] Establishment or first cost (undiscounted). Average of estimates reported in the literature. Most estimates do not include land, infrastructure, protective fencing, education and training costs. Figures in parenthesis indicate the range of cost estimates.

[c] Cost figures in column 4 are per t of vegetation C. Total costs (column 5) are thus lower than the figure obtained by multiplying t C in column 3 by $/t C in column 4.

[d] For slowing deforestation and enhancing regeneration combined.

amount of carbon that can be conserved and sequestered in tropical forests. In summary, policies aimed at promoting mitigation efforts in the tropical zone are likely to have the largest payoff, given the significant potential for carbon conservation and sequestration in tropical forests. Those aimed at forestation in the temperate zone also will be important.

7.3 Measures for Reducing GHG Emissions in the Forest Sector

Forest management practices with the largest potential for carbon conservation and sequestration range (in declining order of importance) from slowing deforestation and assisting regeneration in the tropics to forestation schemes and agroforestry in tropical and temperate zones (Table 14). To the extent that forestation schemes yield wood that can substitute for fossil fuel-based material and energy, their carbon benefit will be multiplied. The following subsections examine the measures relevant to the implementation of each type of practice.

7.3.1 Slowing Deforestation and Assisting Regeneration

The causes of deforestation range from clearing of forest land for agriculture, mineral extraction and hydro-reservoirs to degradation of forests for fuel wood. Land cleared for agriculture may eventually lose its fertility and become suitable only as rangeland. Socio-economic and political pressures, often brought about by the needs of growing populations living in marginal areas at subsistence levels, are principal factors causing deforestation in much of the tropics (SAR II, 24.3.1.1). In Brazil, on the other hand, wealthier investors are major agents of deforestation, clearing land for cattle ranches that often derive part of their financial attractiveness from land speculation.

Both forest-related and non-forest measures and policies have contributed to deforestation. These include short-duration contracts that specify annually harvested amounts and poor harvesting methods, which encourage contractors to log without considering the concession’s sustainability. Royalty structures that provide the government with too little revenue to permit reforestation adequate for arresting forest degradation after harvesting also lead to deforestation. Non-forest policies that lead to direct physical intrusion of natural forests are another prime cause of deforestation. These include land tenure policies that assign property rights to private individuals on the basis of “improvement” through deforestation, settlement programmes, investments promoting dams and mining, and tax credits or deductions for cattle ranching.

Table 15 shows the measures whose successful implementation would slow deforestation and assist regeneration of biomass. Each of these measures will conserve biomass, which is likely to have a high carbon density, and will maintain or improve the current biodiversity, soil and watershed benefits. The capital costs of these measures are low, except in the case of recycled wood, where the capital cost depends on the product being recycled. The first two measures are likely to reduce sectoral (agricultural) employment as deforestation is curtailed. If the subsidies are gainfully invested, they have the potential to create jobs elsewhere in the economy to offset this loss. Sustainable forest management has the potential to create economic activity and employment on a long-term basis. The implementation of forest conservation legislation requires strong political support and may incur a high administrative burden. Removing subsidies may run into strong opposition from vested interests. Jointly implemented projects have been slow to take off as the perceived transaction costs are high and financing is difficult to obtain when carbon sequestration is the main benefit. Although sustainable forest management is politically attractive, its implementation requires local participation, the establishment of land tenure and rights, addressing gender and equity issues, and the development of institutional mechanisms to value scarcity; the combination of these factors may incur high administrative costs.

Although reducing deforestation rates in the tropics may appear to be difficult, the potential for significant reduction is high, and there are countries, such as Brazil, India and Thailand, where governments have adopted explicit measures and policies to halt further deforestation (SAR II, 24.3.1.1). For instance, in June 1991, the Brazilian government issued a decree (No. 151) suspending the granting of fiscal incentives to new ranching projects in Amazonian forest areas in order to further decrease the annual rate of deforestation (which, as a consequence of economic recession, had reduced to 1.1 Mha for 1990–91 from 2 Mha/yr during 1978–88). The long-term impact of this decree is not yet known, but additional measures could be applied if necessary.

In addition to national measures, protection projects supported by foreign governments, non-governmental organizations and private companies are being formed to arrest deforestation and conserve and/or sequester carbon. The Rio Bravo Preservation and Forest Management Project in Belize, which has been

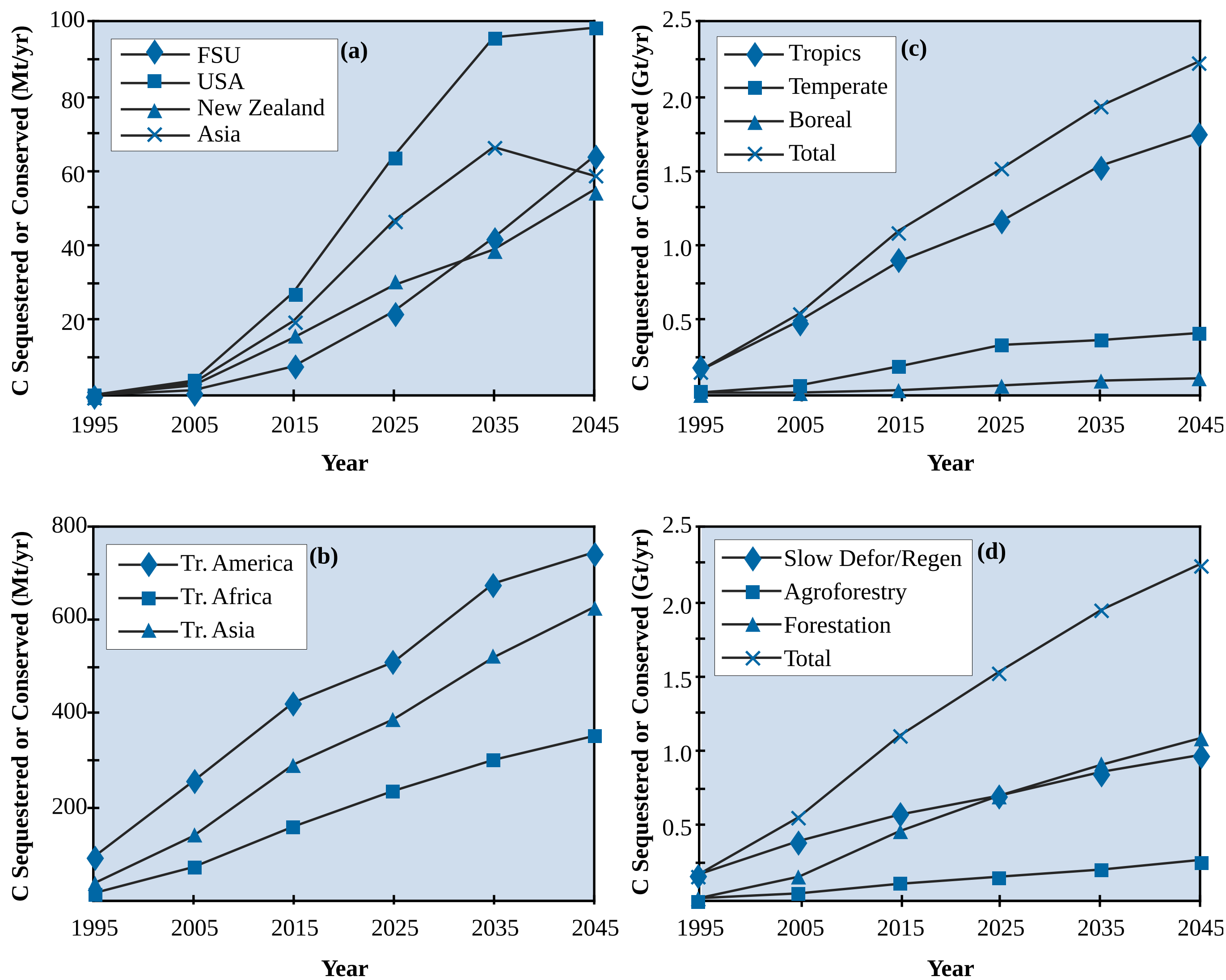

Figure 3: Average annual rates of carbon conservation and sequestration per decade through implementation of forest management options listed in Table 14: (a) by four countries or regions of the high- and mid-latitudes with the highest total sequestration rates, (b) for the three tropical (Tr.) regions, (c) latitudinal region, and (d) forest management practice. Note that Defor = deforestation and Regen = natural and assisted regeneration (SAR II, 24.4.2.2, Figures 24-1 and 24-2).

Table 15: Selected examples of measures to mitigate GHG emissions through slowing deforestation and assisting regeneration.

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Forest Practices/Goals – Reduce slash and burn agriculture/ranching – Increase field and satellite monitoring – Reduce forest fires – Improve boundary measures – Improve logging techniques	**Market-based Programmes** – Jointly implement projects with bilateral and multilateral funding (also applies to forestation and susbtitution management projects) – Promote sustainable forest management **Regulatory Measures** – Enact forest conservation legislation (including bans on logging) – Eliminate subsidies for activities that encourage deforestation (cattle ranching, mining, agriculture, etc.)	**Climate Benefits** – Maintain C density, up to 300 t C/ha **Other Effects** – Maintain biodiversity, soil conservation and watershed benefits	**Cost-effectiveness** – Monetary benefits from product sales may outweigh costs **Macro-economic Issues** – Low capital cost, high opportunity cost – Reduces government expenditure – Increased foreign investment – Increased technology transfer – Higher operating costs beyond routine forest management **Equity Issues** – Concern regarding loss of sovereignty on land ownership – Loss of sectoral jobs, yet sustained job creation – Potential for equitable benefits depends on implementation approach	**Administrative/ Institutional Factors** – High enforcement burden – Higher transaction costs – Lack of access to appropriate financing – Monitoring and verification uncertainty – Requires local commitment and participation; better defined tenure rights; explicit consideration of gender and equity issues; and development of institutional mechanisms to value scarcity – Global initiatives such as ITTO can strengthen the sustainable forest management approach **Political Factors** – Requires strong political support – Strong opposition from vested interests
Fuel Wood Conservation and Substitution – Improved stoves – Charcoal kilns	**Market-based Programmes** – Investment incentives **Regulatory Measures** – Licensing/regulation of standards **RD&D** – Government reasearch, development, demonstration and dissemination	**Climate Benefits** – Maintain C density, up to 300 t C/ha – Potential to reduce non-sustainably extracted share of 1.27×10^9 m^3 of fuel wood	**Macro-economic Issues** – Higher cost of efficient stoves **Equity Issues** – Creates sustained rural employment – Reduces women's drudgery and improves health – Reduces time and cost of gathering fuel wood	**Administrative/ Institutional Factors** – Commercially feasible – High potential for replication – Need to overcome cultural barriers (may require the establishment of formal markets for stoves) **Political Factors** – Politically acceptable
Use of Recycled and More Efficient Wood Products	**Market-based Programmes** – Tax incentives to industry **Regulatory Measures** – Labelling of products **RD&D** – Consumer awareness campaigns	**Climate Benefits** – Maintain C density, up to 300 t C/ha **Other Effects** – Maintain biodiversity, soil conservation and watershed benefits – Recycling may require disposal of contaminants from treated wood products	**Cost-effectiveness** – Cost of recycling and more efficient use is product specific **Macro-economic Issues** – Monetary benefit from more productive use of wood	**Administrative/ Institutional Factors** – High replicability – Some administrative costs **Political Factors** – Politically attractive

approved under the U.S. Initiative on Joint Implementation (US IJI), will purchase a 6 000 ha parcel of endangered forest land to protect two adjacent tracts from conversion to farmland, and is estimated to sequester 3 Mt C. The project participants include Wisconsin Electric Power Company, The Nature Conservancy, Programme for Belize, Detroit Edison Company, Citienergy and PacfiCorp. The ECOLAND Project will preserve tropical forest through purchase of 2 000–3 000 ha in the Esquinas National Park, which is under threat of deforestation in southwestern Costa Rica. The project partners include U.S., Costa Rican and Austrian institutions.

Sustaining the programmes, projects and measures that are being implemented to slow deforestation will pose many challenges. In India, declining rural population growth rates have helped policymakers sustain the slowed deforestation rate. Elsewhere, however, the fundamental challenge will be to continue to find an alternative livelihood for forest dwellers or deforesters, which may require integrating dwellers into the urban social fabric of a nation. Deforesters may be drawn to the forest for reasons other than land cultivation, and policymakers need to resort to largely non-forest policies in such situations. Another challenge in the protection of forests and national parks is to increase government budgets allocated for this purpose, which often are inadequate to provide enough forest rangers, and fencing and other infrastructure to halt land encroachment.

7.3.2 Forestation

Forestation means increasing the amount of carbon stored in vegetation (living above- and below-ground), dead organic matter, and medium- and long-term wood products. This process consists of reforestation, which means replanting trees in areas that were recently deforested (less than 50 years), and afforestation, which means planting trees on areas which have been without forest cover for a long time (for over 50 years). In temperate regions, reforestation rates tend to be high: Canadian reforestation during the 1980s was reported to be 720 000 ha/yr (SAR II, 24.4.1) and U.S. rates have averaged 1 Mha/yr between 1990 and 1995. There are significant afforestation efforts in both tropical and temperate countries. China alone boasts of having planted 30.7 Mha between 1949 and 1990, while India had 17.1 Mha planted by 1989 (SAR II, 24.4; see Box 4). The United States had 5 Mha of forest plantations by 1985, while France has more than doubled its forest area since the beginning of the last century, from 7 to 15 Mha; by 1994, New Zealand was managing 1.4 Mha of planted forest on sustained yield principles.

Measures for forestation and agroforestry include: (i) government investment programmes targeted towards these practices on government-owned land; (ii) community forestry programmes that may be supported by government extension services; and (iii) private plantations with financial and other

Box 4. India Example

Since 1980, the Indian government has pursued a series of policies and programmes that have stabilized its forested area at about 64 Mha, and, as a consequence, forests are estimated to have sequestered 5 Mt C in 1990. Prior to 1980, the government had a priority to increase food production by increasing area under food grains and to distribute land to the landless poor. This had resulted in significant deforestation during the period 1950–1975, when about 4.3 Mha were converted largely to agriculture. The Indian policies and programmes to slow deforestation and assist regeneration include:

Policies

1) Forest Conservation Act 1980: This powerful legislation has made it very difficult to convert forest land to other uses.
2) Ban on logging on state-owned primary forests in many states since the mid 1980s.
3) Significant reduction in concessions to forest-wood-based industry and promotion of a shift to farmland for wood raw material.

Programmes

1) Conversion of 15 Mha of forests to protected areas (national parks and wildlife sanctuaries).
2) Joint Forest Management programme where degraded forest lands are revegetated jointly by the local communities and forest department.
3) Reforestation of 18–20 Mha during 1980–95, yielding 58 Mt of industrial and fuel wood.

The policies have survived for nearly 15 years, despite a growing population and increasing demand for food and biomass. The Indian government appears to have successfully relied on conservation legislation, reforestation programmes and community awareness to achieve forest conservation.

Source: SAR II, Chapters 15 (Box 15.3) and 24 (Section 24.3.1.1).

incentives provided by the government (see Table 16). These measures may be targeted towards production forests, agroforestry and conservation forests. Conservation forests include those managed for soil erosion and watershed management. Those managed primarily for carbon sequestration would have to be located on lands with low opportunity costs, or else they would be likely to be encroached upon for other uses. Government subsidies may take the form of taxation arrangements that do not discriminate against forestry, tax relief for projects that meet specific objectives, and easy access to bank financing at lower-than-market interest rates.

Government subsidies have been important for initiating and sustaining private plantations. Since World War II, 3.15 Mha have been afforested in France, and the 1995 French National Programme for the mitigation of climate change calls for an afforestation rate of 30 000 ha/yr from 1998 onward, which will sequester 79–89 Mt C over 50 years at a cost of $70/t C. An interesting development in India in the last few years has been the planting of teak (*Tectona grandis*) by private entrepreneurs, with capital raised in private capital markets (SAR II, 15.3.3). This programme, while occupying only a few thousand ha at present, has the potential to expand to 4–6 Mha of India's 66 Mha of degraded lands. The teak may be used in buildings and furniture.

In addition to national programmes, other programmes are being initiated and supported in some countries by foreign governments, non-governmental organizations and private companies. One example is RUSAFOR, which is a US IJI-approved afforestation project in the Saratov region of Russia (SAR II, Box 24-2). The project proposes to plant seedlings on 500 ha of marginal agricultural land or burned forest stands. Initial seedling survival rate is 65%. The project will serve as an example for managing a Russian forest plantation as a carbon sink. Another example is the Reduced-Impact Logging Project, for which funds were provided by New England Power Company (SAR II, Box 24-2). This project aims to reduce by half the damage to residual trees and soil during timber harvesting, thus producing less woody debris, decomposition and release of carbon.

For government forestation and agroforestry policies to succeed, the formulation of a coordinated land-use strategy,

Table 16: *Selected examples of measures to mitigate GHG emissions via adoption of forestation and agroforestry.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Production Forestry/ Agroforestry	**Market-based Programmes** – Promote programmes on government-owned land – Provide extension services for community or private forestry – Provide financial and other incentives for private plantations	**Climate Benefits** – Up to 75 t C/ha in standing vegetation (additional C conservation from avoided harvesting of primary forest) – Agroforestry may have lower C density **Other Effects** – Proper site and species selection needed for soil conservation and watershed benefits	**Macro-economic Issues** – Capital cost of $5–8/t C – Other costs vary with type of land, soil quality, and level of government intervention, including infrastructure – Benefit from timber and non-timber product sales – Creates jobs – Reduces timber imports and hard currency outflow	**Administrative/ Institutional Factors** – Requires assured markets for products, and institutions to provide extension services **Political Factors** – Requires unambiguous land tenure rights
Conservation Forests[a]	**Regulatory Measures** – Direct action by government aimed at forests managed for: • Watershed protection • Soil conservation • C sequestration	**Climate Benefits** – High potential, up to 300 t C/ha, but C sequestration stops at maturity **Other Effects** – Has soil conservation, watershed, etc., benefits – Proper site and species selection needed for soil conservation and watershed benefits	**Macro-economic Issues** – Capital cost of $5–8/t C – High opportunity cost of land – Can create rural jobs – Yields non-timber forest products	**Political Factors** – Difficult to justify politically and sustain over the long term

[a] Policies and programmes for conservation forests will largely focus on government land, but also include provision of extension services for growing vegetation on non-government lands.

agreed-upon land tenure rights that are unambiguous and not open to legal challenges, and markets developed enough to ensure a sustained demand for forest products will be essential.

7.3.3 Substitution Management

Substitution management has the greatest mitigation potential in the long term. It views forests as renewable resources, and focuses on the transfer of biomass carbon into products that substitute for—or reduce the use of—fossil fuels, rather than on increasing the carbon pool itself. Growing trees explicitly for energy purposes has been attempted with mixed success in Brazil, the Philippines, Ethiopia, Sweden and other countries, but the potential for bioenergy is very large (see Section 5.2.5 for estimates of bioenergy supply potential; see also Box 5). Over time, the displacement of fossil fuels for low energy-intensive wood products is likely to be more effective in reducing carbon emissions than sequestering carbon in plantations on deforested and otherwise degraded lands in developing countries, and on excess cropland in OECD Annex I countries. For example, substituting plantation wood for coal in the generation of electricity can avoid carbon emissions by an amount up to four times the carbon sequestered in the plantation (see Table 17) (SAR II, 24.3.3). The generation of biofuels and bioelectricity is far more complex, since commercialization is not easy and energy pricing and marketing barriers are yet to be overcome. Town and village biomass energy systems have the advantage of providing employment, reclaiming degraded land and providing associated benefits to rural areas. Central heating systems could be converted to biomass-based ones to supply heat and electricity in colder climates.

Table 17: *Selected examples of measures to mitigate GHG emissions via adoption of substitution management.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Bioelectricity Production from Wasteland and Degraded Lands	**Market-based Programmes** – Set appropriate energy prices based on cost of avoided fossil fuel energy **RD&D** – Promotion and commercialization of bioelectricity and biofuel, including biogas	**Climate Benefits** – Can avoid C emissions by an amount up to four times the C sequestered in the plantation – Biofuels/ bioelectricity generally have lower non-GHG emissions **Other Effects** – Can have soil conservation and watershed benefits	**Cost-effectiveness** – Benefits may outweigh costs **Macro-economic Issues** – Capital cost of plantations is $5–8/t C – Additional capital cost of bioenergy equipment – Low opportunity cost of land – Yields timber and non-timber forest products **Equity Issues** – Creates sustained rural employment and biomass opportunities	**Administrative/ Institutional Factors** – High potential for replicability – May need technology R&D and transfer **Political Factors** – Energy pricing and marketing barriers need to be resolved
Substitute sustainably Grown Wood for Non-sustainably Harvested Wood and for Non-wood Products (e.g., cement, steel, etc.)	**Market-Based Programmes** – Provide tax incentives – Institute wood industry policy to make its products technically and economically competitive with substitutes like steel, cement, coal, etc. – Stumpage pricing policy favoring sustainably grown wood over subsitutes **RD&D** – Increase awareness	**Climate Benefits** – Commensurate with the emissions avoided in the manufacture/harvest of substituted material or wood – Biofuels/ bioelectricity generally have lower non-GHG emissions **Other Effects** – Can have soil conservation and watershed benefits	**Cost-effectiveness** – Benefits may outweigh costs **Macro-economic Issues** – May reduce fuel imports – Retooling and retraining costs – Loss of respective jobs – Yields timber and non-timber forest products **Equity Issues** – Creates sustained rural employment and bio-	**Administrative/ Institutional Factors** – Long-term product markets not assured

Box 5. Potential for Bioenergy for Rural Electrification

In non-Annex I countries, the majority of rural areas (where over 70% of the population lives) is not electrified, but the demand for electricity in these areas is likely to grow. The electricity loads are low and dispersed, in the range of 10–200 kW. Field demonstrations in southern India have shown the technical and operational feasibility of meeting rural electricity needs through decentralized woody biomass-based electricity systems using producer gas generators and cattle dung-based biogas systems. Bioenergy systems could also lead to reclamation of degraded lands, promotion of biodiversity with appropriate forestry practices and creation of rural employment. Thus, given the low loads, dispersed demand for electricity and local benefits, bioenergy systems could be considered as "no regrets" options for meeting the growing rural electricity needs.

In non-Annex I countries, the use of electricity in rural areas is low. In many countries, such as in sub-Saharan Africa, less than 5% of villages are electrified; in countries such as India, even though over 80% of rural settlements are electrified, less than a third of rural households have electricity. Appropriate government policies are needed that will: (i) permit small-scale independent power producers to generate and distribute biomass electricity; (ii) transfer technologies within the country or from outside; (iii) set a remunerative price for electricity; and (iv) remove restrictions on the growing, harvesting, transportation and processing of wood (except possibly restrictions on conversion of good agricultural land to an energy forest) (SAR II, 24.3.3).

8. SOLID WASTE AND WASTEWATER DISPOSAL[21]

8.1 Introduction

Methane is emitted during the anaerobic decomposition of the organic content of solid waste and wastewater. There are large uncertainties in emissions estimates, due to the lack of information about the waste management practices employed in different countries, the portion of organic wastes that decompose anaerobically and the extent to which these wastes will ultimately decompose.

About 20–40 Mt CH_4 (110–230 Mt C), or about 10% of global CH_4 emissions from human-related sources, are emitted from landfills and open dumps annually. Ten Annex I countries represent about two-thirds of global CH_4 emissions from solid-waste disposal, with the United States representing about 33%, or around 10 Mt (SAR II, 22.4.4.1).

CH_4 emissions from domestic and industrial wastewater disposal are estimated to be 30–40 Mt (170–230 Mt C) annually, again about 10% of total global emissions from human sources. Industrial wastewater, principally from the food processing and pulp and paper industries, is the major contributor, with domestic and commercial wastewater making up 2 Mt CH_4 annually. Unlike solid-waste emissions, the majority of wastewater emissions is believed to originate in non-Annex I countries, where domestic sewage and industrial waste streams often are unmanaged or maintained under anaerobic conditions without CH_4 control (SAR II, 22.4.4.1).

8.2 Technical Options for Controlling Methane Emissions

CH_4 emissions may be reduced through source reduction or through CH_4 recovery and/or reduction from solid waste and wastewater.

8.2.1 Source Reduction

The most important technical option for source reduction is decreasing the use of materials that eventually turn up in the waste stream. This section, however, focuses on solid waste after it has been generated (consistent with SAR II, 22.4.4.2). The amount of organic solid waste may be reduced by recycling paper products, composting, and incineration. Paper products make up a significant part of solid waste in Annex I countries (e.g., 40% in the United States) and in urban centers of upper-income non-Annex I countries (typically 5–20%). A variety of recycling processes, differing in technical complexity, can often turn this waste into material indistinguishable from virgin products. Composting—an aerobic process for treating moist organic wastes that generates little or no CH_4—is most applicable to non-Annex I countries, where this type of waste is a larger fraction of the total, although there is also potential in Annex I countries (SAR II, 22.4.4.2). As a secondary benefit, the residue can be used as fertilizer. Reduced land availability and the potential for energy recovery are increasing use of waste incineration in many countries: 70% of Japan's solid waste is incinerated. Stack air pollutant emissions and ash disposal are still issues, however, and characteristics such as moisture content and composition may make incineration more difficult and costly in non-Annex I countries.

The technical complexity of these source reduction options can vary significantly, although this does not greatly influence their effectiveness. In non-Annex I countries, where labour is cheap compared to equipment costs, labour-intensive recycling and composting are common. Annex I countries typically use more complicated, labour-saving machinery requiring higher operating skills.

Costs will depend on the type of system, the size of the facility, and local factors. Capital costs for solid-waste composting facilities can range from $1.5 million for a 300 ton per day (TPD) plant to $45 million for a more complex 550 TPD plant that also composts sewage sludge; associated operating costs can range from $10–90/t, but generally average $20–40. Yard waste facilities are typically smaller and less complex; capital costs range from $75 000–2 000 000 in the United States for plants handling 2 000–60 000 t/yr of waste; operating costs are roughly $20/t. Capital costs for incineration can be quite high, ranging from $60–300 million for 10–80 MW facilities, or approximately $125 000 per TPD capacity (SAR II, 22.4.4.2).

8.2.2 Methane Recovery from Solid-waste Disposal

Source reduction is applicable to future solid-waste generation. CH_4 may be recovered from existing as well as future landfills, since organic materials in dumps and landfills continue to emit CH_4 (often called landfill gas) for 10–30 years or more. Frequently, more than half of the CH_4 can be recovered and used for heat or electricity generation, a practice already common in many countries (SAR II, 22.4.4.2). Landfill gas also can be purified and injected into a natural gas pipeline or distribution system; there are several such projects in the United States. In Minas Gerais, Brazil, purified landfill gas has been used to provide power for a fleet of garbage trucks and taxicabs.

Costs of recovering CH_4 from solid-waste disposal facilities are highly dependent on technology and site characteristics. For a landfill with 1 million tons of waste (serving a population

[21] This section is based on SAR II, Chapter 22, *Mitigation Options for Human Settlements* (Lead Authors: M. Levine, H. Akbari, J. Busch, G. Dutt, K. Hogan, P. Komor, S. Meyers, H. Tsuchiya, G. Henderson, L. Price, K. Smith and Lang Siwei) and Chapter 23, *Agricultural Options for Mitigation of Greenhouse Gas Emissions* (Lead Authors: V. Cole, C. Cerri, K. Minami, A. Mosier, N. Rosenberg, D. Sauerbeck, J. Dumanski, J. Duxbury, J. Freney, R. Gupta, O. Heinemeyer, T. Kolchugina, J. Lee, K. Paustian, D. Powlson, N. Sampson, H. Tiessen, M. van Noordwijk and Q. Zhao).

of about 50 000–100 000), collection and flare capital costs will be approximately $630 000, increasing to $3.6 million for a 10 million-ton landfill. Annual operating costs could range from less than $100 000 to more than $200 000. Energy recovery capital costs (including gas treatment) can range from $1 000–1 300 per net kW. Direct use is typically less expensive, with pipeline construction representing the principal cost. Overall, typical electric generation costs for a complete system (gas collection and energy recovery) range from 4–7¢/kWh. These costs are based on equipment and labor costs in the United States, and may vary over a wider range in other countries. Also, in many countries, some landfills and other solid-waste disposal sites already collect their CH_4 and either vent or flare it (often for safety reasons). For these sites, the cost of electric generation would be lower than stated above (SAR II, 22.4.4.2; SAR III, 9.4.1).

8.2.3 Methane Recovery and/or Reduction from Wastewater

CH_4 emissions can be virtually eliminated if wastewater and sludge are stored and treated under aerobic conditions. Options for preventing CH_4 production during wastewater treatment and sludge disposal include aerobic primary and secondary treatment and land treatment. Alternatively, wastewater can be treated under anaerobic conditions and the generated CH_4 can be captured and used as an energy source to heat the wastewater or sludge digestion tank. If additional CH_4 is available, it can be used as fuel or to generate electricity. As a last resort, the gas may be flared, which converts the CH_4 to CO_2, with a much lower global warming potential.

Wastewater treatment costs are highly dependent on the technological approach employed and site-specific conditions. Capital costs of aerobic primary treatment can range from $0.15–3 million for construction, assuming a range of 0.5–10 million gallons (2 000–40 000 m^3) of wastewater flow per day; annual operation and maintenance costs are estimated to range from $20 000–500 000 for these volumes. Costs of aerobic secondary treatment can be moderately high because of the energy and equipment requirements, and depend to a great extent on the daily volume of wastewater flow into the facility. Costs can range up to $10 million depending upon the technology selected and volume requirements, with the high-end handling approximately 100 million gallons (0.4×10^6 m^3) per day. Finally, costs for anaerobic digestors of wastewater and flaring or utilization can range from $0.1–3 million for construction and $10 000–100 000 for operation and maintenance, assuming wastewater flows of 0.1–100 million gallons (400 to 0.4×10^6 m^3) per day (SAR II, 22.4.4.2).

High-rate anaerobic processes for the treatment of liquid effluents with high organic content (e.g., sewage, food processing wastes) can help reduce uncontrolled CH_4 emissions and are particularly suited to the warmer climates of most developing countries. Both Brazil and India, for example, have developed extensive and successful infrastructure for these technologies, which have lower hydraulic retention times than aerobic processes and therefore are much smaller and cheaper to build. More importantly, unlike aerobic processes, no aeration is involved and there is little electricity consumption.

For upflow anaerobic sludge blanket reactors of 4 000–10 000 m^3 capacity (capable of handling a chemical oxygen demand of 20–30 kg/m^3/day), capital costs have been estimated to be in the range of $1–3.5 million, with annual operating costs in the range of $1–2.7 million. At these costs, the total CH_4 production cost would fall in the range of $0.45–1.05/GJ, with values at the upper end for Europe and at the lower end for Brazil. Using these estimates, all of the costs would be recovered, as CH_4 would be produced at a price lower than that of natural gas almost anywhere in the world (SAR II, 22.4.4.2).

8.3 Measures for Methane Reduction and Recovery

In many countries, future actions that reduce CH_4 emissions from solid-waste disposal sites and wastewater treatment facilities are likely to be undertaken for environmental and public health reasons; CH_4 reductions will be seen as a secondary benefit of these actions. In spite of the benefits, however, a number of barriers prevents CH_4 recovery and source reduction efforts described above from tapping more than a small portion of the potential, especially in non-Annex I countries. These barriers include the following (SAR II, 22.5.3):

- There is a lack of awareness of relative costs and effectiveness of alternative technical options.
- While recently developed anaerobic processes are less expensive than traditional aerobic wastewater treatment, there is less experience available.
- It is less economical to recover CH_4 from smaller dumps and landfills.
- Many countries and regions where natural gas is not used extensively and equipment may not be readily available [e.g., Mexico City, New Delhi, Port-au-Prince (Haiti), and much of sub-Saharan Africa] have limited infrastructure and experience for CH_4 use.
- The existing waste disposal “system” may be an open dump or an effluent stream with no treatment, therefore no capital or operating expenses. The barriers previously noted, combined with the unhygienic conditions of the proposed site, may make it difficult to attract investment capital for CH_4 recovery and use.
- Different groups are generally responsible for energy generation, fertilizer supply and waste management, and CH_4 recovery and use can introduce new actors into the waste disposal process, potentially disturbing the current balance of economic and political power in the community (e.g., failure to reach an agreement has delayed the start-up of a landfill gas recovery demonstration project funded by the Global Environment Facility in Lahore, Pakistan). This problem applies to both Annex I and non-Annex I countries.

For the successful implementation of CH_4 control projects, these barriers need to be addressed through appropriate measures. In

***Table 18:** Selected examples of measures to reduce GHG emissions from solid waste disposal and wastewater treatment facilities.*

Technical Options	Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Source Reduction – Recycling – Composting – Incineration **Methane Recovery** – Solid waste disposal facilities – Wastewater treatment plants	**Institution Building and Technical Assistance** – Focus on strengthening local and national institutions for managing waste disposal and wastewater treatment	**Climate Benefits** – Significant CH_4 reductions (up to 70% or more) depending on technical options and scope – For CH_4 recovery projects and incineration, associated CO_2 reductions through fossil fuel displacement **Other Effects** – Local air quality improvements, including reduced VOC emissions – Reduced odors – Public health benefits, including reduced disease – Improved safety	**Cost-effectiveness** – Lower cost measure **Macro-economic Issues** – Wide-ranging benefits **Equity Issues** – Significant quality of life improvements for current and future generations	**Administrative/ Institutional Factors** – Difficult to measure results – May shift power balances – Widely replicable **Political Factors** – Opposition from some institutions – More support than regulations
	Voluntary Programmes – Cooperative programmes with industry, government and facility operators to encourage implementation of technical options	**Climate Benefits** – May have smaller benefits than regulatory or financial programmes, because only profitable reductions will be undertaken voluntarily **Other Effects** – Local air quality and public health benefits as above	**Cost-effectiveness** – Lower cost than regulatory measures – Promotes profitable projects **Macro-economic Issues** – Removes barriers to economically justified projects **Equity Issues** – As above	**Administrative/ Institutional Factors** – Limited certainty in reductions – Requires institutional support – Widely replicable, if institutional framework exists **Political Factors** – More support than regulations
	Regulatory Programmes – Establishing standards or regulations for waste disposal, wastewater management and/or CH_4 recovery	**Climate Benefits** – Can deliver large, definite benefits due to mandatory nature (depending on action level) **Other Effects** – Local air quality and public health benefits as above	**Cost-effectiveness** – Higher cost, depending on stringency of regulation **Macro-economic Issues** – Higher social costs **Equity Issues** – As above, but higher social costs for larger emission reductions	**Administrative/ Institutional Factors** – Certainty in reductions – Requires institutional infrastructure – Replicable if enforcement infrastructure exists and politically supported **Political Factors** – Opposition from industry
	Market-Based Programmes – Provision of market incentives for desired waste management practices or direct CH_4 recovery activities	**Climate Benefits** – Can deliver large benefits, depending upon level of assistance **Other Effects** – Local air quality and public health benefits as above	**Cost-effectiveness** – Higher cost, depending on incentive level **Macro-economic Issues** – Can reflect social value of emission reductions **Equity Issues** – As above	**Administrative/ Institutional Factors** – Less certainty in reductions – Requires inst. support – Should be customized to local economic conditions **Political Factors** – Opposition possible due to cost

general, the measures are not specific to technology options (see Table 18). The following measures are arranged in the sequence that they would need to be invoked in a country with little or no current waste management infrastructure (more advanced countries and regions would start at a later step):

- Institution building and technical assistance policies
- Voluntary agreements
- Regulatory measures
- Market-based programmes.

8.3.1 Institution Building and Technical Assistance Policies

The prior existence of an adequate waste management infrastructure, including a legal framework, is a prerequisite to any measure to control CH_4. Where such infrastructure is weak or missing, it needs to be strengthened either within countries (e.g., from more developed areas to less developed ones) or internationally through multilateral or bilateral assistance. For instance, the Interamerican Development Bank gives priority to building waste management infrastructure as part of its developmental assistance programmes. Support for institution building may include both financial and technical assistance. Technical assistance and financing are available from the U.S. Country Studies Program, joint implementation initiatives[22] and the Global Environment Facility.

8.3.2 Voluntary Agreements

Voluntary agreements also can be used to overcome the barriers to waste management projects. In the United States, a landfill outreach programme encourages state agencies (who permit projects) and utilities (who frequently purchase landfill energy) to voluntarily promote and participate in landfill projects. This type of programme can be quite low-cost and flexible in targeting key barriers and providing effective information and assistance to overcome them. The U.S. programme, for example, provides a variety of tools, including detailed descriptions of candidate project sites, and software to assess economic and technical potential.

8.3.3 Regulatory Measures

A major regulatory measure to reduce the quantity of solid waste through recycling is requiring separation at source (e.g., into paper, glass, metal and plastics). Regulations also can include setting standards for recycled paper use or recycled material content. In the United States, for example, many states have recycling goals, often included in mandatory programmes. For existing dumps and landfills, regulatory measures can range from the mandatory recovery and combustion of CH_4 to actions aimed at clarifying existing regulations and ensuring that they are supportive of CH_4 recovery. The United States recently enacted a mandatory regulation to require CH_4 recovery and combustion at the largest landfills, which will result in annual CH_4 reductions of about 60% (or ~6 Mt CH_4 in 2000) (SAR II, 22.4.4.2).

8.3.4 Market-based Programmes

Once an appropriate infrastructure as well as technical awareness exists, market-based programmes may be helpful to reduce perceptions of risk or high up-front capital costs. Domestic actions can include providing tax credits or low-cost financing. In the United States, for example, landfill gas energy recovery projects are eligible for an "unconventional gas" tax credit worth approximately 1¢/kWh of electricity generated. International financial support also may be provided through mechanisms such as the Global Environment Facility or other similar funds. The Global Environment Facility currently is funding a landfill gas-to-energy project in Pakistan, which should demonstrate the potential of this technology for CH_4 reduction throughout the region.

8.4 Comparison of Alternative Measures and Policies

Most of the technical options for CH_4 emissions reduction are independent of each other, and not mutually exclusive. Recycling of some solid waste and composting of others can occur simultaneously. The remainder may be placed in landfills where land disposal costs are low, or incinerated. CH_4 from landfills may be used for energy where possible, and flared if recovery costs are not competitive with alternative energy sources. Overall, 30–50% reductions in CH_4 emissions are economically feasible (SAR II, 22.4.4.2; SAR III, 9.4.1). Using the range of emissions estimates in the IS92 scenarios, this implies equivalent carbon reductions of about 55–140 Mt in 2010, 85–170 Mt in 2020, and 110–230 Mt in 2050.

Wastewater CH_4 removal options involve a choice between traditional aerobic treatment and recently improved anaerobic processes. The latter appears to have a cost advantage (both capital and operating costs).

The associated environmental impacts of CH_4 reduction alternatives are generally positive. Indeed, CH_4 reduction may be a secondary benefit of processes that reduce water and air pollution and improve health. Difficulties in quantifying these primary economic benefits make it difficult to estimate the cost-effectiveness of CH_4 reduction. For solid wastes, costs for recycling are expected to be low, for composting medium (as a consequence of land disposal costs), and for incineration relatively high (as a consequence of high investment and operational costs); the feasibility of specific applications depends on local circumstances. Costs for CH_4 recovery from landfills are expected to be low to medium. Aerobic treatment of wastewater is expected to have medium to high

[22] Chapter 11 of SAR III uses the term "joint implementation" to include "activities implemented jointly" and that usage is continued here.

costs, while anaerobic treatment costs will be in the low to medium range.

Macro-economic consequences also are generally favourable. The waste stream is a source of raw material for the production of recycled products, compost or energy recovery—contributing to economic production and creating jobs, while providing health and air pollution benefits that can make major contributions to development for lower-income countries. Acquiring knowledge in some technologies may imply foreign exchange costs for those non-Annex I countries that do not have them. For this reason, technical assistance is an important measure from a developmental and environmental perspective for lower-income non-Annex I countries.

Equity considerations are also generally favourable, within and across countries, as well as across generations. The poor suffer more the consequences of improper waste management, and are also more likely to benefit from the jobs created. Future generations will benefit insofar as today's waste stream is a considered a resource, reducing the consumption of primary raw materials.

As with the technical options, the measures are not mutually exclusive. The choices involved depend on the circumstances within a given region or country. Institution building and technical assistance may be starting points for non-Annex I countries, while voluntary and regulatory initiatives may be more appropriate for Annex I countries. In countries with well-developed waste management infrastructures, opposition to regulatory measures could be expected from the affected industry, although U.S. experience indicates that this opposition can be surmounted. Regulatory programmes may be hardest to implement successfully in most countries, while market-based programmes will depend both on national priority given to waste management and on international financing sources available.

9. ECONOMIC INSTRUMENTS[23]

9.1 Introduction

This section describes measures to control GHG emissions from more than one sector. The measures discussed include subsidies, taxes, tradable quotas and permits, and joint implementation.[24]

Climate change policy must be considered in the context of existing economies. In the real world, climate change is only one of many externalities; competition is not perfect; information and markets are not complete; and distorting taxes and transfers are widespread. These observations are important because many analyses of climate change policy assume that the externality of climate change is the only distortion that exists. The conclusions of such analyses may be misleading or incorrect (SAR III, 11.3).

This section first discusses national-level economic instruments, which are relevant when a country either acts unilaterally to reduce its GHG emissions or joins other countries in an international agreement to do so. These instruments include subsidies, taxes and tradable permits. Next, international-level economic instruments—international tax agreements, tradable emission quotas and joint implementation—are discussed.[25]

9.2 National-level Economic Instruments

9.2.1 Subsidies and Subsidy Elimination

An activity can be subsidized in many ways. A government may transfer funds to an enterprise, provide preferential tax treatment, supply commodities at below market prices, or restrict competing products to assist a particular activity. Many countries currently subsidize some activities that emit GHGs (e.g., subsidies that reduce the prices of fossil fuels). Eliminating permanent subsidies that encourage fossil fuel use would reduce GHG emissions and increase real incomes in the long run.

On the other hand, temporary subsidies could be offered for particular activities aimed at limiting GHG emissions. Such subsidies might be directed at fostering adoption of emission abatement technologies, creating additional sinks, or stimulating development of improved GHG mitigation technologies.

Eliminating subsidies changes the incomes of affected groups. Compensation for groups whose incomes are adversely affected may need to be considered. In the case of financial subsidies, the net effect depends on how the revenues are redistributed. Raising distortionary taxes to finance the subsidies increases the cost of this option (SAR III, 11.3.1.1).

9.2.2 Domestic Taxes[26] (SAR III, 11.5.1)

Under an emission tax system, sources that produce GHG emissions must pay a tax per unit of emissions.[27] To ensure that the cost of a given emission abatement is minimized, all emissions should be taxed at the same rate per unit of contribution to climate change. The tax rate needed to achieve a particular emission target must be found by trial and error over a number of years.

A tax on the carbon content of fossil fuels—a carbon tax—is generally proposed in lieu of a tax on the CO_2 emissions from fossil fuel use, since it has a similar impact and is much simpler to administer. A CO_2 emissions tax would require every source that uses fossil fuels to monitor its emissions and to pay the corresponding taxes. A carbon tax would affect the same emissions, but would involve only the fuel producers or distributors, most of which already are involved in the collection of other energy-related taxes. In practice, existing excises on energy products complicate the design of a carbon tax that changes prices in proportion to CO_2 emissions.

A carbon tax is a more efficient instrument for reducing energy-related CO_2 emissions than are taxes levied on some other bases, such as the energy content of fuels or the value of energy products (*ad valorem* energy tax). Model simulations for the United States indicate that for an equivalent reduction in emissions, an energy tax would cost 20–40% more than a carbon tax, and an *ad valorem* tax would be two to three times more costly. This is because an energy tax raises the price of all forms of energy, whether or not they contribute to CO_2 emissions, whereas a carbon tax changes relative costs, and so provides incentives for fuel switching.

Analysts agree that actions to respond to climate change should include all GHGs (taking into consideration their heat-trapping potentials and atmospheric lifetimes) and carbon sinks. A carbon tax on fossil fuels (or a tax on fossil fuel CO_2 emissions) could therefore be complemented by emissions taxes on non-energy sources of CO_2, emissions taxes on other GHGs, and tax rebates or subsidies for carbon sequestration. The administrative challenges and difficulties of monitoring emissions (sequestration) by these diverse sources may make the use of taxes (rebates/subsidies) impractical in some or all of these situations.

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[23]This section is based on SAR III, Chapter 11, *An Economic Assessment of Policy Instruments for Combatting Climate Change* (Lead Authors: B.S. Fisher, S. Barrett, P. Bohm, M. Kuroda, J.K.E. Mubazi, A. Shah and R.N. Stavins).

[24]The term “tradable quota” is used to describe internationally traded emission allowances, while “tradable permit” refers to domestic trading schemes. Chapter 11 of SAR III uses the term “joint implementation” to include “activities implemented jointly” and that usage is continued here.

[25]Technology transfer is not included since it is the subject of a Special Report.

[26]In most economic systems, a tax will be shifted, at least in part, to customers or to suppliers of capital, labour and other inputs in unpredictable ways.

[27]Strictly speaking, the term “emission charge” or “fee” would be more appropriate, because this is a payment for a right to emit; however, the term “emission tax” is adopted because it is so widely used.

9.2.3 Tradable Permits[28] (SAR III, 11.5.2)

A country committed to limiting its GHG emissions could implement such a policy using tradable permits for energy-related CO_2 emissions, non-energy sources of CO_2, emissions of other GHGs, and carbon sequestration. Energy-related CO_2 emissions could be controlled by a system of tradable permits for the carbon content of fossil fuels consumed. Under such a scheme, regulated sources are given (or must buy) permits for the carbon content of the fossil fuel. Tradable permits could also be applied to actual energy-related CO_2 emissions.[29] Participants are free to sell surplus permits or to buy permits to achieve regulatory compliance. Downstream of the permit system, the effect is comparable to that of a carbon tax.

In principle, tradable permit systems could also be used to regulate non-energy CO_2 emissions, emissions of other GHGs, and carbon sequestration. Permits earned for carbon sequestration could be sold to sources that need permits for their emissions. The difficulties of monitoring emissions (sequestration) may make the use of tradable permits impractical in some or all of these situations. Considerations such as the number of participants, the share of total emissions covered, industry structure, and enforcement will influence the choice among alternative trading system designs.

Regardless of the specific design, a number of factors can adversely affect the performance of emissions trading systems, including situations where a few participants can influence the permit market or where a few firms can influence the output market, transaction costs, non-profit maximizing behavior, the pre-existing regulatory environment, and the degree of monitoring and enforcement required. Some of these factors also affect the performance of other policies and measures.

A government may choose one of two main ways to distribute permits to participating sources. Sources could be allocated permits *gratis* based on an agreed allocation rule, such as emissions during some historical period, or the government could sell the permits at auction, although the latter approach has never yet been adopted. Combinations of these two approaches also may be feasible.

These approaches differ primarily in two respects. First, allocating permits *gratis* transfers wealth to the regulated sources, while selling permits at auction transfers this wealth to the government. Second, allocating permits *gratis* may increase the wealth of existing sources, thus reducing the rate of entry of new firms and slowing technological change, although mechanisms can be designed to reduce such potential impacts.

Allowing permits to be banked for use at a later date is important for both the efficiency and the political acceptability of a tradable permit scheme. Without a banking option, permit-liable sources would be confronted with greater end-of-period permit price uncertainty. Banking also facilitates adjustments to lower emission caps.

Both taxes and tradable permits tend to equate the marginal cost of emissions abatement for all affected sources. The difference is that the tax is set by the government, and the level of emissions is determined by the responses of the affected sources; whereas in a tradable permit system, the government determines the overall level of emissions, and permit prices are determined by the market.

9.2.4 Revenue Recycling and Tax Substitution (SAR III, 11.3.2)

Auctioned permits have the same distributional implications as a carbon tax—leading to the same emissions level when auction and tax revenues are not redistributed to permit buyers/taxpayers, respectively. At the other extreme, permits distributed *gratis* have the same distributional implications as a carbon tax, if the tax revenue is redistributed according to the rule used for the distribution of the permits. Parties other than regulated sources may be affected by GHG limitation actions and may need to be compensated. Revenue from a carbon tax or sale of permits could be used for this purpose.

The effect of a carbon tax, or an equivalent tradable permit system, on an economy will depend in part on what is done with the net government revenue, if any. There is widespread agreement that this revenue can be used to reduce pre-existing distortionary taxes, hence significantly lower the costs of emission reduction. Some researchers have suggested that it may be possible to increase national income by using the revenue to replace or reduce more distortionary existing taxes. However, others argue that this is an argument for general reform of the tax system rather than for the introduction of a carbon tax (or a corresponding tradable permit system) *per se*.

9.3 International-level Economic Instruments

International cooperation will be required to meet a global emission target at least cost. Economic instruments such as international taxes, harmonized domestic taxes, tradable quotas and joint implementation can help achieve a global target, but require—or would benefit from—international cooperation.

9.3.1 International Taxes and Harmonized Domestic Taxes (SAR III, 11.5.3)

At the international level, a GHG emissions tax could be implemented in one of two ways. Countries could agree to create an

[28]Conceptually, a permit could be defined either as a right to release repeated emissions (e.g., 1 t C/yr for the indefinite future) or a one-time right to emit a given quantity (e.g., 1 t/C).

[29]As in the case of a carbon tax, it is impractical to include mobile and other small sources in a trading system based on actual emissions. This trading system (or tax) based on the carbon content of fossil fuels automatically incorporates these emissions.

international agency that would impose a GHG emissions tax on participating countries. Alternatively, countries could agree that each would levy comparable GHG emissions taxes domestically. The agreement to create an international GHG emissions tax agency would need to specify both the tax rate(s) and a formula for distributing the revenues from the tax.[30]

A harmonized tax requires that each country impose the same tax rate. Due to differences in resource endowments, consumption patterns, climate change impacts and other factors, this tax rate may not be the most appropriate from a national perspective, thus side-payments are likely to be required to secure broad participation. Under a harmonized tax system, the reallocation of tax revenues could involve lump-sum payments; whereas under the international tax system, the agreement could specify what shares of the international tax revenues would go to each participating country. In principle, international transfers could be negotiated to yield the same international distribution of the tax in either case. A GHG emissions tax imposed by an international agency would impinge on national sovereignty and would therefore be difficult to negotiate.

A uniform tax rate for all countries is required for reasons of cost-effectiveness but, given different existing energy tax regimes in participating countries, this could become very complex.

9.3.2 Tradable Quotas[31] (SAR III, 11.5.4)

Countries could negotiate national limits on emissions of GHGs—either voluntary or legally binding targets/quotas—to be achieved by specific dates. These could be negotiated for a single gas, for a group of gases, or as an aggregate CO_2 equivalent. A more comprehensive approach allows more flexibility and larger cost savings.

Given differences in marginal emission control costs among countries, allowing international trade of emission quota would reduce the cost of achieving compliance with national emission limits regardless of the initial allocation. Each country would be expected either to reduce its emissions, or to purchase quota from other countries so that the sum of these two was not more than its national emission limit.

The national quota allocations can be used to address distributional issues and to draw countries into the agreement. Most proposals for allocating emission quota among countries envisage proportionately higher reductions in national emissions by industrialized countries and slower rates of emission growth by developing countries. Thus, international negotiations will seek quota allocations that do not harm Annex I countries with economies in transition and non-Annex I countries, and that distribute the burden equitably among Annex I countries.

An international tradable quota system presupposes the existence of one or more markets where quota can be traded. For a trading scheme to be effective in controlling emissions, it is clear that there must be a reasonable probability of detecting and penalizing those responsible for unauthorized emissions. This, however, does not distinguish a tradable quota system from any other international agreement on emissions reductions.

Under an international tradable quota system, participating countries could use whatever domestic policies they preferred to achieve compliance. For example, a country might employ tradable permits, a domestic tax or regulations. Where a domestic tradable permit system exists, the government could allow permit holders to trade directly on the international market. If a domestic carbon tax is used, the efficient tax rate for the coming period would be the (unknown) quota price for that period.

There is some experience with the use of tradable permit schemes within countries, whereas international tradable quota systems so far have been applied only on a small scale (e.g., the international CFC production quota trade and the CFC consumption quota trade within the European Union).

Under an international tax agreement, the tax rate is known but the effect on emissions is uncertain and the international transfer payments may or may not be known, depending on how they are defined in the agreement. Except for the effects of carbon leakage, a tradable quota system has a known effect on emissions, but quota prices and the distributional effects of the quota trade are uncertain, so protection against unfavorable price movements may need to be provided.[32] This means that the benefits of known effects on emissions in a tradable quota system must be bought at the price of some distributional uncertainty.

9.3.3 Joint Implementation (SAR III, 11.5.5)

Joint implementation, provided for by Article 4.2(a) of the FCCC, involves cooperation between countries to meet the goals of the Convention. One country (or firm in that country) funds emission reduction actions in a second country that are additional to the reductions that would otherwise occur. Following the Berlin meeting (COP 1, March–April 1995), pilot projects now are being undertaken on activities implemented jointly by a number of countries.

The potential economic merits and demerits of joint implementation proposals have been widely discussed. In essence, there are three possible roles for joint implementation: (i) as a

[30]All GHG emissions (adjusted for their heat-trapping potentials and atmospheric lifetimes) should be taxed (and carbon sequestration subsidized) at the same rate in all countries. As discussed earlier, it may not be practical to design a tax (rebate) that covers all of the sources (sinks).

[31]Defining quotas as the right to emit a given quantity once reduces the risk of a present government selling future emission rights that might not be honoured by future governments. This also reduces the possibility of large countries gaining power to distort the quota market.

[32]If only a limited set of countries is involved, carbon leakage must be taken into account in both the tax and tradable quota cases.

cost-effective option for developed countries to fund GHG emission reduction projects in other countries, while meeting local development needs; (ii) as the first step toward establishing an international tradable quota system for GHGs among parties that have made a firm commitment to limit their emissions; and (iii) as a means for exploring when it is cost-effective to bring new emission sources or sinks into an existing international GHG management system.

The potential driving force behind joint implementation is that both buyer and seller countries benefit from the trade. However, for case (i) in particular, monitoring and high transactions costs could become problems in using joint implementation as a means of achieving significant cost-effective reductions of GHG emissions. In addition, according to present international agreements, investors in joint implementation projects cannot credit the emission reductions from these projects against national commitments.

9.3.4 Policies to Reduce Free Riding and Emission Leakage

Can a unilateral policy by one country alone or by a group of countries prove effective in abating global GHG emissions? The answer depends on how the other countries respond to the policies adopted by the cooperating countries. These responses in turn reflect two phenomena: "leakage" and "free riding." Free riding arises when countries that benefit from global abatement do not bear their share of the costs of its provision. Leakage arises when abatement actions by the cooperating countries cause emissions in other countries to increase.

9.3.4.1 Policies to Reduce Free Riding

As long as participation in an international greenhouse management policy is voluntary, countries will have incentives to free ride. None of the existing empirical models has been used to estimate the magnitude of potential free riding; however, some insights into the gains from full cooperation have been explored.

The stability of the group of countries acting to control GHGs will depend on the ability of the cooperating countries to punish countries that might withdraw and to reward countries that might join. To be effective, such punishments and rewards must be both substantial and credible. One example of such a punishment is the threat of a ban on trade of carbon-based fuels and products with non-cooperating countries, once a threshold number of countries agrees to participate (SAR III, 11.6.4.1).

9.3.4.2 Policies to Reduce Leakage

Emission leakage is the net result of a number of effects, some of which counteract each other. First, the implementation of a carbon abatement policy by a country or group of cooperating countries could shift production of carbon-intensive goods toward other countries, thus increasing their emissions. Second, the mitigation actions would lower world demand for carbon-intensive fuels and reduce the world price for such fuels—hence increase the use of (thus the emissions from) these fuels in non-participating countries. Third, the abatement actions could affect incomes in cooperating countries and so reduce imports from other countries which could, in turn, lower their income and emissions. Fourth, investment flows and exchange rates also could be affected, with unpredictable impacts on emissions.

Leakage is measured in terms of net GHG emissions relative to the emissions reduction in cooperating countries; estimates vary widely (SAR III, 11.6.4.2).

What can be done to reduce emission leakage? Basic trade theory suggests that (treating the cooperating countries as a single entity and the rest of the world as another single entity) a tariff should be imposed on imports of carbon-intensive products, or their exports should be subsidized, depending on whether the cooperating countries are net importers or net exporters before the mitigation actions are implemented. Alternatively, a production subsidy (tax) and consumption tax (subsidy) could be implemented in the cooperating countries instead of the import tariff (export subsidy).[33]

Application of border tax adjustments, such as import tariffs or export subsidies, while theoretically appropriate for reducing leakage, pose a number of practical problems. Determining the emissions associated with the manufacture of a particular product, hence the border tax adjustment, is likely to be very complex because of differences in the fuel mix and production techniques used in different regions. Furthermore, the appropriate border tax adjustments may not be compatible with current multilateral trading rules. Likewise, implementing production and consumption subsidies and taxes at the appropriate level in all cooperating countries, given the differences in their existing tax systems, is likely to prove practically impossible (SAR III, 11.6.4.3).

9.4 Assessment of Economic Instruments

This section evaluates economic instruments against the criteria discussed in the Introduction (see Table 19). This evaluation focuses on taxes and tradable permits/quotas in both the domestic and international context. First, it is important to recognize that countries differ in their institutional structures, economic structures, and existing policy structures and that the choice of policy instruments will be made in a political environment. As a result, the ability to enforce the different instruments is likely

[33]World Trade Organization rules allow for border tax adjustments where the taxed or controlled inputs are physically incorporated in the final product. However, it is not clear if this rule applies to GHG emissions associated with the manufacture of a good, or whether it would be feasible in practice to implement such a system of border tax adjustments.

Table 19: *Selected examples of economic instruments to mitigate GHG emissions.*

Measures	Climate and Other Environmental Effects	Economic and Social Effects	Administrative, Institutional and Political Considerations
Subsidy Removal	– Depends on extent of existing subsidies and degree of subsidy reduction	– Increases real incomes in the long run – Changes distribution of income; effect depends on how revenues are redistributed	
Domestic Taxes	– Can be designed to achieve a specified national/international emission target	– Encourages implementation of most cost-effective mitigation measures – Tax rate determined through trial and error – Carbon tax regressive, but effect depends on how the tax revenue is recycled	– Could be linked to existing energy tax collection systems
Tradable Permits	– Can be designed to achieve a specified national/international emission target	– Encourages implementation of the most cost-effective mitigation measures – Market price for permits and cost of measures implemented is uncertain – Distributional effects depend on how permits are allocated and the disposition of revenue, if any, from the sale of permits	– Requires a competitive permit market – Administrative costs depend on the design of the system – Futures contracts for permits can spread the risks of price fluctuations
Harmonized Taxes	– Can be designed to achieve a specified national/international emission target	– Encourages implementation of most cost-effective mitigation measures – Tax rate determined through trial and error – Equity across countries depends on the transfer payments negotiated	– Little information on implementation available – Domestic policies could reduce the effectiveness of the tax
Tradable Quotas	– Can be designed to achieve a specified national/international emission target	– Encourages implementation of most cost-effective mitigation measures – Market price for quotas and cost of measures implemented is uncertain – Equity across countries depends on the quota allocations	– Requires a competitive quota market – Little information on implementation available – Allows flexibility in the choice of domestic policy
Joint Implementation	– Can reduce emissions from levels that would otherwise occur	– Transfers resources and technologies to host countries	– Administrative costs can be relatively high – Projects can be launched relatively quickly

to vary across nations. Second, adoption of any international instruments will have some impact on the distribution of wealth among countries, as will domestic instruments on the distribution of wealth within them. All instruments can, and probably will have to, be connected with compensatory measures such as side-payments or specific permit/quota allocations; no differences arise among instruments in this regard.

9.4.1 Environmental Results

Tradable permit/quota systems can be designed to achieve national/international GHG emission targets. Achieving a specified emission target with a carbon/emissions tax requires trial and error adjustment of the tax rate. Both tax and tradable permit/quota systems assume effective monitoring and enforcement and, if the international agreement is non-global, insignificant carbon leakage.

9.4.2 *Economic and Social Effects (SAR III, 11.5.6)*

Conceptually, both taxes and tradable permit/quota systems encourage implementation of the most cost-effective reduction measures. To achieve a given emissions target, the tax and the market price for permits/quotas should be the same, assuming that both apply to the same sources; that transactions costs are comparable; and that trades are not arbitrarily restricted.

Tradable permits can be allocated free of charge or sold at auction. Similarly, tax revenue can be redistributed to sources that would otherwise receive permits *gratis*, or can remain with the government. The way in which the net revenue from a carbon tax or the sale of permits is recycled can have significant macro-economic effects.

There is an extensive literature on the distributional impacts of carbon taxes, emission taxes, gasoline taxes and energy taxes in Annex I countries. These taxes are usually portrayed as regressive, because expenditures on fossil fuel consumption as a proportion of current annual personal income tend to fall as incomes rise. However, recent studies using U.S. and European data show that carbon taxes are considerably less regressive relative to lifetime income or annual consumption expenditures than to annual income.

Very few studies of the distributional effects of tradable permit systems are available. If the permits are sold, then the distributional implications are similar to those of an equivalent tax. If permits are allocated *gratis*, the initial allocation determines the distributional impacts.

Equity across countries is determined by the quota allocations in the case of a tradable quota system, the revenue sharing agreement negotiated for an international tax, or the transfer payments negotiated as part of a harmonized domestic carbon tax system. Reaching agreement on equitable quota allocations or revenue sharing arrangements should take account of the fact that mitigation actions by any country have economic impacts on other countries.

9.4.3 *Administrative, Institutional and Political Issues (SAR III, 11.6.2, 11.6.3)*

Administrative and transaction costs can vary widely for both taxes and tradable permits. Proper design can reduce these costs significantly. In some countries, it has proven to be possible to implement a carbon tax at relatively low cost by relying heavily on existing energy tax collection systems; in other countries, it has proven to be politically difficult to introduce any energy-related taxes. Trading systems that use government-issued permits (such as the sulfur dioxide allowance trading system in the U.S.) have lower transactions costs than do systems that use self-defined credits. Permits appear to have a distinct advantage in creating the basis for a futures market that could enable more efficient spreading of the risks associated with changing emissions targets. For a tradable permit system to work effectively, relatively competitive conditions must exist in the permit (and product) market. Should a firm control a significant share of the total number of permits, it might attempt to manipulate permit prices to improve its position in the permit or product market (e.g., by withholding permits, thus forcing others to cut production or keeping new entrants out). These risks can be reduced by government auctioning of permits and other mechanisms. Little information is available on the administrative costs for monitoring, enforcement and management of an international tax system, internationally harmonized taxes or a tradable quota system.

9.5 Comparing Tradable Permit/Quota and Tax Systems (SAR III, 11.7.2, 11.7.3)

Both taxes and tradable permits impose costs on industry and consumers. Sources will experience financial outlays, either through expenditures on emission controls or through cash payments to buy permits or pay taxes.[34] In either case, they will seek to minimize these costs through investment in new facilities and equipment.

Under a GHG tax, the tax rate is known but the effect on emissions is uncertain, and the distributional effects may or may not be known. A tradable permit system has a known effect on emissions, but permit prices and the distributional effects through trade are uncertain. A system of harmonized domestic taxes could involve an agreement about compensatory international financial transfers, as well as about adjustments required to compensate for differences in pre-existing tax structures. To be effective, a system of harmonized domestic taxes also requires that participants not be allowed to implement policies that indirectly increase GHG emissions.

A tradable quota scheme allows each participant to decide what domestic policy to use. The initial allocation of quota among countries addresses distributional considerations, but the exact distributional implications cannot be known beforehand, since the quota price will only be known after trading begins. Under a tradable quota scheme, the resulting global emissions will be known with certainty for a global agreement and, net of carbon leakage, for a non-global agreement.

[34] An exception, of course, is when a source has received enough permits *gratis* to cover its emissions. Even in this case, however, it will be subjected to an implicit marginal cost of emissions, since reducing emissions would allow it to sell more permits.

Appendix A

BASELINE PROJECTIONS

Table A1: Global data—primary energy consumed[a] and carbon emitted[b] *in the IS92 scenarios, subdivided into the elements of the fuel cycle where the primary fuel is consumed.*

	1990[c]		2010						2020						2050					
	Energy Used	CO_2 Emitted	Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted		
SCENARIO	*all*	*all*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*
Supply Side																				
Energy Supply/Transformation																				
Electric Generation	123	1.7	198	165	221	2.7	1.9	3.5	253	199	292	3.3	2.1	4.5	370	242	503	3.8	1.6	6.4
Synfuels Production[d]	0	0.0	0	1	1	0.0	0.0	0.0	4	6	8	–0.2	–0.3	–0.3	68	35	101	–0.1	–0.8	0.2
Direct Use of Fuels by Sector																				
Residential/Commercial/Institutional	62	1.2	83	68	93	1.5	1.2	1.7	94	74	109	1.7	1.4	2.0	143	86	177	2.6	1.6	3.3
Industry[e]	91	1.8	123	102	137	2.4	2.0	2.7	146	114	171	2.8	2.2	3.3	176	107	216	3.5	2.1	4.2
Transportation	68	1.3	95	77	112	1.8	1.4	2.1	114	87	140	2.1	1.6	2.6	177	102	243	3.3	1.9	4.5
TOTAL	344	6.0	499	412	564	8.4	6.5	9.9	610	480	720	9.8	7.0	12.1	934	572	1240	13.1	6.4	18.6
Demand Side																				
Residential/Commercial/Institutional	112	1.9	151	125	170	2.5	1.9	2.9	174	138	203	2.7	1.9	3.3	261	165	344	3.8	1.9	5.3
Industry[e]	161	2.8	251	209	281	4.1	3.2	4.9	317	250	372	5.0	3.5	6.2	442	283	583	6.1	3.1	8.8
Transportation	70	1.3	97	78	115	1.8	1.4	2.1	119	91	148	2.1	1.6	2.7	231	124	313	3.2	1.4	4.5
TOTAL	344	6.0	499	412	565	8.4	6.5	9.9	610	480	723	9.8	7.0	12.1	934	572	1240	13.1	6.4	18.6
By Source																				
Solids	100	2.5	142	113	164	3.6	2.9	4.2	179	127	221	4.5	3.2	5.6	326	141	485	8.3	3.6	12.3
Liquids	123	2.3	154	119	195	2.8	2.2	3.6	165	122	224	3.0	2.3	4.1	144	102	214	2.7	1.9	3.9
Gases	79	1.2	129	100	141	1.9	1.5	2.1	150	101	160	2.2	1.5	2.4	145	66	156	2.2	1.0	2.3
Other	42	0.0	74	81	65	0.0	0.0	0.0	117	129	117	0.0	0.0	0.0	318	263	385	0.0	0.0	0.0
TOTAL	344	6.0	499	412	565	8.4	6.5	9.9	610	480	723	9.8	7.0	12.1	934	572	1240	13.1	6.4	18.6

[a] Energy expressed in EJ.
[b] Carbon expressed as Gt C.
[c] 1990 data are from the estimates in the IS92 scenarios. They are included here for purposes of calculating percentage change in future energy use and emissions. They do not represent actual energy consumption and emissions. The 1990 actual data appear in Figure 1 and Table 9.
[d] Where synfuel production is shown to generate negative CO_2 emissions in the energy supply sector, it is because the synfuels are produced from biomass, which takes up CO_2 from the atmosphere during growth. The combustion of these fuels is shown as a positive figure at the point of end use.
[e] In the IS92 scenarios, the industrial sector includes industrial activities related to manufacturing, agriculture, mining and forestry.

Table A2: Global data—energy used[a] and carbon emitted[b] *by end-use sector in the IS92 scenarios, subdivided into the elements of the fuel cycle where the primary fuel is consumed.*

	1990[c]		2010						2020						2050					
	Energy Used	CO_2 Emitted	Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted		
SCENARIO	*all*	*all*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*
Residential/Commercial/Institutional																				
Electric Generation	51	0.7	69	57	77	0.9	0.7	1.2	79	62	91	1.0	0.7	1.4	109	71	148	1.1	0.5	1.9
Synfuels Production[d]	0	0.0	0	0	0	0	0	0	1	2	4	0.0	–0.1	–0.1	10	8	19	0	-0.1	0.1
Direct Use of Fuels	62	1.2	83	68	93	1.5	1.2	1.7	94	74	109	1.7	1.4	2.0	143	86	177	2.6	1.6	3.3
TOTAL	112	1.9	151	125	170	2.5	1.9	2.9	174	138	203	2.7	1.9	3.3	261	165	344	3.8	1.9	5.3
Industry[e]																				
Electric Generation	70	1.0	128	107	143	1.7	1.3	2.2	171	134	197	2.2	1.4	3.1	256	168	348	2.6	1.1	4.4
Synfuels Production[d]	0	0.0	0	0	0	0	0	0	1	2	4	0.0	–0.1	–0.1	10	8	19	0	-0.1	0.1
Direct Use of Fuels	91	1.8	123	102	137	2.4	2.0	2.7	146	114	171	2.8	2.2	3.3	176	107	216	3.5	2.1	4.2
TOTAL	161	2.8	251	209	281	4.1	3.2	4.9	317	250	372	5.0	3.5	6.2	442	283	583	6.1	3.1	8.8
Transportation																				
Electric Generation	3	0.0	1	1	2	0.0	0.0	0.0	3	3	4	0.0	0.0	0.1	5	4	7	0.1	0.0	0.1
Synfuels Production[d]	0	0.0	0	0	1	0.0	0.0	0.0	1	2	1	–0.1	–0.1	–0.1	48	18	63	–0.2	–0.5	–0.1
Direct Use of Fuels	68	1.3	95	77	113	1.8	1.4	2.1	114	87	143	2.1	1.6	2.6	177	102	243	3.3	1.9	4.5
TOTAL	70	1.3	97	78	115	1.8	1.4	2.1	119	91	148	2.1	1.6	2.7	231	124	313	3.2	1.4	4.5
All End-use Sectors																				
Electric Generation	123	1.7	198	165	221	2.7	1.9	3.5	253	199	292	3.3	2.1	4.5	370	242	503	3.8	1.6	6.4
Synfuels Production[d]	0	0.0	0	1	1	0.0	0.0	0.0	4	6	8	–0.2	–0.3	–0.3	68	35	101	–0.1	–0.8	0.2
Direct Use of Fuels	221	4.2	301	246	343	5.7	4.6	6.4	354	275	423	6.7	5.2	7.9	496	295	637	9.3	5.6	12.0
TOTAL	344	6.0	499	412	565	8.4	6.5	9.9	610	480	723	9.8	7.0	12.1	934	572	1240	13.1	6.4	18.6

[a] Energy expressed in EJ.
[b] Carbon expressed as Gt C.
[c] 1990 data are from the estimates in the IS92 scenarios. They are included here for purposes of calculating percentage change in future energy use and emissions. They do not represent actual energy consumption and emissions. The 1990 actual data appear in Figure 1 and Table 9.
[d] Where synfuel production is shown to generate negative CO_2 emissions in the energy supply sector, it is because the synfuels are produced from biomass, which takes up CO_2 from the atmosphere during growth. The combustion of these fuels is shown as a positive figure at the point of end use.
[e] In the IS92 scenarios, the industrial sector includes industrial activities related to manufacturing, agriculture, mining and forestry.

***Table A3:** Annex I—primary energy consumed[a] and carbon emitted[b] in the IS92 scenarios, subdivided into the elements of the fuel cycle where the primary fuel is consumed.*

	1990		2010						2020						2050					
	Energy Used	CO_2 Emitted	Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted		
SCENARIO	*all*	*all*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*
Supply Side																				
Energy Supply/Transformation																				
Electric Generation	96	1.3	141	120	153	1.9	1.4	2.4	165	135	183	2.2	1.4	2.9	187	135	234	1.9	1.0	3.1
Synfuels Production	0	0.0	0	1	1	0.0	0.0	0.0	2	4	5	–0.1	–0.2	–0.2	38	18	61	0.2	–0.4	0.7
Direct Use of Fuels by Sector																				
Resid./Comm./Inst.	47	0.9	59	49	65	1.1	0.9	1.2	64	52	73	1.2	0.9	1.3	73	48	87	1.3	0.9	1.6
Industry[c]	68	1.4	74	63	81	1.4	0.0	0.0	74	61	86	1.4	1.2	1.6	61	42	69	1.2	0.8	1.4
Transportation	51	0.9	64	53	74	1.2	0.0	0.0	65	52	78	1.2	1.0	1.4	69	45	85	1.3	0.8	1.6
TOTAL	262	4.5	338	286	375	5.6	2.3	3.6	370	304	425	5.9	4.4	7.1	427	288	535	5.9	3.1	8.3
Demand Side																				
Resid./Comm./Inst.	86	1.4	108	91	119	1.7	1.4	2.0	116	95	132	1.8	1.3	2.2	134	92	166	2.0	1.1	2.7
Industry[c]	122	2.1	165	141	181	2.7	2.1	3.1	186	154	211	2.9	2.1	3.5	196	140	242	2.6	1.4	3.7
Transportation	53	1.0	65	0	76	1.2	1.0	1.4	68	55	82	1.2	0.9	1.4	98	56	127	1.4	0.6	1.9
TOTAL	262	4.5	338	232	375	5.6	4.5	6.5	370	304	425	5.9	4.4	7.1	427	288	535	5.9	3.1	8.3
By Source																				
Solids	77	1.9	99	79	115	2.5	2.0	2.9	113	84	140	2.9	2.1	3.5	163	76	256	4.1	1.9	6.5
Liquids	91	1.7	100	79	122	1.8	1.4	2.3	92	71	119	1.7	1.3	2.2	46	41	49	0.9	0.8	0.9
Gases	61	0.9	85	68	93	1.3	1.0	1.4	88	62	94	1.3	0.9	1.4	63	31	60	0.9	0.5	0.9
Other	34	0.0	54	60	45	0.0	0.0	0.0	77	87	72	0.0	0.0	0.0	155	140	170	0.0	0.0	0.0
TOTAL	262	4.5	338	286	375	5.6	4.5	6.5	370	304	425	5.9	4.4	7.1	427	288	535	5.9	3.1	8.3

[a]Energy expressed in EJ.

[b]Carbon expressed as Gt C.

[c]In the IS92 scenarios, the industrial sector includes industrial activities related to manufacturing, agriculture, mining and forestry.

Table A4: *Annex I—energy used[a] and carbon emitted[b] by end-use sector in the IS92 scenarios, subdivided into the elements of the fuel cycle where the primary fuel is consumed.*

	1990		2010						2020						2050					
	Energy Used	CO_2 Emitted	Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted			Energy Used			CO_2 Emitted		
SCENARIO	*all*	*all*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*	*a*	*c*	*e*
Residential/Commercial/Institutional																				
Electric Generation	40	0.6	49	41	53	0.7	0.5	0.8	51	42	57	0.7	0.4	0.9	55	40	69	0.6	0.3	0.9
Synfuels Production	0	0.0	0	0	0	0	0	0	0	1	2	0.0	–0.1	–0.1	6	4	11	0	–0.1	0.2
Direct Use of Fuels	47	0.9	59	49	65	1.1	0.9	1.2	64	52	73	1.2	0.9	1.3	73	48	87	1.3	0.9	1.6
TOTAL	86	1.4	108	91	119	1.7	1.4	2.0	116	95	132	1.8	1.3	2.2	134	92	166	2.0	1.1	2.7
Industry[c]																				
Electric Generation	54	0.8	91	77	99	1.2	0.9	1.5	111	91	124	1.5	1.0	1.9	129	93	162	1.3	0.6	2.1
Synfuels Production	0	0.0	0	0	0	0	0	0	0	1	2	0.0	–0.1	–0.1	6	4	11	0	–0.1	0.2
Direct Use of Fuels	68	1.4	74	63	81	1.4	1.2	1.6	74	61	86	1.4	1.2	1.6	61	42	69	1.2	0.8	1.4
TOTAL	122	2.1	165	141	181	2.7	2.1	3.1	186	154	211	2.9	2.1	3.5	196	140	242	2.6	1.4	3.7
Transportation																				
Electric Generation	2	0.0	1	1	1	0.0	0.0	0.0	2	2	2	0.0	0.0	0.0	3	2	3	0.0	0.0	0.0
Synfuels Production	0	0.0	0	1	1	0.0	0.0	0.0	1	1	1	–0.1	–0.1	–0.1	27	9	39	0.1	–0.2	0.3
Direct Use of Fuels	51	0.9	64	53	74	1.2	1.0	1.4	65	52	78	1.2	1.0	1.4	69	45	85	1.3	0.8	1.6
TOTAL	53	1.0	65	54	76	1.2	1.0	1.4	68	55	82	1.2	0.9	1.4	98	56	127	1.4	0.6	1.9
All End-Use Sectors																				
Electric Generation	96	1.4	141	120	153	1.9	1.4	2.4	165	135	183	2.2	1.4	2.8	187	135	234	1.9	0.9	3.0
Synfuels Production	0	0.0	0	1	1	0.0	0.0	0.0	2	4	5	–0.1	–0.2	–0.2	38	18	61	0.2	–0.4	0.7
Direct Use of Fuels	166	3.2	198	165	221	3.7	3.1	4.1	203	164	236	3.8	3.1	4.4	202	136	241	3.8	2.5	4.5
TOTAL	262	4.5	338	286	375	5.6	4.5	6.5	370	304	425	5.9	4.4	7.1	427	288	535	5.9	3.1	8.3

[a]Energy expressed in EJ.
[b]Carbon expressed as Gt C.
[c]In the IS92 scenarios, the industrial sector includes industrial activities related to manufacturing, agriculture, mining and forestry.

Appendix B

IPCC DOCUMENTS USED AS SOURCES OF INFORMATION

SAR I

IPCC, 1996: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.J., L.G. Meiro Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell (eds.)]. Cambridge University Press, Cambridge and New York, 584 pp.

SAR II

IPCC, 1996: *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analyses. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowera and R.H. Moss (eds.)]. Cambridge University Press, Cambridge and New York, 880 pp.

SAR III

IPCC, 1996: *Climate Change 1995: Economic and Social Dimensions of Climate Change. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Bruce, J., Hoesung Lee and E. Haites (eds.)]. Cambridge University Press, Cambridge and New York, 464 pp.

SAR Syn.Rpt.

IPCC, 1996: *IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change*. World Meteorological Organization, Geneva, 17 pp.

IPCC 1994

IPCC, 1994. *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* [Houghton, J.T., L.G. Meira Filho, J.P. Bruce, Hoesung Lee, B.T. Callander, E.F. Haites, N. Harris and K. Maskell (eds.)]. Cambridge University Press, Cambridge and New York, 339 pp.

IPCC 1992

IPCC, 1992. *Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment. Report of the IPCC Scientific Assessment Working Group* [Houghton, J.T., B.T. Callander and S.K. Varney (eds.)]. Cambridge University Press, Cambridge and New York, 200 pp.

Appendix C

ACRONYMS AND ABBREVIATIONS

AGBM	Ad Hoc Group on the Berlin Mandate
CHP	combined heat and power
CNG	compressed natural gas
COP	Conference of the Parties
FAO	UN Food and Agriculture Organization
FCCC	UN Framework Convention on Climate Change
GDP	gross domestic product
GEF	Global Environment Facility
GHG	greenhouse gas
GWP	global warming potential
HDV	heavy duty vehicle
ICAO	UN International Civil Aviation Organization
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LDV	light duty vehicle
LESS	Low CO_2-Emitting Energy Supply System
LNG	liquid natural gas
LPG	liquefied petroleum gas
NGO	non-governmental organization
OECD	Organisation for Economic Cooperation and Development
PPP	purchasing power parity
PURPA	Public Utilities Regulatory Policy Act
R&D	research and development
RD&D	research, development and demonstration
SAR	Second Assessment Report
SPM	Summary for Policymakers
TPD	tons per day
UNITAR	UN Institute for Training and Research
US IJI	U.S. Initiative on Joint Implementation

Chemical Symbols

CFC	chlorofluorocarbon
CFC-14	carbon tetrafluoride (CF_4)
CFC-116	hexafluoroethylene (C_2F_6)
C_2F_6	hexafluoroethylene (CFC-116)
CF_4	carbon tetrafluoride (CFC-14)
CH_4	methane
CO_2	carbon dioxide
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
N_2O	nitrous oxide
NO_x	nitrogen oxides
PFC	perfluorocarbon
SF_6	sulfur hexafluoride
SO_2	sulfur dioxide
SO_x	sulfur oxides

Appendix D

UNITS

SI (Système Internationale) Units

Physical Quantity	Name of Unit	Symbol
length	metre	m
mass	kilogram	kg

Multiple	Prefix	Symbol
10^3	kilo	k
10^6	mega	M
10^9	giga	G
10^{12}	tera	T
10^{15}	peta	P
10^{18}	exa	E

Special Names and Symbols for Certain SI-derived Units

Physical Quantity	Name of SI Unit	Symbol for SI Unit	Definition of Unit
energy	joule	J	$kg\ m^2\ s^{-2}$
power	watt	W	$kg\ m^2\ s^{-3}$ (= Js^{-1})

Decimal Fractions and Multiples of SI Units Having Special Names

Physical Quantity	Name of Unit	Symbol for Unit	Definition of Unit
area	hectare	ha	$10^4\ m^2$
weight	ton	t	10^3 kg

Non-SI Units

°C	degrees Celsius (0°C = ~273K); temperature differences are also given in °C rather than the more correct form of "Celsius degrees"
kWh	kilowatt-hour
MW_e	megawatts of electricity
ppmv	parts per million (10^6) by volume
ppbv	parts per billion (10^9) by volume
pptv	parts per trillion (10^{12}) by volume
tce	tons of coal equivalent
toe	tons of oil equivalent
TWh	terawatt-hour

Appendix E

GLOSSARY OF TERMS

Annex I Countries
Annex I of the FCCC lists the countries who were members of the OECD in 1992, 11 countries undergoing the process of transition to a market economy, and the European Economic Community. Annex I parties are committed to adopt national policies and take measures to mitigate climate change.

Capital Costs
Costs associated with the capital or investment expenditures on land, plant, equipment and inventories. Unlike labour and operating costs, capital costs are independent of the level of output.

Commercialization
Sequence of actions necessary to achieve market entry and general market competitiveness of new innovative technologies, processes and products.

Cost-effective
A criterion that specifies that a technology or measure deliver a good or service at equal or lower cost than current practice. In this paper, environmental externalities are not internalized; payback periods vary, depending on the particular sector and market.

Economic Potential
The portion of the technical potential for GHG emissions reductions or energy-efficiency improvements that could be achieved cost-effectively in the absence of market barriers. The achievement of the economic potential requires additional policies and measures to break down market barriers.

Emission Permit
A non-transferable or tradable allocation of entitlements by a government to an individual firm to emit a specified amount of a substance.

Emission Quota
The portion or share of total allowable emissions assigned to a country or group of countries within a framework of maximum total emissions and mandatory allocations of resources or assessments.

Emission Standard
A level of emission that under law may not be exceeded.

Energy Intensity
Ratio of energy consumption and economic or physical output. At the national level, energy intensity is the ratio of total domestic primary energy consumption or final energy consumption to gross domestic product or physical output.

Externalities
By-products of activities that affect the well-being of people or damage the environment, where those impacts are not reflected in market prices. The costs (or benefits) associated with externalities do not enter standard cost accounting schemes.

Final Energy
Energy supplied that is available to the consumer to be converted into useful energy (e.g., electricity at the wall outlet).

Full-cost Pricing
The pricing of commercial goods—such as electric power—that would include in the final prices faced by the end user not only the private costs of inputs, but also the costs of the externalities created by their production and use.

GHG Reduction Potential
Possible reductions in emissions of greenhouse gases (quantified in terms of absolute reductions or in percentages of baseline emissions) that can be achieved through the use of technologies and measures.

Information and Education Measures
Actions that provide information, training or encouragement, or help to develop understanding. Such measures may provide information about the availability, performance and other characteristics of technologies, practices and measures.

Marginal Cost Pricing
The pricing of commercial goods and services such that the price equals the additional cost that arises from the expansion of production by one additional unit.

Market Barriers
Conditions that prevent or impede the diffusion of cost-effective technologies or practices that could mitigate GHG emissions.

Market-based Incentives
Measures intended to directly change relative prices of energy services and overcome market barriers.

Market Penetration
The share of a given market that is provided by a particular good or service at a given time.

Market Potential (or Currently Realizable Potential)
The portion of the economic potential for GHG emissions reductions or energy-efficiency improvements that could be achieved under existing market conditions, assuming no new policies and measures.

Measures
Actions that can be taken by a government or a group of governments, often in conjunction with the private sector, to accelerate the use of technologies or other practices that reduce GHG emissions.

No Regrets
Measures whose benefits—such as improved performance or reduced emissions of local/regional pollutants, but excluding the benefits of climate change mitigation—equal or exceed their costs. They are sometimes known as "measures worth doing anyway."

Opportunity Cost
The cost of an economic activity foregone by the choice of another activity.

Policies
Procedures developed and implemented by government(s) regarding the goal of mitigating climate change through the use of technologies and measures.

Primary Energy
Energy embodied in natural resources (e.g., coal, crude oil, sunlight, uranium) that has not undergone any anthropogenic conversion or transformation.

Project Costs
All financial costs of a project such as capital, labour and operating costs.

Regulatory Measures
Rules or codes enacted by governments that mandate product specifications or process performance characteristics.

Research, Development and Demonstration
Scientific/technical research and development of new production processes or products, coupled with analysis and measures that provide information to potential users regarding the application of the new product or process; demonstration tests the feasibility of applying these products or processes via pilot plants and other pre-commercial applications.

Scenario
A plausible description of how the future may develop, based on a coherent and internally consistent set of assumptions about key relationships and driving forces (e.g., rate of technology changes, prices). Note that scenarios are neither predictions nor forecasts.

Standards/Performance Criteria
Set of rules or codes mandating or defining product performance (e.g., grades, dimensions, characteristics, test methods, rules for use).

Structural Changes
Changes, for example, in the relative share of GDP produced by the industrial, agricultural or services sectors of an economy; or, more generally, systems transformations whereby some components are either replaced or partially substituted by other ones.

Technical Potential
The amount by which it is possible to reduce GHG emissions or improve energy efficiency by using a technology or practice in all applications in which it could technically be adopted, without consideration of its costs or practical feasibility.

Technology
A piece of equipment or a technique for performing a particular activity.

Voluntary Measures
Measures to reduce GHG emissions that are adopted by firms or other actors in the absence of government mandates. Voluntary measures help make climate-friendly products or processes more readily available or encourage consumers to incorporate environmental values in their market choices.

List of IPCC outputs

I. IPCC FIRST ASSESSMENT REPORT (1990)

a) **CLIMATE CHANGE — The IPCC Scientific Assessment.** The 1990 report of the IPCC Scientific Assessment Working Group *(also in Chinese, French, Russian and Spanish).*
b) **CLIMATE CHANGE — The IPCC Impacts Assessment.** The 1990 report of the IPCC Impacts Assessment Working Group *(also in Chinese, French, Russian and Spanish).*
c) **CLIMATE CHANGE — The IPCC Response Strategies.** The 1990 report of the IPCC Response Strategies Working Group *(also in Chinese, French, Russian and Spanish).*
d) **Overview and Policymaker Summaries, 1990.**

Emissions Scenarios (prepared by the IPCC Response Strategies Working Group), 1990.

Assessment of the Vulnerability of Coastal Areas to Sea Level Rise — A Common Methodology, 1991.

II. IPCC SUPPLEMENT (1992)

a) **CLIMATE CHANGE 1992 — The Supplementary Report to the IPCC Scientific Assessment.** The 1992 report of the IPCC Scientific Assessment Working Group.
b) **CLIMATE CHANGE 1992 — The Supplementary Report to the IPCC Impacts Assessment.** The 1990 report of the IPCC Impacts Assessment Working Group.

CLIMATE CHANGE: The IPCC 1990 and 1992 Assessments — IPCC First Assessment Report Overview and Policymaker Summaries, and 1992 IPCC Supplement *(also in Chinese, French, Russian and Spanish).*

Global Climate Change and the Rising Challenge of the Sea. Coastal Zone Management Subgroup of the IPCC Response Strategies Working Group, 1992.

Report of the IPCC Country Study Workshop, 1992.

Preliminary Guidelines for Assessing Impacts of Climate Change, 1992.

III. IPCC SPECIAL REPORT, 1994

a) **IPCC Guidelines for National Greenhouse Gas Inventories** (3 volumes), 1994 *(also in French, Russian and Spanish).*
b) **IPCC Technical Guidelines for Assessing Climate Change Impacts and Adaptations,** 1994 *(also in Arabic, Chinese, French, Russian and Spanish).*
c) **CLIMATE CHANGE 1994 — Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios.**

IV. IPCC SECOND ASSESSMENT REPORT, 1995

a) **CLIMATE CHANGE 1995 — The Science of Climate Change.** (including Summary for Policymakers). Report of IPCC Working Group I, 1995.
b) **CLIMATE CHANGE 1995 — Scientific-Technical Analyses of Impacts, Adaptations and Mitigation of Climate Change.** (including Summary for Policymakers). Report of IPCC Working Group II, 1995.
c) **CLIMATE CHANGE 1995 — The Economic and Social Dimensions of Climate Change.** (including Summary for Policymakers). Report of IPCC Working Group III, 1995.
d) **The IPCC Second Assessment Synthesis of Scientific-Technical Information Relevant to Interpreting Article 2 of the UN Framework Convention on Climate Change,** 1995.

(Please note: the IPCC Synthesis and the three Summaries for Policymakers have been published in a single volume and are also available in Arabic, Chinese, French, Russian and Spanish).

IPCC Procedures for the Preparation, Review and Publication of its Technical Papers

At its Eleventh Session (Rome, 11-15 December 1995), the Intergovernmental Panel on Climate Change adopted by consensus the following procedures for the preparation of Technical Papers.

IPCC Technical Papers are prepared on topics for which an independent, international scientific/technical perspective is deemed essential. They:

a) are based on the material already in the IPCC assessment reports and special reports;
b) are initiated: (i) in response to a formal request from the Conference of the Parties to the UN Framework Convention on Climate Change or its subsidiary bodies and agreed by the IPCC Bureau; or (ii) as decided by the Panel;
c) are prepared by a team of authors, including a convening lead author, selected by the IPCC Bureau, in accordance with the guidelines of the selection of lead authors contained in the IPCC Procedures;*
d) are submitted in draft form for simultaneous expert and government review at least four weeks before the comments are due;
e) are revised by the lead authors based upon the comments reviewed in the step above;
f) are submitted for final government review at least four weeks before the comments are due;
g) are finalized by the lead authors, in consultation with the IPCC Bureau which functions in the role of an editorial board, based on the comments received; and,
h) if necessary, as determined by the IPCC Bureau, would include in an annex differing views, based on comments made during final government review, not otherwise adequately reflected in the paper.

Such Technical Papers are then made available to the Conference of the Parties or its subsidiary body, in response to its request, and thereafter publicly. If initiated by the Panel, Technical Papers are made available publicly. In either case, IPCC Technical Papers prominently state in the beginning:

> "This is a Technical Paper of the Intergovernmental Panel on Climate Change prepared in response to a [request from the United Nations Framework Convention on Climate Change]/[decision of the Panel]. The material herein has undergone expert and government review but has not been considered by the Panel for possible acceptance or approval."

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* Preparation of the first draft of a report should be undertaken by lead authors identified by the relevant Working Group bureau from those experts cited in the lists provided by all countries and participating organizations, with due consideration being given to those known through their publication or work. In so far as practicable, the composition of the group of lead authors for a section of a report shall reflect fair balance among different points of view that can reasonably be expected by the Working Group bureau, and should include at least one expert from a developing country.