SLOWING GLOBAL WARMING:

OPTIONS FOR GREENHOUSE GAS SUBSTITUTION

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Abstract

Substitution of existing technologies giving rise to greenhouse gases is one of several options for controlling global warming. The following paper provides a framework for evaluating the cost-effectiveness of the various substitution prospects for the major sources of greenhouse gases, notably fossil fuel combustion, methane production and CFC emissions. We consider both replacement technologies, e.g. substituting a greenhouse gas technology with a non-greenhouse gas technology, and reduction technologies, e.g. substituting a greenhouse gas technology with an alternative technology that reduces greenhouse gas emissions. Relevant data and country examples from around the world are examined, including analysis of developing countries where appropriate. Significant substitution technologies are beginning to achieve market penetration on a large scale; for example, many renewable energy technologies are at a critical transition phase between proven capability and commercial viability. Once market penetration is assured, costs may fall rapidly due to economies of scale and improved reliability. Costs also vary significantly from country to country and within countries. However, our analysis has been limited by the available data to comparing the direct resource costs of different substitution options. A full cost analysis should include any social costs, including environmental externalities, and constraints, such as land availability, and the impacts on cost-effectiveness of changes in policy. A general equilibrium approach including all these cost interactions should be pursued.

CONTENTS

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Abbreviations

Energy Units

W = Watts
kW = Kilowatts
Wh = Watt hours
kWh = Kilowatt hours
Btu = British thermal units
MBtu = Million British thermal units (10^6 Btu)

Weight Units

g = gram
kg = kilogram (10^3 grams)
t = tonne, metric ton (10^6 grams)

Emission Units

C = Carbon or Carbon Equivalents
GHG = Greenhouse Gases

Emission Conversion Factor

3.67 tonnes Carbon Dioxide (tCO_2) = 1 tonne Carbon (tC)

Metric System Multipliers

kilo (k) = 10^3
mega (M) = 10^6
giga (G) = 10^9
tera (T) = 10^{12}
peta (P) = 10^{15}

1. INTRODUCTION

Increasing concern over the impacts of greenhouse gas emissions on the global climate has focused attention on efforts to avert or ameliorate global warming. The options for controlling the greenhouse effect are:

- reduced fossil fuel burning through energy conservation
- investing in carbon sinks, especially afforestation
- slowing or halting deforestation
- slowing economic activity
- slowing population growth
- substitution of existing technologies giving rise to greenhouse gases.
- carbon removal and disposal options

This paper is concerned with the option of greenhouse gas substitution. The paper provides:

- a framework for evaluating the substitution prospects for the major sources of greenhouse gases, notably fossil fuel combustion, methane production and CFC emissions;
- a survey of both what is currently known about alternatives to existing technologies as well as the prospects for developing substitutes in the future;
- suggestions concerning the priorities for the development of substitutes; and,
- indications on the role of policy in securing substitution.

The main objective is to delineate the substitutes for each greenhouse gas technology/activity and to assess their cost-effectiveness in terms of dollars-per-unit of greenhouse gas removed.

We interpret the term 'substitution' to exclude energy conservation/efficiency measures, investments in afforestation (sinks) and greenhouse gas removal or abatement technologies. Our working definition of greenhouse gas substitution includes:

- replacement technologies, e.g. substituting a greenhouse gas technology/activity with a non-greenhouse gas technology/activity; and,
- reduction technologies, e.g. substituting a greenhouse gas

technology/activity with an alternative technology/activity that reduces greenhouse gas emissions.

Essentially, replacement technologies involve 100% reduction in CO_2, reduction technologies involve a partial reduction in CO_2.

The following sections outline the relative contributions and sources of greenhouse gases, as well as the methods for determining the scale of adjustment needed for controlling emissions. The principal section of the paper is devoted to analysing the available greenhouse gas substitution options and their costs. We concentrate particularly on substitions for fossil fuel combustion (e.g., electricity, buildings/industrial and other stationary sources and transport fuels), for CFCs production and consumption and methane sources. We conclude by summarising the potential for greenhouse gas substitution, the cost-effectiveness of the various options and the design of incentives for substitution.

The sources of greenhouse gases are both natural and man-made. However, it is the growth in man-made emissions since pre-industrial times that is causing the major concerns for global warming. Of the man-made emission sources, energy use contributes by far the largest share. The energy sector in most countries is already reviewed, regulated and supported in line with government economic and development policies. It is therefore likely to offer more traditional and effective targets for near-term policy intervention, e.g. through encouraging energy conservation and greenhouse gas substitutions, than some of the more long-term and complex options listed above, e.g. slowing population growth, halting or slowing deforestation, slowing economic activity or investing in carbon sinks. Although the energy sector is a principal source of most greenhouse gases, other human activities are also important, e.g agriculture for methane (CH_4) and nitrous oxide (N_2O) and industry for chlorofluorocarbons (CFCs). In these sectors substitution of existing technologies giving rise to greenhouse gases is the crucial policy to consider.

2. GREENHOUSE GAS CONTRIBUTIONS TO GLOBAL WARMING

Concentrations of greenhouse gases in the atmosphere have increased rapidly in recent years, and certainly since pre-industrial times (see Table 1). Allowing for differences in radiative forcing and time horizons, carbon dioxide (CO2) has contributed to at least half of the global warming impact over the period 1950-1985. The other significant greenhouse gases are methane (CH_4), nitrous oxide (N_2O), CFCs and tropospheric ozone (O_3). Carbon monoxide (CO) and various nitrogen gases (NO_x) are important precursors for tropospheric ozone.

The potential climatic effects of the different greenhouse gas emissions in the future will differ according to their warming effect, their residence time, their concentration in the atmosphere, and their annual growth rate. Tables 1 and 2 summarise the recent estimates of global warming potentials for the major greenhouse gases. Note that although their atmospheric emissions and concentrations are relatively small, gases such as CH_4, N_2O, CFCs and O_3 are more powerful as warming agents than CO_2. However, the sheer quantity of CO_2 emissions accounts for a substantial impact on global climate. For example, in the absence of any global agreements, CO_2 will continue to account for more than 60% over a 100 year time horizon. Methane accounts for the next largest contribution, around 15% of the warming potential. CFC emissions have grown the fastest in recent years, at least 5% per annum, and could account for around 9% of the warming effect. However, if the Montreal Protocol is implemented, CFC contribution could fall by half. This would make nitrous oxide the next most important contributor after CO_2 and methane.

Of the man-made sources of greenhouse gases, energy is the most significant, and is expected to contribute to at least half of the global warming effect in the near future (Table 3).[1] The majority of this impact is from fossil fuel combustion as a source of CO_2, although fossil fuels also contribute significantly to methane, to nitrous oxide and to low-level ozone through production of NO_x and CO. Global carbon emissions from fossil fuel combustion are estimated to total 5.5 GtC annually, and an additional 0.5 GtC is from biomass energy, whereas emissions due to deforestation and land use changes are estimated to vary from 0.8 to 2.2 GtC per year. The growth rate of total global CO_2 emissions from fossil fuel use was around 4.5% per annum until the early 1970s. Since 1973, this rate has declined in the industrialised countries, while the rate of increase has not changed in developing countries. Global CO_2 emissions from energy (overwhelmingly fossil fuel) combustion are expected to increase by 2.3% per annum between 1987 and 2005, while over this

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[1] CO_2 and CO_2 equivalents can be expressed either in units of <u>gas</u> or in units of <u>carbon</u>. These two units can be easily equated; i.e., the standard conversion is 3.67 tonnes Carbon Dioxide (tCO_2) = 1 tonne Carbon (tC). In this paper we will use units of <u>carbon</u> as far as possible.

Table 1

Greenhouse Gases and Their Man-Made Sources

	CO_2	Methane	Nitrous Oxide	CFCs	Ozone
% contribution to GH effect 1950-1985	56	14	7	23	a/
% contribution to GH effect 1990-2090	61	15	4	9	11
concentration of GH gases - pre-industrial	275ppmv	700ppbv	280ppbv	0	15ppbv
concentration of GH gases - 1988	350ppmv	1700ppbv	310ppbv	0.7	335ppbv
annual growth of concentrations 1980's	0.5%	0.5%	0.25%	5-5.5%	1%
sources of GH gases	fossil fuel burning deforestation land use change	rice paddy cultivation rearing ruminants (eg cows) biomass burning fossil fuel extraction & burning	fertilzers fossil fuel & biomass burning land conversion for agriculture	solvents aerosals foam package	product of sun & pollutants

Notes: a/ contributions of ozone not estimated, perhaps around 8% of total.
ppmv = parts per million, ppbv = part per billion.

Source: M. Holdgate et al. <u>Climate Change: Meeting the Challenge</u>, Commonwealth Secretariat, London, 1989, Tables 2.1 and 2.3 and IPCC.

Table 2

Global Warming Potentials of Greenhouse Gases

A. Global Warming Potentials a/

	Time Horizon		
	20 yr	100 yr	500 yr
Carbon dioxide (CO_2)	1	1	1
Methane (CH_4)	63	21	9
Nitrous Oxide (N_2O)	270	290	190
CFC11	4500	3500	1500
CFC12	7100	7300	4500
HCFC22	4100	1500	510

B. Relative Cumulative Effect of 1990 Emissions

	GWP (100 yr horizon)	1990 emissions (Tg)	Relative contribution over 100 yr
Carbon dioxide (CO_2)	1	26000 b/	61%
Methane (CH_4)	21	300	15%
Nitrous Oxide (N_2O)	290	6	4%
CFC11	3500	0.3	2%
CFC12	7300	0.4	7%
HCFC22	1500	0.1	0.4%
Others c/			10.6%

Notes: a/ Global warming potentials (GWP) estimate the warming effect of an emission of 1 kg of each gas relative to that of CO_2.

b/ 26000 Tg of carbon dioxide = 7 Gt of carbon.

c/ Including indirect effects, eg that of NO_2 and CO on tropospheric ozone.

Source: IPCC.

Table 3

Estimates of Contributions to Global Warming over 1980-2030 by Sector and Gas

	CO_2	Methane	Ozone	Nitrous oxide	CFCs	% by sector
Energy						
-direct	35	3	-	4	-	42
-indirect		1	6	-		7
Deforestation	10	4	-	-	-	14
Agriculture	3	8	-	2	-	13
Industry	2	-	2	-	20	24
% by Gas	50	16	8	6	20	100

Source: M. Holdgate et al. Climate Change: Meeting the Challenge, Commonwealth Secretariat, London, 1989, Tables 2.1 and 2.3.

period energy emissions of CH_4, NO_x and CO are expected to grow by 1.8%, 1.9% and 0.4% annually.[2]

However, non-energy sources of some greenhouse gases are also significant. For example, industrial production of solvents, refrigerator and air conditioning fluids, foaming agents, aerosol propellants and other products are virtually the only sources of CFCs emissions. Agriculture - principally from livestock raising and rice paddies - accounts for around 50% of world man-made methane emissions, and for around one third of nitrous oxide emissions - notablly from nitrogen fertilizer applications and land conversion.

As a result of the Montreal Protocol, countries that produce CFCs are now seeking ways to phase out these gases and introduce substitutes. However, developing countries, who for the most part did not ratify the Protocol, account for approximately 12% of the world's CFCs consumption. Based on current trends, their consumption of CFCs is expected to grow by 6% annually between 1986 and 2000. Consumption in India and China, the largest developing country CFCs users, is expected to grow 13% annually over this period.[3]

Man-made methane emissions have been growing at least 0.5% each year, and are about 260-445 Mt per annum, or anywhere between 80 to 90% of total emissions. Ruminants account for about 20-25% of man-made emissions and paddy fields around 25-40%. Biomass burning may add a further 20-25%, fossil fuels - e.g., leakage from gas, coal and oil cycles - another 15-25% and landfill gases the remaining releases. Man-made emissions of N_2O have been growing 0.2-0.3% annually, mainly from fossil fuels (ca. 60%), fertilizer applications (ca. 10%), biomass burning (ca. 10%) and land conversion (ca. 20%).[4]

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[2] IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension, A Working Paper Submitted to the White House Conference on Science and Economics Research Related to Global Change, 17-18 April 1990.

[3] UNEP, The Economic Implications for Developing Countries of the Montreal Protocol, Open-ended Working Group of the Parties to the Montreal Protocol, UNEP, Nairobi, 1990.

[4] H.J. Bolle, W. Seiler, and B. Bolin, "Other Greenhouse Gases and Aerosols", in B. Bolin, B.R. Doos, J. Jaeger and R.A. Warrick (eds.), The Greenhouse Effect, Climatic Change and Ecosystems, SCOPE 29, John Wiley, Chichester, 1986.

3. SCALE OF ADJUSTMENT REQUIRED

Efforts to control future greenhouse gas emissions should be based on efficient strategies to ameliorate adverse climatic changes. This implies actions to reduce global warming that are cost-effective, i.e. the costs of adjustment are minimized, and that maximize net benefits, i.e. at the margin the costs to society of any actions to avert global warming are more than compensated by the benefits from reducing the damages from climatic change, including the risks and uncertainties attached to the future damages.[5] More specifically, the incremental cost of reducing greenhouse gases by one unit must be balanced by the incremental damage to society of that additional unit of greenhouse gases. From this approach an 'acceptable', or 'optimal', level (and rate) of global warming may be determined. It is essential to know this acceptable level in order to determine the scale of adjustment required, and it is important to know the scale of adjustment to assess the role of technology substitution in greenhouse gas abatement.

However, deriving the acceptable level of greenhouse gas emissions from an evaluation of costs and benefits is fraught with empirical difficulties. Estimates are required of the costs of abating greenhouse gas emissions and of the damages that would result from different levels of emissions and atmospheric concentrations. This requires projecting the contributions of individual greenhouse gases, the markets for the activities/sources producing them, the technologies available for abatement and substitution and their relative costs, future economic growth scenarios and structural changes, the warming potential of greenhouse gases, the time-responses of climate and environmental systems and the impacts of such climatic and environmental changes on economies and societies. Not surprisingly few cost-benefit evaluations have been attempted to determine, even approximately, an 'acceptable' level of emissions.

One analysis has recently been conducted by Nordhaus.[6] Assuming that the 1981 sectoral composition of the United States economy will hold for the global economy in the mid-21st century, Nordhaus estimates marginal cost and damage schedules for global greenhouse gas emissions. For a low damage function - which includes only currently identifiable costs of climatic change and assumes a moderate discount rate of 1 percentage point above the output growth rate - the acceptable level of emissions is one that leads to a current reduction of 10% of CO_2-equivalent

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[5] E.B. Barbier and D.W. Pearce, "Thinking Economically About Climate Change", Energy Policy, January/February 1990, pp. 11-18.

[6] W.D. Nordhaus, "To Slow or Not to Slow: The Economics of the Greenhouse Effect", Mimeo, Economics Dept., Yale University, New Haven, February 1990.

greenhouse gas emissions. Of this, 1% comes from strategies to reduce CO_2, and 9% from reducing CFC emissions. For a more moderate damage function - which includes additional damages that raise total damages to 1% of GNP and assumes the same discount rate - the current reduction is 17% of CO_2-equivalent emissions. Of this, about 0.5% results from afforestation, 4.5% from CO2 reduction and 12% from a CFCs phase-out. All scenarios suggest that major reductions in CFCs are the most cost-effective control option for controlling emissions. The major difference in scenarios is the extent to which CO_2 emissions are reduced.

To calculate CO_2 reductions, Nordhaus first estimates the marginal cost of control in terms of the reduction in CO_2 emissions as a function of the penalty or tax imposed upon those who emit CO_2. That is, it is in response to increased marginal costs of emitting CO_2 (i.e. as would result from a carbon tax) that economy-wide reductions in CO_2 are estimated. For example, a modest tax or marginal cost of around $20 per tonne of CO_2 results in a 10% reduction in carbon dioxide. However, the cost of controlling emissions rises sharply as the rate of reduction increases: a 40% reduction in CO_2 requires a $100 per tonne tax. Nordhaus assumes that any reduction over the long run would arise from a combination of increased energy efficiency, through greenhouse gas substitution (as defined in Section 1, above) and through changes in the energy-intensity of final products and services. The relative cost-effectiveness of these different options is not analysed, although the assumption is that any reductions are efficiently attained. Clearly, the next stage of the cost-benefit approach would be to assess the cost-effectiveness of the substitution and other abatement options.

The lack of cost-benefit evaluations to determine even an approximate estimate of acceptable greenhouse gas emissions has meant that most policy options have been developed around target 'stabilisation' levels based on some judgement of acceptability, i.e. the greenhouse gas reductions needed to stabilise at some pre-determined level of emissions. For example, to stabilise emissions in 2005 at 1980s levels, CO_2 emissions would have to be reduced by 50-80%, methane by 10-20%, N_2O by 80-85% and CFCs by 75-100%.[7] CO and NO_x would need to be frozen at 1980s levels. These stabilisation levels have become the basis for global negotiations on actual targets for reducing greenhouse gases. Out of this process, international agreements and recommendations on actual targets of reduction will be established. For example, the Montreal Protocol has targets for reducing CFCs consumption to 15% of 1986 levels by 1998 for developed countries and by 2008 for developing countries, and the IPCC is recommending CO_2 emissions to be stabilised at their 1990 levels, which requires a 20% reduction in their projected levels for 2005.

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[7] Intergovernmental Panel on Climate Change (IPCC), Policymakers Summary of the Scientific Assessment of Climate Change, Working Group 1, Third Draft, May 1990, World Metereological Office and United Nations Environment Programme, Geneva.

Scientific discussion of 'acceptable' warming have not made explicit comparisons of costs and benefits. Instead, they have looked at 'maximum ecological tolerance' as an upper bound to rates of warming. Essentially, the idea is that ecosystems have maximum limits of tolerance to external shocks such as climatic change. Beyond such levels, ecosystem change is unpredictable and could include catastrophic surprises such as ecosystem collapse. Forests have been a particular focus of interest, with the view being that 0.1°C per decade is a 'limit' beyond which forest movement (i.e., colonisation of new areas) is likely to be impossible. The presumption of this risk-avoidance approach, which very much characterises the IPCC reports, is that the cost (damage done) of the resulting surprises exceeds the costs of control.[8]

However, achievement of stabilisation levels will also require careful analysis of the cost-effectiveness of different greenhouse gas control options. An analysis of the sources of greenhouse gas substitutions and their relative costs is therefore essential to both the targeting and cost-benefit approaches.

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[8] For further discussion see D.W. Pearce, 'Economics and the Global Warming Challange', Millennium, forthcoming 1990.

4. SUBSTITUTION OPTIONS AND THEIR COSTS

This section discusses the technical substitution possibilites for various greenhouse gas technologies/activities and, where possible, assesses their cost-effectiveness in terms of dollars-per-unit of greenhouse gas removed. The main focus is on substitutes for fossil fuel combustion, e.g. for electricity generation, buildings/industrial and other stationary sources and transport, but substitutes for CFC production and consumption and non-energy sources of methane will also be reviewed.

No detailed attempt is made to aggregate the combined effects of all the substitution options and to derive a global 'marginal cost' function of the possible measures to reduce greenhouse gases.
There are several reasons limiting such an approach:

i. The analysis of substitution options is not comprehensive. Because of the lack of data, some important supply and end-use technologies have not been considered.

ii. All the technical options, and their relative cost-effectiveness, are extremely location specific. It is more instructive to show how the cost-effectiveness of each option varies by country and region rather than derive aggregate cost functions for a global economy.

iii. To derive an aggregate marginal cost curve for the combined effects of all options requires assumptions concerning the feasibility of substitution over a specific time horizon. For example, what might be the technical potential for, say, generating electricity from wind power in the UK by the year 2005 as opposed to the year 2020, and how do costs change with the level of substitution? Establishing such a substitution scenario for a single country or region is difficult enough; deriving a global scenario for all feasible options and across all countries is probably impossible. This is the case even if we limited the analysis to current rather than future substitution options.

iv. An aggregate cost function indicating the cumulative effects in terms of reducing greenhouse gas emissions of all options is likely to give a misleading impression of the actual aggregate economic costs of these reductions. Each option is likely to have significant second-round economic impacts on its own if it is adopted on a large scale. For example, a significant expansion in nuclear power electricity generation may actually reduce the demand for fossil fuels. Any resulting fall in fossil fuel prices may make other greenhouse gas replacement and reduction options less attractive, and could increase the demand for fossil fuels in other sectors of the economy (e.g., transport). Such impacts will be further compounded, and be more difficult to predict, by the cumulative effects of a combination of substitution options. In other words, a full analysis of costs should involve general equilibrium analysis. Some research efforts are underway to secure more comprehensive estimates of cost, but none are sufficiently advanced for us to report on them here.

Where possible, our assessment of the cost-effectiveness of each substitution option will be in terms of its levelized costs, i.e. costs which are averaged over the lifetime of a plant, representing the uniform revenue required over the life of a project to recover all costs. However, these costs include only the direct costs (i.e., fuel, capital and maintenance) of each option, which do not represent the full economic costs of introducing the technology. Indirect benefits and costs, such as any diversion of capital resources, the impact on overall demand for the final product and the effects on labour productivity, are not included. Similarly, the external benefits and costs, such as the positive or negative impacts on the pollution damages incurred by society, are excluded. Calculating these full economic costs would involve comparing two alternative states of the energy-economic system, one with the new substitution option in place and one with the existing technology. The difference in the value of goods and services (including both marketed and non-marketed, e.g. environmental quality) available under the two states, would measure the cost or benefit of the substitution option.[9] Section 5 discusses these issues further.

4.1 Fossil Fuel Substitution Options

Table 3 indicates that energy use will continue to be the major source of global warming from CO_2, N_2O and O_3, as well as a significant source of CH_4. World primary energy requirements are expected to increase by around 55% from 1987 to 2005, with a much larger increase in developing countries (120%) and in centrally planned economies (70%) than in OECD countries (25%). By 2005 the developing country (DC) share of world energy requirements will rise from 16% to 23%, the CPE share will remain roughly constant at around 32-35%, and the OECD share will fall from 51% to 42% (see Table 4).[10] As a result, all greenhouse gas emissions from energy use will rise significantly over the 1987-

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[9] For an interesting discussion of these issues in relation to US studies of CO_2 emissions reduction, see J.A. Edmonds, W.B. Ashton, H.C. Cheng and M. Steinberg, A Preliminary Analysis of U.S. CO_2 Reduction Potential from Energy Conservation and the Substitution of Natural Gas for Coal in the Period to 2010, Prepared for the US Department of Energy, Washington DC, February 1989, pp. 40-41.

[10] The IEA/OECD scenarios in Tables 4-9 assume a continuation of current government energy policies and practices and current trends in environmental protection but assume rising real oil prices in 1987 US dollars. For further details, see IEA/OECD Greenhouse Gas Emissions, op. cit., ch. 2.

Table 4: WORLD PRIMARY ENERGY REQUIREMENTS (Mtoe)

	OECD		CPE		DC		WORLD	
	1987	2005	1987	2005	1987	2005	1987	2005
Oil	1708	1968	660	960	650	1138	3018	4066
Natural Gas	730	939	618	1345	201	701	1549	2985
Solid Fuels	936	1250	1039	1530	273	666	2248	3446
Nuclear	312	449	56	168	21	27	389	644
Hydro/Other	255	292	89	144	124	246	468	743
TOTAL	3941	4959	2462	4147	1269	2778	7672	11884

Notes: Non-commercial fuels in centrally planned (CP) and developing countries (DC) not included.

Source: IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension,
A Working Paper to the White House Conference on Science and Economics Research
Related to Global Change, 17-18 April, 1990.

2005 period, with fossil fuels accounting for the largest and increasing share (see Tables 5 and 6).

The share of the OECD in total world greenhouse gas emissions will decline over 1987-2005, and its share of emissions will be matched or even exceeded by emissions from other regions (see Table 5). For example, OECD CO_2 emissions in 2005 of 3.37 GtC will be only marginally higher than CPE emissions of 3.31 GtC and only slightly more than DC emissions of 2.39 GtC. Table 7 indicates the current and future breakdown of OECD CO_2 emissions by region and fuel source. North America is expected to remain the major emitter within the OECD; however, emissions in the Pacific region are expected to grow the fastest. Emissions from coal, which has the highest carbon content of the fuels, are expected to increase the most over 1987-2005, and account for over a third of all OECD emissions.

Electricity generation dominates world energy sectoral sources of CO_2 and methane, whereas transport accounts for the largest share of NO_x and CO emissions (see Table 8). This pattern also holds for the OECD region, although transport and industry are more significant emitters of CO_2 (see Table 9). Electricity generation will continue to dominate most greenhouse gases, especially in the OECD where the sector's relative share will be increasing. By 2005, electrical power will account for over 30% of world CO_2 emissions, with power generation in the OECD accounting for 43% of total world electricity emissions of carbon dioxide.

Given the significant impact of electricity generation on global warming, substitution options in this energy sector may have an important role in ameliorating climatic change. Other important substitution options for fossil fuel use may occur in the buildings/industrial and transport sectors. The following sub-sections discuss these options and their relative cost-effectiveness. We have relied heavily on data from OECD countries for this analysis. This is mainly due to the lack of data on substitution possibilities in other regions. However, many of the substitution technologies and activities will most probably be developed in the OECD, and then transferred to other regions. Thus the options available and their relative costs in OECD countries are relevant for global trends. Where possible, we will discuss specific examples of substitution and applications in non-OECD regions.

Note that the cost-effectiveness of all fossil fuel substitution options will be highly sensitive to energy supply and demand and price projections, notably the price of oil and other fossil fuels. For example, in electricity generation, all the levelized cost calculations for different generating technologies are based on a projected price for oil. If actual prices differ, then the relative cost-effectiveness of the various options will also differ.

For substitution options involving renewable energy technologies, cost-effectiveness will be highly sensitive to the maturity and

Table 5: REGIONAL SHARES OF GREENHOUSE GAS EMISSIONS FROM ENERGY

	OECD		CPE		DC		WORLD	
	1987	2005	1987	2005	1987	2005	1987	2005
CO2 (Mt of C)	2713	3372	2095	3315	1237	2390	6045	9077
CH4 (Mt of CH4)	25	26	30	48	27	42	83	115
NOx (Mt of NOx)	38	35	26	44	16	36	80	115
CO (Mt of CO)	143	77	53	79	146	175	342	370

Note: The figures are approximate estimations.
For NOx and CO the year should read 1986 rather than 1987.

Source: IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension,
A Working Paper to the White House Conference on Science and Economics Research
Related to Global Change, 17-18 April, 1990.

Table 6: WORLD FUEL SHARES OF GREENHOUSE GAS EMISSIONS FROM ENERGY

	Coal		Oil		Gas		Biomass		Total	
	1987	2005	1987	2005	1987	2005	1987	2005	1987	2005
CO2 (Mt of C)	2302	3595	2260	3051	992	1912	491	518	6045	9077
CH4 (Mt of CH4)	25	41	10	6	28	47	20	21	83	115
NOx (Mt of NOx)	31	47	40	50	7	16	2	2	80	115
CO (Mt of CO)	26	27	206	222	1	2	108	118	342	370

Note: The figures are approximate estimations.
For NOx and CO the year should read 1986 rather than 1987.

Source: IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension,
A Working Paper to the White House Conference on Science and Economics Research
Related to Global Change, 17-18 April, 1990.

Table 7: OECD EMISSIONS OF CO2 (Mt of Carbon)

	North America		Europe		Pacific		OECD Total	
	1987	2005	1987	2005	1987	2005	1987	2005
Oil	636	699	445	520	175	223	1257	1443
Natural Gas	298	350	136	191	34	60	468	601
Coal	499	651	279	412	107	160	885	1222
Biomass	73	74	27	27	4	4	104	104
TOTAL	1506	1774	886	1149	321	448	2713	3371

Source: IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension, A Working Paper to the White House Conference on Science and Economics Research Related to Global Change, 17-18 April, 1990, Annex A, Table A-1.

Table 3: WORLD SECTORAL SHARES OF GREENHOUSE GAS EMISSIONS FROM ENERGY

	Transport		Industry		Res/Com		Electricity		Other		Total	
	1987	2005	1987	2005	1987	2005	1987	2005	1987	2005	1987	2005
CO2 (Mt of C)	1000	1900	1200	1800	1300	2000	2300	2800	200	600	6000	9100
NOx (Mt of NOx)	34	45	11	13	7	9	25	41	4	6	80	115
CO (Mt of CO)	205	221	3	4	130	138	3	5	1	1	342	370

Note: Figures are approximate estimations.
For NOx and CO the year should read 1986 rather than 1987.

Source: IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension,
A Working Paper to the White House Conference on Science and Economics Research
Related to Global Change, 17-18 April, 1990.

Table 9: OECD EMISSIONS OUTLOOK BY SECTOR

	Transport		Industry		Res/Comm		Electricity		Other		Total	
	1987	2005	1987	2005	1987	2005	1987	2005	1987	2005	1987	2005
CO2 (Mt of C)	600	900	650	700	550	400	700	1200	250	200	2713	3400
NOx (Mt of NOx)	20	18	4	3	2	2	11	11	1	1	38	35
CO (Mt of CO)	128	65	1	1	12	8	1	2	1	0	143	77

Note: The figures are approximate estimations.
For NOx and CO the year should read 1986 rather than 1987.

Source: IEA/OECD, Greenhouse Gas Emissions: The Energy Dimension,
A Working Paper to the White House Conference on Science and Economics Research
Related to Global Change, 17-18 April, 1990.

proven capabilities of the technologies, as well as economies of scale. Figure 1 indicates the current state of technological development of renewable energy technologies. Only hydropower, hydrothermal, some biomass applications, passive solar and small remote photovoltaic (PV) systems are mature technologies today with proven capabilities. These are likely to be the most cost-effective systems currently. However, renewable technologies are responding rapidly to research, development and demonstration efforts. Some of these technologies - wind, solar thermal, ethanol, active solar heating, advanced hydrothermal and larger remote PV systems - are already in a transition phase of development and capable of penetrating the market. In the medium to long term - i.e. in the next ten years or more - some advanced renewable technologies will show significant potential. These will include advanced applications of wind, solar thermal and geothermal, as well as ocean thermal conversion, energy crops for transport and grid connected PV. Other future energy supplies that might become available include tidal power and wave energy.

Assessing the greenhouse gas reduction potential of biomass substitution options offers particular problems. In most studies of this potential only the direct impact of biomass combustion on greenhouse gas emissions is included. These emissions per unit of energy output can often be as high as for fossil fuels. However, this underestimates the full reduction potential offered by biomass fuels. The full impact of biomass as a substitution option should also include the indirect impacts of carbon fixing by biomass when it is growing. Biomass grown for fuel is therefore part of a carbon cycle. The combustion of this biomass to displace the combustion of fossil fuels should represent a net reduction in carbon emitted into the atmosphere. As this net reduction would depend on the stock of standing biomass, its rate of growth and its rate of CO_2 uptake, measuring the full impact of biomass combustion on CO_2 emissions is complicated.

4.1.1 Electricity Generation

As indicated in Section 1 above, it is useful to distinguish substitution options in terms of replacement technologies/activities and reduction technologies/activities. For electricity, replacement technologies would involve the substitution of fossil fuels in power generation by nuclear energy and renewables - hydropower, wind, tidal, wave, geothermal, solar/photovoltaics and refuse incineration. Reduction technologies would involve substituting one fossil fuel source of electricity with an alternative that lowers greenhouse gas emissions. The options here include changing the fuel mix, e.g. from coal to natural gas or biomass and developing advanced fossil fuel technologies, such as fluidized bed combustion of coal and combined cycle gas turbines. Combined heat and power (CHP) is another important reduction technology, but we discuss this option more thoroughly in section 4.1.2.

Assessing the potential role of renewable energy in electricity generation is particularly problematic, as this potential is dependent on the suitability of these technologies to large-

Figure 1

Renewable Energy Potential

Proven Capability	Transition Phase	Future Supplies
Hydropower	Wind	Advanced Wind
Geothermal -hydrothermal (high temp electric) (low temp heat)	Solar Thermal	Advanced Solar Thermal
Biomass -direct combustion -gasification	Ethanol (corn)	Transportation fuel from energy crops
Passive Solar in buildings	Active Solar in buildings	Ocean Thermal
Small, remote PV	Geothermal -hydrothermal (mod temp electric)	Advanced Geoth. -hot dry rock -geopressure -magma
	Remote PV	Grid connected PV
		Wave
		Tidal

Notes: Proven capability - mature technologies.
Transition Phase - has or is entering market as technology develops, often preferential tax or rate considerations.
Future Supplies - advanced technologies that show potential.

Source: Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories and Solar Energy Research Institute, <u>The Potential of Renewable Energy: An Interlaboratory White Paper</u>, Solar Energy Research Institute, Colorado, USA, March 1990.

scale grid generation. Although historically the majority of renewable energy supply for electricity generation has been available on demand (i.e. dispatchable), there is an increasing proportion of energy resources that are subject to fluctuations over time (i.e. intermittent). This distinction between dispatchable and intermittent renewable energy resources is important because of influence on electricity generation, and the need for complementary systems and technologies, such as storage and integrated system response strategies.

The dispatchable sources include hydropower, biomass, geothermal, and ocean energy. Hydropower contributes the largest single input into electricity generation from all renewable resources and, although costs vary significantly from site to site, they often compete favourably with conventional fossil fuels.

Power production from intermittent generating technologies such as solar thermal, wind power and photovoltaics are highly dependant upon the natural forces from which they derive their energy, and are extremely vulnerable to the periodic fluctuations of these natural forces. These intermittent sources of power generation can be used in integration with other sources of power to ensure the continuity of power availablity, or be combined with storage facilities to reduce the need for other sources of power. For example, solar thermal systems use concentrated sunlight to generate heat for thermal conversion processes, including electricity generation. There are three types of solar thermal technologies - parabolic trough systems, central receiver plants, and parabolic dish systems - which are currently available. All solar thermal systems have their greatest outputs and lowest costs in regions of high insolation.

The technology for fossil fuel powered electricity will also be changing rapidly in the next few years (see Figure 2). Assessing the potential contribution of these new technologies in terms of reducing CO_2 emissions is difficult. The development of fluidized bed coal combustion and advanced gas turbines are among the most promising alternatives to conventional fossil fuel plants. The greater efficiency of these technologies will yield lower greenhouse gas emissions per output of delivered electricity. In particular, given the lower level of greenhouse gas emissions for natural gas as compared to coal, the substitution of advanced gas technologies for current coal powered generation plants could lead to significant reductions in overall greenhouse gas emissions. However, a recent US review of the potential impact of this substitution option notes that these technologies alone are insufficient to achieve a 10% reduction of US CO_2 emissions from 1985 levels by 2010.[11] A UK study suggests that deploying advanced coal and advanced gas technologies might

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[11] J.A. Edmonds, et al., op. cit.

Figure 2

Advance Fossil Fuel Power Generation Technologies

Technology	Efficiency (% ECF)	Status
Conventional Rankine plant + FGD	36-37	Deployed
Advanced Rankine plant + FGD	38	Under deployment
AFBC + sulphur removal	39	Near deployment
PFBC + sulphur removal	40	Near deployment
CCCG + sulphur removal	38-43	Near deployment
Topping cycle - PFBC	44.5	Future deployment
Topping cycle - AFBC	45.5	Future deployment
Combined cycle gas turbine (CCGT)	42-46	Deployed
Intercooled STIG	47	Future deployment
Advanced CCGT	47-50	Under deployment
Magnetohydrodynamics	48	Future deployment
Molten carbonate fuel cell	49	Future deployment

Notes:
ECF = Energy conversion factor.
FGD = Fluidized gas desuplphurization.
AFBC = Atmospheric fluidized bed combustion.
PFBC = Pressurized fluidized bed combustion.
CCCG = Combined cycle coal gasification.
CCGT = Combined cycle gas turbine.
STIG = Steam turbine injected gas.

Source: UK Department of Energy An Evaluation of Energy Related Greenhouse Gas Emissions and Measures to Ameliorate Them, Energy Paper 58, London, October 1989, Table 5.2.12 and J.A. Edmonds, W.B. Ashton, H.C. Cheng and M. Steinberg, A Preliminary Analysis of US CO_2 Emissions Reduction Potential from Energy Conservation and the Substitution of Natural Gas for Coal in the Period to 2010, Prepared for the US Department of Energy, Washington DC, February 1989, Table 10.

be mutually exclusive options for abating CO_2 emissions.[12] Unless the price of gas rises substantially relative to coal, the economics of building new efficient coal capacity to displace generation from existing conventional coal stations are unlikely to compare favourably with advanced gas plants. It is worth noting that substantial displacement of coal and gas could increase the price of gas, limiting substitution and hence CO_2 savings.

OECD

Table 10 outlines the trends and projections for electricity generation by fuel in the OECD. Coal clearly dominates and its share will increase, although the share of nuclear power is also expected to rise marginally. This situation could change significantly if global warming concerns give rise to the introduction of carbon taxes, in one form or another, shifting relative prices back to favour nuclear power. Oil is anticipated to fall in both absolute and relative terms, and natural gas will tail off after 1995. Use of renewables increases in absolute terms but not relative to conventional fuels.

These trends largely reflect the projected levelized costs for electricity generation for conventional compared to renewable energy sources (see Tables 11 and 12). Table 11 compares the costs per kilowatt hour (kWh) of different conventional power generation options for new plants beginning construction in 1995. The fossil fuel plants include the additional costs of different emission controls (flue gas desulphurization (FGD)and selective catalytic reduction (SCR)). Coal and nuclear power appear to offer the least-cost generating options. New coal plants are less competitive in importing regions with full emission controls imposed, and the nuclear plants are less competitive with higher discount rates and longer lead times. However, the main obstacles to nuclear power expansion may be more political and social; in addition, the costs of nuclear power include decommissioning costs but not any calculations of environmental risks, hazardous waste transport and disposal or the external costs of location policies.[13]

From Table 12 one can see that few renewable alternatives compete favourably with the conventional fuels, either currently or in the near future. The exceptions may be wind, geothermal and some

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[12] UK Department of Energy, An Evaluation of Energy Related Greenhouse Gas Emissions and Measures to Ameliorate Them, Energy Paper 58, HMSO, London, October 1989, p. 62.

[13] For an interesting discussion of some of these issues and costs, see D. Chapman, "The Eternity Problem: Nuclear Power Waste Storage", Contemporary Policy Issues, 7, July 1990, pp. 1-15, and B. Keepin and G. Kats, "Greenhouse Warming: Comparative Analysis of Nuclear and Efficiency Abatement Strategies", Energy Policy, December 1988, pp. 538-561.

TABLE 10. ELECTRICITY GENERATION BY PRIMARY FUEL, OECD COUNTRIES

	1973		1986		1995		2000	
	TWh	(%)	TWh	(%)	TWh	(%)	TWh	(%)
Coal	1609.8	38.4	2525.0	42.2	3376.6	44.3	3956.5	46.4
Oil	1031.3	24.6	502.6	8.4	457.3	6.0	392.2	4.6
Natural Gas	507.3	12.1	520.6	8.7	609.8	8.0	562.8	6.6
Nuclear	180.3	4.3	1304.4	21.8	1775.9	23.3	2012.4	23.6
Hydropower, etc.	863.6	20.6	1130.9	18.9	1402.5	18.4	1603.1	18.8
TOTAL	4192.2	100.0	5983.4	100.0	7622.0	100.0	8527.0	100.0

Source: International Energy Agency, Emission Controls in Electricity Generation and Industry, IEA/OECD, Paris 1988, Table 2. International Energy Agency, World Energy Statistics and Balances, 1971-1987, IEA/OECD 1989.

TABLE 11. ELECTRICITY GENERATING COSTS OF CONVENTIONAL FUELS, OECD COUNTRIES (1989 US cents/kWh)

	Oil	Coal		Gas	Nuclear	
	(2x600 MW)	(2x600 MW)		(2x600 MW)	(2x1100 MW) Lead Time	
		Importing Region $61/tonne	Low Price Region $40/tonne		6 Years	10 Years
1. Base (5%)	5.3	3.6	3.1	4.6	3.5	3.7
w/FGD	5.7	4.1	3.5			
w/FGD + SCR	5.8	4.5	3.9	4.7		
2. Base (10%)	5.8	4.5	3.9	5.0	5.2	5.7
w/FGD	6.3	5.0	4.5			
w/FGD + SCR	6.5	5.4	4.9	5.1		
3. Middle Load (5%)	5.8	4.2	3.6	4.9		
w/FGD	6.3	4.8	4.2			
w/FGD + SCR	6.5	5.2	4.6	5.0		

Notes: FGD = flue gas desulpherisation SCR = selective catalytic reduction
Establishment of new plants, 1995 conditions, 5% & 10% discount rates etc.

Source: International Energy Agency, Emission Controls in Electricity Generation and Industry, IEA/OECD, Paris 1988, Annex 4.

TABLE 12. ELECTRICITY GENERATING COSTS OF RENEWABLES, OECD COUNTRIES (1989 US cents/kWh) 1/

	Current		Future	
	Minimum	Maximum	Minimum	Maximum
Wind (60 MW)	5.3	9.0	4.1	4.9
Geothermal (50 MW)	4.1	10.9		
Mun. Solid Waste 2/	4.9			
Tidal 3/ (6-7 GW)	6.7	24.8		
Solar Thermal (CRS, 100 MW)	15.3	26.6	13.5	
Photovoltaics (< 500 kW)	56.9	101.7	5.9	6.8
Wave	7.9	9.4		
Hydro-power 4/	5.7	17.1		

Notes: 1/ Unless indicated, source is International Energy Agency, Renewable Sources of Energy, IEA/OECD, Paris, 1987, Annex 2.

2/ Mass combustion of municipal solid waste (MSW) with a capacity of 5 MW, from Japan.

3/ UK Department of Energy, An Evaluation of Energy Related Greenhouse Gas Emissions and Measures to Ameliorate Them, Energy Paper No. 58, London, October 1989.

4/ The data for hydro-power is based on estimates made in West Germany, G. Kolb et al, 'CO2 Reduction Potential Through Rational Energy Utilization and Use of Renewable Energy Sources in the Federal Republic of Germany', KFA, 1989.

biomass applications. Hydro-electric power may also be a cost effective alternative. However, the availability and costs of generating electricity from hydro-power tend to be very site specific and may vary considerably. Photovoltaics (PV) are currently expensive, but decreased capital investment, extended system life expectancy and improved conversion efficiency, coupled with economies of scale, could enable PV systems to penetrate into the field of central power station applications by the late 1990s.[14]

To assess the costs of reducing greenhouse gas emissions in terms of dollars-per-unit of greenhouse gas removed, it is necessary to estimate the quantity of greenhouse gases that are emitted by the various electricity generating options. As noted in Section 2, the warming potential of the greenhouse gases depends upon a range of factors, including warming effect, residence time, atmospheric concentration and annual growth rate. Although the uncertainty of these factors is considerable, calculations of the conversion factors of the greenhouse gases to reflect their warming potentials in terms of CO_2 equivalent have been made (see Table 13).[15] Using these emission weightings it is possible to deduce the total CO_2 equivalent emissions produced from the range of greenhouse gases by the conventional sources of electricity generation. The warming potential of generating electricity from coal (average) plants is the greatest at 1440.1 g/kWh of CO_2 (or 392.4 g/kWh of C). This is over two and a half times the warming potential derived from natural gas power stations. Switching from coal (average) to oil or modern coal plants reduces the level of CO_2 equivalent emissions by around 18-20%.

The estimated costs of achieving reductions in greenhouse gas emissions by the various substitution options for electricity generation in the OECD region are given in Table 14, which expresses these costs in terms of both gas and carbon CO_2 equivalents. Here, coal is taken as the base against which all the substitution options are set. The substitution options consist of both reduction activities/technologies (fuel switching) and replacement activities/technologies (nuclear and renewables).

In Table 14, the two left-hand columns are used to calculate the additional costs of each reduction or replacement option over the

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[14] IEA, Renewable Sources of Energy, IEA/OECD, Paris 1987.

[15] CO_2 equivalents can be expressed either in units of gas or in units of carbon. As noted above, these two measurements can be easily equated, 3.67 tonnes Carbon Dioxide (tCO_2) = 1 tonne Carbon (tC), and in this paper we will mainly refer to CO_2 and CO_2 equivalents in terms of units of carbon. Table 13 is an exception in that it expresses CO_2 equivalents in units of gas. The conversion of other greenhouse gases into CO_2 equivalents is usually calculated in terms of units of gas as the radiative forcing of these gases in the atmosphere determines their relative warming potentials.

TABLE 13. CO2 EQUIVALENT EMISSIONS OF GHG FROM ELECTRICITY GENERATION, OECD COUNTRIES (gCO2/kWh)

	CO2	CH4	N2O	NO2	CO	NMVOC	TOTAL
1. Own Units	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	gCO2/kWh
Coal (Avg) 1/	1077.42	4.14	0.06	5.21	0.16	0.03	-
Coal (Modern) 2/	946.71	3.64	0.05	2.72	0.14	0.02	-
Oil	986.32	0.05	0.20	2.48	0.22	0.16	-
Gas	448.93	1.98	0.01	0.88	0.44	0.02	-
Weightings 3/	1.0	29.0	220.0	44.0	3.0	13.0	-
2. CO2 Equivalents	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh	gCO2/kWh
Coal (Avg)	1077.42	120.09	12.70	229.07	0.49	0.33	1440.1
Coal (Modern)	946.71	105.47	11.45	119.74	0.43	0.29	1184.1
Oil	986.32	1.34	44.82	109.33	0.66	2.12	1144.6
Gas	448.93	57.44	1.74	38.52	1.31	0.32	548.3

Notes: 1/ coal (average) = typical coal steam turbine plant currently in operation, no emissions technology assumed.
2/ coal (modern) = typical new coal fired power station, with higher than average efficiency, flue gas desulpherisation emissions technology and low NOx burners.
3/ Based on R.G. Derwent, "Trace Gases and Their Relative Contribution to the Greenhouse Effect", Harwell Laboratory, Oxford, January 1990, Table 1.

Emission factors include emissions of greenhouse gases incurred during distribution, generation, transport, processing, and extraction stages of electricity generation.

Source: N.J. Eyre, Gaseous Emissions due to Electricity Fuel Cycles in the UK, Energy and Environment Paper 1, ETSU for the Department of Energy, March 1990,

Table 14: COSTS OF SUBSTITUTING FOR GHG EMISSIONS FROM ELECTRICITY GENERATION, OECD COUNTRIES (1989 US$)

Technology	Energy generation costs (USc/kWh)		Additional costs compared to base (USc/kWh)		GHG intensity (tCO2/GWh) 1/		GHG saved (tCO2/GWh) 1/		Additional costs of GHG savings (US$/tCO2) 1/		Additional costs of GHG savings (US$/tC) 2/	
BASE												
coal (average) 3/	3.3		BASE		1440.1		BASE		BASE		BASE	
REDUCTION - FOSSIL FUELS												
coal (modern) 4/	3.8		0.5		1184.0		256.1		19.5		71.7	
gas	5.0		1.7		548.3		891.8		19.1		70.0	
oil (average) 5/	5.3		2.0		1144.6		295.5		67.7		248.4	
oil (modern) 6/	5.7		2.4		1144.6		295.5		81.2		298.1	
REDUCTION - MSW												
MSW	4.9		1.6		1620.5 7/		-180.4		NA		NA	
REPLACEMENT - NUCLEAR												
nuclear (6yr lead)	5.2		1.9		0.0		1440.1		13.2		48.4	
nuclear (10yr lead)	5.7		2.4		0.0		1440.1		16.7		61.2	
REPLACEMENT - RENEWABLES												
	min	max	min	max	min	max	min	max	min	max	min	max
geothermal	4.1	10.9	0.8	7.6	0.0	0.0	1440.1	1440.1	5.6	52.8	20.4	193.7
wind (c)	5.3	9.0	2.0	5.7	0.0	0.0	1440.1	1440.1	13.9	39.6	51.0	145.3
wind (f)	4.1	4.9	0.8	1.6	0.0	0.0	1440.1	1440.1	5.6	11.1	20.4	40.8
hydro-power	5.7	17.1	2.4	13.8	0.0	0.0	1440.1	1440.1	16.7	95.8	61.2	351.7
tidal	6.7	24.8	3.4	21.5	0.0	0.0	1440.1	1440.1	23.6	149.3	86.6	547.9
wave	7.9	9.4	4.6	6.1	0.0	0.0	1440.1	1440.1	31.9	42.4	117.2	155.5
solar thermal (c)	15.3	26.6	12.0	23.3	0.0	0.0	1440.1	1440.1	83.3	161.8	305.8	593.8
solar thermal (f)	13.5		10.2		0.0		1440.1		70.8		259.9	
photovoltaics (c)	56.9	101.2	53.6	97.9	0.0	0.0	1440.1	1440.1	372.2	679.8	1366.0	2494.9
photovoltaics (f)	5.9	6.8	2.6	3.5	0.0	0.0	1440.1	1440.1	18.1	24.3	66.3	89.2

Notes: c = current, f = future, 5% discount rate used.
1/ Greenhouse gas (GHG) expressed as CO2 (in gas units).
2/ Greenhouse gas (GHG) expressed as CO2 (in carbon units).
3/ No emissions technology assumed, average of importing and low price region for coal.
4/ FGD emissions technology assumed, average of importing and low price region for coal.
5/ No emissions technology assumed.
6/ FGD emissions technology assumed.
7/ S. Piccot, J. Buzun and H. Frey, " Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NOx, N2O, CH4, CO, and CO2", Report for US Environmental Protection Agency, Washington DC, May 1990.

Source: Calculated from Tables 11, 12 and 13.

coal base case. The next two columns indicate, in terms of tonnes of CO_2 gas equivalents, the amount of greenhouse gases emitted per GWh generated by each option and the amount of greenhouse gas emissions saved per GWh by the option over the base case. For each option, the ratio of the additional costs (column two) to the amount of greenhouse gases saved (column four) gives the additional costs incurred in saving a unit of greenhouse gas. We initially calculate these costs in terms of US$ per tonne of CO_2 gas equivalents. In the far right-hand column we translate this amount into carbon units - i.e., US$ per tonne of carbon-equivalent emissions saved.

For example, generating electricity from modern coal plants when FGD emissions technology is employed increases the generation costs by US¢0.5/kWh. However, due to the improved efficiency of the plant, the CO2 equivalent emissions are lowered by 256.1 tonnes of CO_2 generated per GWh. Thus the additional costs of reducing greenhouse gas emissions is US$19.5 per tonne of CO_2 gas equivalent saved, or US$71.7 per tonne of carbon equivalent. Although this cost is reasonable in comparison to other substitution options, it must be noted that substantial substitution of modern for old coal plants must occur to have a significant impact on total greenhouse gas emissions.

Of the remaining fossil fuel reduction options, switching to oil generation (both with and without emissions technology) is an expensive option for lowering greenhouse gas emissions, with costs in the region of US$250 to US$300/tC. Switching to gas, on the other hand, is a less expensive choice, with additional costs of reducing greenhouse gas emissions of around US$70/tC. As greenhouse gas emissions would be more than halved, substituting gas for coal in electricity generation may be a relatively effective, as well as cheap, way of lowering these emissions.

In contrast, the biomass fuel reduction option of burning municipal waste instead of coal actually increases greenhouse gas emissions.[16] This option should not be considered as a means for reducing these emissions from electricity generation.

The replacement technologies for electricity generation in Table 14 all have the advantage of not emitting any greenhouse gases.[17]

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[16] In this case, combustion of municipal solid waste is not considered as part of any biomass carbon cycle, so only the direct impact of combustion on greenhouse gas emissions is relevant. Most of this impact was in terms of CO_2 emissions.

[17] However, in their construction stage, the generation plants employing replacement technologies indirectly involve emissions of greenhouse gases. Such emissions are relatively small. For example, a plant using solar thermal emits 3.6 t/GWh of CO_2 in its construction stage, photovoltaics 5.4 t/GWh of CO_2, wind 7.4 t/GWh, hydropower (depending on size) from 3.1 to 10 t/GWh, nuclear 1.0 t/GWh and geothermal 1.0 t/GWh of CO_2. A geothermal plant also emits 0.3 t/GWh of CO_2 in its fuel

Replacing coal generated electricity by nuclear power appears to incur relatively low additional costs per tonne of carbon removed (US$48 to US$61/tC). However, as noted above, employing this substitution option may be constrained by concern for other social costs. There exists a wide range of renewable replacement activities/technologies that have a substantial potential for cost-effectively reducing greenhouse gas emissions, both currently and especially in the future. Of the renewable replacement options currently available, the minimum costs per tonne of greenhouse gas removed of geothermal, wind, hydro-power, tidal and wave lie at the lower end of the cost spectrum (from US$20 to US$120/tC). However, the estimated maximum costs of tidal are over five times greater than its minimum costs, and the maximum costs of reducing greenhouse gases by hydro-power double its minimum costs.

Currently, the most expensive method for reducing CO_2 emissions is photovoltaics (PV), with costs ranging from US$137 to US$250/tC, followed by solar thermal (US$305 to US$594/tC saved). It is predicted that PV costs will decrease dramatically in the future to less than US$100/tC saved, making it a relatively attractive substitution option. The costs of wind power are also expected to decline to levels that make substitution more attractive. In general, economies of scale and future technological breakthroughs could make switching from conventional electrical generation options to alternative, renewable methods more financially viable.

As the costs of substitution differ considerably across the OECD region, we examine in more detail the costs of reducing greenhouse gas emissions in a few selected countries - the USA, the UK, West Germany and Australia.

United States

The United States is the major primary energy consuming country and accounts for nearly a quarter of total world energy consumption.[18] The US emits over 1.26 Gt of CO_2 as carbon annually from energy consumption, around 21% of total world emissions from energy.[19] The electricity generation sector comprises around 35% (7,860 TWh) of total US energy consumption,

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extraction stage, and a nuclear plant 1.5 t/GWh. See R.L. San Martin, "Environmental Emissions from Energy Technology Systems: The Total Fuel Cycle", in OECD/IEA, Energy Technologies for Reducing Emissions of Greenhouse Gases, Vol. 1, Proceedings of an Experts' Seminar, Paris, 12-14 April 1989. As these indirect emissions from replacement technology plants are relatively insignificant, they are not included in our calculations.

[18] BP Statistical Review of World Energy, The British Petroleum Company, London, July 1989.

[19] US Council of Economic Advisors, Report of the Task Force on Economics of Global Warming, 1990, draft.

with coal supplying the major input (57%, 4,480 TWh), and the rest split between nuclear (18%), gas (10%) hydropower/other renewables (10%) and oil (5%).[20] Consequently, electricity generation contributes to around 37% (0.47 GtC) of total US CO_2 emissions from energy, with coal accounting for 31% (0.39 GtC) of these emissions.

Table 15 reviews various options for reducing CO_2 emissions through fuel switching in the United States. As gas is a cheaper option for generating electricity than pulverized coal, the costs of reducing CO_2 emissions by switching from coal to gas are negative, between - US$68 to - US$231/tC saved. Carbon emissions per GWh generated would be reduced by about 63% if gas turbine combined cycle plants were deployed. Although switching from coal to oil would also be economically attractive, the amount of CO_2 savings would be much less, i.e. around 32% per GWh. However, the long term potential for switching from coal to gas in the US may be limited. The United States currently consumes around 28% of total world gas supplies. Power generation accounts for 16% of total US gas consumption - slightly less than the OECD average. However, the United States has only 4.7% of the world's proven reserves, and if current US production is maintained, its reserves will last for only 11.2 years.[21]

The reduction potential for biomass as a substitute for coal generated electricity is also included in Table 15. Municipal solid waste (MSW) is an expensive substitution option and does not yield any savings in per unit greenhouse gas emissions. In addition, further assessment of MSW needs to address the problems of removing dioxins, chlorinated gases and other toxins that are emitted during the combustion process. Wood generation is more economically attractive, but also produces high direct emissions of greenhouse gases (2335 tCO_2/GWh). However, the overall impact of wood on greenhouse gas emissions may be a net reduction on these emissions as wood grown for fuel would extract carbon from the atmosphere. The capacity of wood generation is severely constrained by the availability and high delivery costs of wood and wood wastes. Currently, installed capacity of total biomass energy for electricity generation stands at 8,000 MW. If trends continue this could reach over 30,000 MW by 2030, and with increased research, development and demonstration amount to almost 38,000 MW by 2030.

The potential of renewable energy technologies as substitutes for conventional sources of energy supply has been researched

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[20] J.C. Burgess, 'The Contribution of Efficient Energy Pricing to Reducing Carbon Dioxide Emissions', Energy Policy, June 1990.

[21] BP Review of World Gas, The British Petroleum Company, London, August 1989.

Table 15: COSTS OF REDUCING GHG EMISSIONS FROM ELECTRICITY GENERATION, UNITED STATES (1989 US$)

Technology	Electricity Gen. Costs USc/kWh	Additional Costs Over Base USc/kWh	GHG Intensity tCO2/GWh	GHG Saved tCO2/GWh	Additional Costs Of GHG Savings US$/tCO2	Additional Costs Of GHG Savings US$/tC
BASE						
Pulverized coal	3.91	BASE	1349.42	BASE	BASE	BASE
REDUCTION - FOSSIL FUELS						
Fluidized bed coal	3.91	0.00	1310.54	38.88	0.00	0.00
CCFB coal	5.15	1.24	1044.48	304.94	40.53	148.74
Oil	2.76	-1.15	922.41	427.01	-27.01	-99.14
Gas turbine	0.41	-3.50	793.91	555.51	-63.03	-231.34
Gas boiler	2.64	-1.28	658.01	691.41	-18.47	-67.79
GTCC	1.77	-2.14	498.69	850.73	-25.18	-92.43
REDUCTION - BIOMASS FUELS						
MSW - mass feed	15.65	11.74	1774.36	-424.94	NA	NA
MSW - refuse	15.65	11.74	1620.45	-271.03	NA	NA
Wood	5.35	1.44	2335.01	-985.59	NA	NA

Notes: CCFB = combined cycle fluidized bed GTCC = gas turbine combined cycle MSW = municipal solid waste
Levelized costs for each technology exclude fuel costs.
CO2 equivalents for various greenhouse gases calculated using the weightings in Table 13.
Greenhouse gas emissions are from generation only.

Source: S. Piccot, J. Buzun and H.C. Frey, "Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NOx, N2O, CH4, CO, and CO2", Prepared for US Environmental Protection Agency, Washington DC, May 1990.

extensively in the United States.[22] The cost-effectiveness of these options to reduce greenhouse gases from electricity generation is shown in Table 16, and the potential contribution of renewable energy is outlined in Table 17. In Table 16, renewable and nuclear technologies are compared against the baseload coal electricity generating costs and greenhouse gas emissions.[23]

Table 16 includes a very optimistic projection of nuclear energy costs for the United States (US¢5.5/kWh). The additional costs in terms of CO_2 savings appear very low - around US$7/tC saved. However, the additional costs associated with nuclear power- waste treatment, transport and storage, environmental and health risks, and other social impacts - have made this option less attractive in the United States in recent years. In addition, nuclear power construction costs in the United States have consistently been underestimated in the past. Construction costs increased from US$200/kW installed in the early 1970s to over US$3200/kW in 1986/87 - a sixfold increase in real terms - and construction lead times have increased to more than 12 years for large plants.[24]

The current additional costs of CO_2 savings from substituting hydropower for baseload coal are US$16/tC, although these are likely to fall in the future and become negative (around- US$11/tC by 2030). In 1988, the aggregate capacity of all existing hydroelectric facilities was 88 GW. It is estimated that added capacity will only reach 8 GW (i.e., total capacity 96 GW) in 2030; however, if research, development and demonstration is intensified added capacity may reach 37 GW (i.e., total capacity 125 GW) by 2030.

Geothermal systems also have potential as substitutes for fossil fuels in electricity generation. There now exists a range of small (1-5 MW), medium (25-60 MW) and large (over 100 MW) hydrothermal plants with a total capacity of 2800 MW. The current costs of generating electricity from this source (US¢4.6/kWh) compete favourably with conventional fossil fuel electricity generation costs. The additional costs of switching from coal to hydrothermal electricity generation to reduce CO_2

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[22] Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories and Solar Energy Research Institute, The Potential of Renewable Energy: An Interlaboratory White Paper, prepared for the Office of Policy, Planning and Analysis, US Deptartment of Energy, and published by Solar Energy Research Institute, Colorado, USA, March 1990. Also see N. Rader, et al., op. cit.

[23] The following discussion draws on Tables 15 and 16 and Idaho National Engineering Laboratory, et al., op. cit.

[24] B. Keepin and G. Kats, op cit.

Table 16: COSTS OF REPLACING GHG EMISSIONS FROM ELECTRICITY GENERATION, UNITED STATES (1989 US$) 1/

Technology	Electricity Gen. Costs USc/kWh		Additional Costs Over Base USc/kWh		GHG Intensity tCO2/GWh a/		GHG Saved tCO2/GWh		Additional Costs Of GHG Savings US$/tCO2		Additional Costs Of GHG Savings US$/tC	
BASE												
Baseload coal (c)	5.21		BASE		1440.10		BASE		BASE		BASE	
Baseload coal (f)	6.26		BASE		1440.10		BASE		BASE		BASE	
REPLACEMENT - NUCLEAR												
Nuclear (c) 2/	5.50		0.29		0.00		1440.10		1.99		7.29	
REPLACEMENT - RENEWABLES												
	min	max	min	max	min	max	min	max	min	max	min	max
Hydropower (c)	5.84		0.63		0.00		1440.10		4.34		15.95	
Hydropower (f)	5.84		-0.42		0.00		1440.10		-2.90		-10.63	
Geothermal (c)												
-hydrothermal	4.59		-0.63		0.00		1440.10		-4.34		-15.95	
-geopressured	7.62		2.61		0.00		1440.10		18.19		66.44	
-hot dry rock	6.78		1.56		0.00		1440.10		10.86		39.86	
-magma	22.84		17.62		0.00		1440.10		122.36		449.12	
Geothermal (f)												
-hydrothermal	3.13	4.69	-3.13	-1.56	0.00	0.00	1440.10	1440.10	-21.72	-10.86	-79.73	-39.86
-geopressured	4.59	5.11	-1.67	-1.15	0.00	0.00	1440.10	1440.10	-11.59	-7.97	-42.52	-29.23
-hot dry rock	3.44	4.80	-2.82	-1.46	0.00	0.00	1440.10	1440.10	-19.55	-10.14	-71.75	-37.21
-magma	4.28	6.26	-1.98	0.00	0.00	0.00	1440.10	1440.10	-13.76	0.00	-50.49	0.00
Ocean thermal (c)	8.34	22.94	3.13	17.73	0.00	0.00	1440.10	1440.10	21.72	123.10	79.73	451.78
Ocean thermal (f)	4.17	12.51	-2.09	6.26	0.00	0.00	1440.10	1440.10	-14.43	43.45	-53.15	159.45
Wave energy (c)	10.43	20.86	5.21	15.64	0.00	0.00	1440.10	1440.10	36.21	108.62	132.88	398.63
Solar thermal (c)	16.48		11.26		0.00		1440.10		76.20		287.01	
Solar thermal (f)	4.17		-2.09		0.00		1440.10		-14.48		-53.15	
Wind energy (c)	8.66		3.44		0.00		1440.10		23.90		87.70	
Wind energy (f)	3.23	4.17	-3.02	-2.09	0.00	0.00	1440.10	1440.10	-21.00	-14.48	-77.07	-53.15
Pholtovoltaics (c)	33.37		28.16		0.00		1440.10		195.51		717.53	
Pholtovoltaics (f)	4.17	5.21	-2.09	-1.04	0.00	0.00	1440.10	1440.10	-14.48	-7.24	-53.15	-26.58

Notes: c = current, f = future (2030), min = business as usual, max = research, development and demonstration
a/ Greenhouse gas intensity (tCO2/GWh) for coal taken from Table 13.

Source: 1/ Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories and Solar Energy Research Institute, 'The Potential of Renewable Energy: An Interlaboratory White paper', Solar Energy Research Institute, Colorado, USA, March 1990.

2/ B. Keepin and G. Kats, 'Greenhouse Warming: Comparative Analysis of Nuclear and Efficiency Abatement Strategies', Energy Policy, December 1988.

Table 17

Contribution of Renewable Energy to Total Energy Demand in the United States (Quads)

	1988		2000		2010		2020		2030	
	min	max	min	max	min	max	min	max	min	max
Hydropower	3.1	3.1	3.4	3.4	3.4	4.0	3.5	4.7	3.5	5.1
Geothermal										
-electric	0.2	0.2	0.3	0.4	0.5	0.8	0.7	2.0	0.9	3.7
-heat	<0.1	<0.1	<0.1	<0.1	0.1	0.3	0.2	0.7	0.2	1.6
Solar Thermal										
-electric	<0.1	<0.1	<0.1	0.2	0.3	1.0	1.2	3.1	3.0	9.0
PV	<0.1	<0.1	<0.1	<0.1	0.2	0.7	0.7	2.6	2.9	6.7
Windpower	<0.1	<0.1	0.2	0.4	1.0	2.3	2.1	5.7	3.3	10.7
OTEC	0.0	0.0	0.0	0.0	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Biomass										
-electric	0.5	0.5	1.0	1.1	1.6	1.9	1.9	2.4	2.2	2.9
-buildings	1.0	1.0	1.0	1.2	1.5	2.0	1.8	2.6	2.2	3.2
-industrial	1.8	1.8	2.2	2.3	2.9	3.3	3.3	3.9	3.8	4.6
-liquidfuel	<1.0	<0.1	0.2	0.3	0.4	2.4	0.8	4.4	2.2	8.4
Solar Heat										
-buildings	<0.1	<0.1	0.2	0.2	0.3	0.5	0.4	0.7	0.5	0.9
-industrial	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	0.2	0.2	0.3
Total RET	6.7	6.7	6.8	9.7	12.1	19.3	16.7	33.1	24.9	57.1
Percentage Total Energy Demand	8	8	9	10	11	18	13	27	17	40

Notes: min = buisness as usual, max = research, development and demonstration intensification.

1 Quad = (1×10^{15}) British Thermal Units (Btu).
(1×10^{15})Btu = 293×10^{9} kWh.

Source: Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories and Solar Energy Research Institute, The Potential of Renewable Energy: An Interlaboratory White Paper, Solar Energy Research Institute, Colorado, USA, March 1990.

emissions are negative (- US$16/tC). These savings are expected to increase further in the future.

Nationwide application of geothermal electricity is likely to depend upon the success of advanced technologies, especially geopressured, hot dry rock and magma systems. These technologies are not yet commercial and require further research to reduce uncertainties and improve technologies. However, they are expected to come on line early next century and greatly expand the total available geothermal resource base in the United States. The costs of generating electricity from these sources is expected to be relatively low, at between US¢3-6/kWh, and incur substantial savings as substitutes for conventional fossil fuels to reduce greenhouse gas emissions (i.e., up to-US$37/tC). The potential benefits are considerably larger if there is substantial support for intensive research, development and demonstration in the next two decades.

Ocean thermal energy conversion (OTEC) technology operates through harnessing the differences in ocean temperatures (i.e. warm surface waters, cold water at depth) to drive baseload electric power generation. Although no commercial OTEC plants are currently in operation, they have significant potential for the future. The current costs of generating electricity from a 10 MW OTEC plant are estimated to be US¢23/kWh; however, if all additional benefits are included (water, mariculture and cooling), electricity generation costs fall to US¢8/kWh. Thus, the current costs of using OTEC technology as an option to reduce greenhouse gas emissions are high, ranging from US$80-450/tC saved. Future costs may fall substantially, although there exists a wide range of uncertainty over potential costs of generating electricity from OTEC technology.

No major projects to assess the potential of wave energy are currently being undertaken in the USA. The costs of generating electricity from wave energy may lie between US¢10-20/kWh depending on the intensity of the waves, leading to high CO_2 reduction costs (US$ 133-339/tC saved).

Other sources of ocean energy that have been considered for electricity generation include ocean currents, tidal power, salinity gradient conversion systems and marine biomass. Although they may have potential in the future, technological uncertainties and cost constraints currently undermine their ability to contribute to options for reducing greenhouse gas emissions.

Current electricity generation costs from existing solar thermal systems (with and without storage facilities) are approximately US¢16.5/kWh, leading to high costs of reducing greenhouse gas emissions (US$287/tC saved). Future solar thermal systems are expected to be used in either peak load without the use of storage, or with an integrated thermal storage facility for intermediate and baseload plants. However, this latter option is highly dependant upon technical improvements in storage facilities. For solar thermal systems with storage facilities generating costs are anticipated to fall to around US¢4/kWh by 2030. Thus the additional costs of CO_2 savings may be negative (- US$53/tC). Systems without storage facilities are expected to have slightly more expensive electricity generation costs (US¢5/kWh).

Wind power currently contributes over 2 TWh of electricity generation in the United States, primarily in California. The potential contribution of wind energy is significant. If current trends continue wind power could expand to 3.3 quads (967 TWh) by 2030, and with increases in research, development and demonstration to as much as 10.65 quads (3120 TWh). The current costs of electricity generation from existing wind energy plants in the United States is just over US¢8.5/kWh, and these costs continue to fall. By 2030 the cost of generating electricity from wind power is estimated to be around US¢3-4/kWh. Wind power is therefore a relatively cost-effective method of reducing greenhouse gases, with current additional costs around US$88/tC. This could fall to - US$77/tC saved by 2030.

Currently, costs of generating electricity from photovoltaic (PV) systems in the US are about US¢33/kWh, which is prohibitive except in remote areas where alternative sources of electrical power are also costly and/or limited in availability. The total existing capacity of photovoltaics in the United States is approximately 42 MW. PV costs are expected to fall rapidly, to between US¢4-5/kWh by 2030, depending upon the level of research, development and demonstration of PV undertaken.[25] Although at present PV systems are an expensive choice for reducing greenhouse gas emissions at over US$700/tC removed, by 2030 these costs of removal may even be negative (- US$27 to 53/tC saved). The potential penetration of PV into the total United States electric power market is 0.8 GW of primary energy by 2000, and 114 GW by 2030 assuming that current trends continue. If research, development and demonstration are intensified, then by 2000 PV supply may reach 3.6 GW, and by 2030 as much as 266 GW. For further market penetration, improved storage or new hybrid facilities are required.

Table 17 gives the potential contribution of renewable energy technologies to total demand for energy in the United States. Of the renewable energy technologies that are possible substitutes

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[25] PV is a research driven technology and should respond with great sensitivity to an intensified research and development budget. The figures of future costs of PV systems for generating electricity may be <u>pessimistic</u> and higher than may actually occur. Taking more optimistic assumptions with greater cost reductions and improved market penetration, PV generation costs fall faster, to US¢13/kWh in 1995, US¢8/kWh in 2000, and US¢5/kWh in 2010. Consequently, PV systems may supply as much as 80 GW by 2010, 240 GW by 2020 and 480 GW by 2030. See the discussion in Idaho National Engineering Laboratory <u>et al.</u>, <u>op. cit.</u>, Appendix G.

for conventional fossil fuel inputs into electricity generation, hydropower plays a dominant role and will continue to do so if current levels of research remain unchanged. Although the current role of geothermal electric is relatively significant amongst the renewable energy technologies for electricity generation, this will not be sustained unless there is intensive research and development. The potential contribution of solar thermal electric, photovoltaics and wind power may rise quickly but are highly sensitive to the level of research, development and demonstration. Wind power has the potential to dramatically increase its energy output, to become the most significant renewable energy technology for electricity generation by 2030, followed by solar thermal and then photovoltaics.

United Kingdom

Current total emissions of CO_2 in the UK are 163 MtC, of which electricity generation comprises 34% (55MtC). These have been virtually constant since the 1970s. By 2005 UK CO_2 emissions are estimated to be between 212-204 MtC (low-high oil price scenario), with electricity generation contributing 68-65 MtC (31-33%) of these total emissions. A study of the practical technical options to curtail emissions of greenhouse gases from energy related activities has been undertaken for the UK.[26] The cost-effectiveness of each substitution option available is assessed on the basis of a range of possible energy related emission scenarios for the years 2005 and 2020. The methodology is based on an abatement strategy of least marginal cost CO_2 abatement, i.e. displacing the fuel with the highest carbon content per unit price - given system stock, operating characteristics and fuel price. In most instances, coal generation will be displaced first; however, under some scenarios - e.g., an increase in the relative price of coal to gas - gas might be the first fuel substituted.

Table 18 outlines the results of the study, which indicate the costs of reducing CO_2 emissions only. For each option, the capacity for electricity generation is projected, and the costs calculated on the basis of the amount of CO_2 emissions reduced at each additional level of generation. Note that the two biomass options (wood and straw combustion) have included the full impact on CO_2 reductions of growing and burning the energy crops. That is, the carbon-fixing impacts of these crops have been included in the calculations of net CO_2 reductions.

The relative cost-effectiveness of the options depend significantly on whether future fossil fuel prices are expected to be high or low and on the time horizon - 2005 or 2020. For

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[26] UK Department of Energy, An Evaluation of Energy Related Greenhouse Gas Emissions and Measures to Ameliorate Them, Energy Paper Number 58, UK Country Study for the Intergovernment Panal on Climate Change Response Strategies Working Group Energy and Industry Sub Group, HMSO, October 1989.

Table 18. COSTS OF SUBSTITUTING FOR CO2 EMISSIONS IN ELECTRICITY GENERATION, UK 1/

	2005						2020					
	Low Price Case			High Price Case			Low Price Case			High Price Case		
PHOTOVOLTAIC												
Capacity (TWh/yr)		2.3			2.3			5.7			5.7	
Reduction in CO2 (Mt C)		0.57			0.57			1.42			1.42	
PV Costs 2/	Low	Mid	High	Low	Mid	High	Low	Mid	High	Low	Mid	High
Average cost (£1988/t)	206	1130	2094	195	1119	2083	42	805	1568	30	793	1557
Marginal cost (£1988/t)	206	1130	2094	195	1119	2083	42	805	1568	30	793	1557
TIDAL												
Capacity (TWh/yr)	1.3	18.3		1.3	18.3		1.3	19.3	23.7	1.3	18.3	23.7
Reduction in CO2 (Mt C)	0.34	4.7		0.35	4.8		0.34	4.6	5.9	0.27	3.8	4.9
Average cost (£1988/t)	142	156		98	112		115	133	146	116	133	148
Marginal cost (£1988/t)	142	157		98	113		115	135	188	116	135	198
WOOD COMBUSTION												
Capacity (TWh/yr)	3	5	7	3	5	7	3	7	11	3	7	11
Reduction in CO2 (Mt C)	0.5	1.0	1.5	0.6	1.2	1.7	0.8	1.8	2.8	0.5	1.3	2.2
Average cost (£1988/t)	79	101	120	18	48	68	29	80	108	5	71	103
Marginal cost (£1988/t)	102	138	157	58	92	111	77	132	157	58	126	155
GEOTHERMAL												
Capacity (TWh/yr)	0.2			0.2			1.9			1.9		
Reduction in CO2 (Mt C)	0.05			0.05			0.48			0.39		
Average cost (£1988/t)	235			189			209			231		
Marginal cost (£1988/t)	235			189			209			231		

Notes: 1/ Low price assumes a scenario with low fossil fuel prices; high price assumes a scenario with high fossil fuel prices.
2/ The low, mid and high scenarios reflect the high uncertainty regarding future PV costs.
US$1 = UK£0.56, assumes 8% discount rate.

Source: UK Department of Energy, An Evaluation of Energy Related Greenhouse Gas Emissions and Measures to Ameliorate Them, Energy Paper No. 58, London, October 1989.

Table 10. COSTS OF SUBSTITUTING FOR CO2 EMISSIONS IN ELECTRICITY GENERATION, UK 1/

	2005						2020					
	Low Price Case			High Price Case			Low Price Case			High Price Case		
NUCLEAR												
Capacity (GW)	2	4	8	2	4	8	13.75	27.5	55	14	28	55
Reduction in CO2 (Mt C)	1.3	2.7	5.5	1.7	3.3	8.9	10	21	40	17	34	69
Average cost (£1988/t)	101	101	104	16	14	16	52	54	49	-72	-118	-165
Marginal cost (£1988/t)		101	108		11	17		55	44		-3	-1
LANDFILL GAS												
Capacity (TWh/yr)	1.0	2.4	3.2	1.0	2.4	3.2	1.0	2.4	3.2	1.0	2.4	3.2
Reduction in CO2 (Mt C)	0.11	0.27	0.36	0.19	0.45	0.60	0.11	0.27	0.36	0.19	0.45	0.60
Average cost (£1988/t)	-43	-34	-23	-57	-51	-45	-60	-50	-40	-67	-61	-55
Marginal cost (£1988/t)	-36	-27	8	-53	-47	-26	-53	-44	-9	-62	-57	-36
WIND												
Capacity (TWh/yr)	4.4	10	18	4.4	10	18	10	19	48	10	19	48
Reduction in CO2 (Mt C)	1.0	2.0	4.3	1.0	2.0	4.3	2.0	4.5	11.5	2.0	3.3	10.5
Average cost (£1988/t)	-23	-7	28	-66	-50	1	-9	31	170	-52	-12	167
Marginal cost (£1988/t)	-17	7	61	-60	-36	50	5	66	423	-38	53	416
GAS TURBINE												
Capacity (GW)	20	41		20	41		8	17		8	17	
Reduction in CO2 (Mt C)	20	28		25	32		6.6	7.8		30	35	
Average cost (£1988/t)	50	73		66	90		72	111		12	38	
Marginal cost (£1988/t)	50	520		79	479		130	363		42	348	
STRAW COMBUSTION												
Capacity (TWh/yr)	1.0	2.0	2.5	1.0	2.0	2.5	1.0	2.0	2.5	1.0	2.0	2.5
Reduction in CO2 (Mt C)	0.26	0.51	0.64	0.26	0.53	0.66	0.26	0.51	0.64	0.26	0.53	0.66
Average cost (£1988/t)	95	103	106	50	57	60	64	72	75	46	53	56
Marginal cost (£1988/t)	95	110	118	59	65	72	64	80	88	46	61	69

example, in the case of nuclear energy, higher fossil fuel prices lower substantially the marginal costs of CO_2 savings; in the 2020 scenario, the marginal costs would actually be negative- implying that switching to nuclear not only reduces CO_2 emissions but also saves on costs.

Other substitution options seem limited by either capacity or cost constraints. Landfill gas appears the most attractive option, as virtually all of its marginal costs of substitution are negative, but its maximum capacity in the UK would be limited to 3.2 TWh/yr. This would only reduce annual CO_2 emissions by 0.36 MtC. Wind power initially has negative and low marginal costs of CO_2 savings, but the costs rise sharply as capacity increases. The study assumes that the best sites available for wind generation are limited, and will be used up quickly, and assumes no economies of scale. Advanced gas turbines could have a substantial impact on CO_2 emissions in the near future by displacing oil and coal. However, substitution capacity is probably limited by costs to around 20 GW. Power generation from gas turbine plants in the future is only cost-effective as a CO_2 abatement measure at very low levels of capacity (less than 8 GW) and only in the high price scenario.

Of the remaining electricity generating options available to the UK, straw combustion is a relatively low-cost technological alternative but only has a small potential capacity. The marginal costs of reducing CO_2 emissions by other options appear prohibitive. The costs of photovoltaics are extremely speculative due to the high level of technical uncertainty - as reflected in Table 18 by the considerable divergence between the low, medium, and high cost estimates. More recent cost estimates suggest that the optimistic low cost scenario may be the most realistic, and that photovoltaics are likely to be an attractive substitute for fossil fuels in the future.[27]

West Germany

A similar assessment of the costs of substitution options to reduce CO_2 emissions in the energy sector has been undertaken in West Germany.[28] Fossil fuel power plants for electricity

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[27] For example, the costs for grid connected PV systems in Table 17 were based on a 1988 cost range of UK£0.08-0.67/kWh and 2025 cost range of UK£0.02-0.37/kWh. More recent analysis suggests that the current likely achievable cost range for centrally generated PV power is UK£0.11-0.17/kWh, and future costs could be in the range of UK£0.06-0.09/kWh. See Review of Solar Energy Technologies, Part III: Photovoltaic Power, Draft Paper, Energy Technology Support Unit, Harwell, UK, November 1989.

[28] G. Kolb, G. Eickhoff, M. Kleemann, N. Krzikalla, M. Pohlmann and H. Wagner, CO_2 Reduction Potential Through Rational Utilization and Use of Renewable Energy Sources in the Federal Republic of Germany, Kernforschungsanlage Julich GmbH, May 1989.

generation emit about 60 MtC of CO_2 per year, which is around 30% of total CO_2 emissions in West Germany (approximately 210 MtC of CO_2 in 1987). However, renewable energy sources appear to have considerable promise as substitutes for fossil fuels in electricity generation.

A comparison of the additional costs of reducing CO_2 emissions per tonne of CO_2 saved (in both gas and carbon units) in West Germany is given in Table 19. The costs of the replacement substitutes are compared against the costs of coal power plants, which are the principal source of electricity generation. In the study, only hydro-power, wind energy and photovoltaic cells were compared as substitutes for fossil fuels (coal) in electricity generation. Of these substitutes, hydro-power plants have the lowest additional costs over coal, which are actually negative at the lower range of generation costs. However, further expansion of hydro-power capacity is severly constrained in West Germany. Wind energy may have the greatest potential for replacing CO_2 emissions. This option has a potential primary energy contribution of 40TWh per annum, could reduce CO_2 emissions annually by 13.2 $MtCO_2$ (3.6 MtC), and only incurs additional costs ranging from US$62-250 per tonne of carbon saved. At present the West German study suggests that photovoltaic cells are not attractive due to the high and uncertain electricity generating costs, but in the future given expected technological improvements and economies of scale, this substitution technology may be a more cost-effective method of reducing CO_2 emissions from electricity generation.

Australia

Substitution options for electricity generation in Australia were examined as part of a study analysing the potential effects of achieving a 20% economy-wide reduction in 1988 CO_2 emissions by 2005.[29] Australia emits around 70 MtC of CO_2 annually, of which about 31 MtC comes from electricity generation. The study notes that options for reducing CO_2 emissions per unit of power generated varies significantly across Australia. Victoria is the highest per unit CO_2 emitter, as it relies principally on brown coal. Other States, such as Tasmania (mainly hydro), South Australia, Western Australia and Northern Territory (mainly natural gas) have relatively lower per unit CO_2 emissions. For these states, the unit costs of reducing emissions will be higher than for coal-burning states.

Table 20 summarises the costs of reducing CO_2 emissions from various reduction and replacement substitution options for electricity generation in Australia. The least expensive way of reducing emissions is to switch from brown to black coal plants,

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[29] McLennan Magasanik Associates, The Feasibility and Implications for Australia of the Adoption of the Toronto Proposal for Carbon Dioxide Emissions, Victoria, Australia, September 1989.

Table 19: COSTS OF SUBSTITUTING FOR CO2 EMISSIONS IN FEDERAL REPUBLIC OF GERMANY

Technology	Energy generation costs (DM/kWh) 1/	Additional costs compared to base technology (DM/kWh) 1/	Additional costs of CO2 savings (DM/kgCO2)	Additional costs of CO2 savings (DM/kgC)
Hydropower	0.1-0.3 2/	(-0.14)-0.06	(-0.15)-0.07	(-0.55)-0.26
Wind energy (25-55 kW)	0.27-0.35	0.03-0.11	0.03-0.12	0.11-0.44
Photovoltaic				
kW unit size	2.0-5.0	1.76-4.76	1.91-5.17	7.01-18.97
MW unit size	1.0-1.7	0.76-1.46	0.83-1.59	3.05-5.83
Wood stove	0.2-0.3 2/	0.01-0.11	0.03-0.32	0.11-1.17
Geothermal heating	0.13-0.35 3/	(-0.06)-0.16	(-0.18)-0.47	(-0.66)-1.72
Solar water heating	0.40-1.00	0.21-0.81	0.62-2.38	2.27-8.73
Electric heat pump	0.26-0.36	0.07-0.17	0.83-2.13	3.23-7.82

Notes: US$1 = DM 1.756
1/ related to energy output
2/ estimation
3/ inclusive 0.05 DM/kWh for heat distribution.

Source: G. Kolb, G. Eickhoff, M. Pohlmann and H.J. Wagner, CO2 Reduction Potential Through Rational Energy Utilization and Use of Renewable Energy Sources in the Federal Republic of Germany, Kernforschungsanlage Julich Gmbh, May 1989.

Table 20: COST OF SUBSTITUTING FOR CO2 EMISSIONS IN AUSTRALIA

Technology	Levelized cost (c/kWh)	Thermal Efficiency (%)	CO2 intensity (tCO2/GWh)	CO2 Saved 1/ (tCO2/GWh)	Cost of CO2 Saved 1/ ($/tCO2)	Cost of CO2 Saved 1/ ($/tC)
FOSSIL FUELS						
Brown coal 2/	4	30.8	1110	Base	Base	Base
Black coal	3.5	35.3	940	170	(30) 3/	(110.1) 3/
Advanced gas turbine 4/	4.7-6.7	33	640	470	15-60	55-220
Combined cycle 4/	5.6-6.9	43	490	620	25-47	92-172
Methane recovery 5/	5-8	28	760	(350) (7000) 6/	(30-115) (1-6) 6/	(110-422) (4-22) 6/
Cogeneration	6-8	50-55	390-420	700	0-57	0-209
RENEWABLE ENERGY						
Hydro	5-10	--	0	1110	9-55	33-202
Wind	6-8	--	0	1110	18-35	66-128
Photovoltaics	10 7/	--	0	1110	55	202

Notes: Figures are on an energy sent out basis using 1988 'state-of-the-art' technology, with capital-related costs based on an 8% real discount rate. Have assumed fossil fuel plants run at 80% capacity factor.

US$1 = A$1.281

1/ Relative to using a brown coal plant.

2/ Based on building Loy Yang B1 & 2. NREC estimates that building the next green-fields brown coal station at Driffield will cost 5.4c/kWh.

3/ Negative because power from black coal is cheaper and less CO2 intensive.

4/ Based on a gas price of $2.50-$4.00/GJ.

5/ The recovery of methane from coal mines and land fill sites, for burning in a gas turbine of stationary internal combustion engine.

6/ This line allocates full credits to avoiding leakage of natural gas into the atmosphere, which would otherwise occur. It is assumed that 1 molecule of CH4 is equivalent to 6 molecules of CO2 in terms of greenhouse activity.

7/ Based on system cost of A$2 per peak watt, which should be achievable by the turn of the century.

Source: McLennan Magasanik Associates, The Feasibility and Implications for Australia of the Adoption of the Toronto Proposal for Carbon Dioxide Emissions, Report to CRA Ltd, September, 1989.

which actually incurs negative costs per tonne of CO_2 saved. However, the amount of CO_2 saved per unit of power (170 tCO_2/GWh) is limited. Switching from brown coal to burning gas in an advanced turbine or a combined cycle plant would reduce CO_2 emissions further, but at a higher cost. Methane recovery would involve collecting and using the methane gas that escapes from coal mines and landfill sites. Not only would this substitution option reduce CO_2 emissions from fossil fuel power generation, but it would also yield additional benefits in reducing the amount of methane escaping into the atmosphere (the latter savings are included in Table 20 as CO_2 equivalents). The costs of methane substitution are estimated to be US$2.86 to US$17.20/tC saved; however, serious doubts exist about the technical feasibility of recovering and using methane. Similarly, cogeneration (combined heat and power) could be a cost-effective means of reducing CO_2 emissions, but its capacity is severely constrained to a maximum of around 2% of total electricity demand.

Only those renewable energy technologies currently near commercialisation - hydropower, wind and photovoltaics - were considered by the Australian study as likely to have a potential impact on CO_2 emissions by 2005. Of these technologies, hydropower and wind appear the most attractive, but hydropower in particular is limited in new capacity. Although photovoltaic cell technology is rapidly improving in cost-effectiveness, the study anticipates that it will still be relatively expensive by the turn of the century with a levelized cost of US¢7.8/kWh. At this cost, PV is not expected to be economically feasible[30] for large scale power generation.

Developing Countries

Average annual developing country growth rates in electricity use were about 10% during the 1970s and 7% during the 1980s. Total installed generating capacity in developing countries is anticipated to increase by 82% during the 1990s, from 471 GW to 855 GW. The majority of current generation is from hydropower (185 GW), followed by coal (169 GW). However, by the end of the 1990s, coal will produce 341 GW compared to 322 GW by hydropower. From 1989-1999, other sources of electricity generation are expected to increase. Oil will increase from 70 to 84 GW, gas from 31 to 65 GW, nuclear from 14 to 38 GW and geothermal from 2

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[30] Economic feasibility here is taken to include the direct costs of electricty generation only. As noted earlier in the text, the economic feasibility of the substitution options to reduce greenhouse gas emissions would ideally account for the full impact of any indirect costs of electricty generation. However, data limitations constrain us to direct costs only.

to 5 GW.[31] In 1989 $ terms the anticipated electricity expansion in developing countries will cost some $745 billion, or $1 trillion allowing for price escalation.[32]

As a rough indicator, power generation accounts for approximately 15% of developing countries' total CO_2 emissions from energy use (around 185 MtC in 1987). The ability of developing countries to reduce these emissions from adoption of <u>replacement</u> and <u>reduction</u> technologies applied to electricity generation will depend on a number of factors:

i. Developing countries will be highly dependent on the transfer of these technologies from OECD countries.[33] As a consequence, the costs of CO_2 savings through substitution in power generation discussed for OECD countries above will give an approximate indication of the options available to developing countries.

ii. The relative cost-effectiveness of the substitution technologies will vary significantly from country to country in the developing world. Differences in population growth and distribution (e.g., rates of urbanisation), economic development, levels of income and growth, government budget constraints, and institutional structures will affect the relative costs across countries.

iii. All substitution options, but especially renewable energy technolgies, in developing countries are highly sensitive to changing international oil prices and the location and scale of the generation facility. Renewable technologies for large-scale generation will be located mainly near urban centres, whereas the smaller, stand alone technologies (e.g., small-scale biomass and photovoltaic systems) are often used in rural and remote applications. As fossil fuel prices are relatively higher in rural than in urban areas, the economic viability of remote rural systems may be greater than the large-scale urban systems, and the rural systems may be less sensitive to falls in international oil

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[31] G. Schramm, "Electric Power in Developing Countries: Status, Problems, Prospects", <u>Annual Review of Energy</u> 15, 1990, pp. 307-33.

[32] E. Moore and G. Smith, <u>Capital Expenditures for Electric Power in the Developing Countries in the 1990s</u>, World Bank, Industry and Energy Working Paper No. 21, February 1990, World Bank, Washington DC.

[33] Lawrence Berkeley Laboratory <u>et al.</u> <u>Energy Technology for Developing Countries: Issues for the US National Energy Strategy</u>, Lawrence Berkeley Laboratory, Berkeley, California, December 1989.

prices. In addition, supplies of fossil fuels tend to be more reliable in urban than in remote areas.[34]

iv. Biomass options are particularly sensitive to varying feedstock costs. These costs fall into two main categories - those which have minimal or zero resource costs, such as on-site waste products found at wood or agro-processing plants, and those which have a market value, such as plantation-based wood and cash crops. Waste products - crop residuals, agricultural wastes and human or animal wastes- are competitive with fossil fuels when used on-site, in areas away from a central grid, or compacted to reduce unit transport costs. Large-scale and commercial biomass applications tend to be attractive only when feedstock costs are low; however, such low costs often depend on a) depressed primary commodity markets (e.g. wood, sugar), b) fewer alternative by-product uses, or c) an unlimited or on-site resource supply.[35]

v. Finally, distortionary government pricing policies for fossil fuel generation of electricity in developing countries may affect the adoption of substitution options. Such distortions also vary significantly from country to country and within a country. Uncontrolled retail prices for small quantity fossil fuel purchases in remote areas may mean fuel prices will be above regulated prices and far above economic fuel costs for many small-scale rural energy systems. In contrast, the regulated fossil fuel prices for large-scale urban electricity generation subsidize the generation costs of such systems.[36]

For example, a study comparing the long run marginal costs of wind to conventionally generated electricity in ten developing countries indicates that wind may be a cost-effective substitute in most cases.[37] However, a World Bank study suggests that lower oil prices can significantly change the comparative costs of wind versus fuel oil electricity generation in developing countries.[38] For example, a 50% drop in diesel and fuel oil import prices

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[34] See E. Terrado, M. Mendis and K. Fitzgerald, Impact of Lower Oil Prices on Renewable Energy Technologies, Industry and Energy Department Working Paper, Energy Series Paper No. 5, World Bank, Washington D.C.

[35] M.M. Gowen, "Biofuel v Fossil Fuel Economics in Developing Countries: How Green is the Pasture?", Energy Policy, October 1989, pp. 455-470.

[36] See E. Terrado et al., op. cit. and J. Burgess, op. cit.

[37] E. Tasdemiroglu, "The Energy Situation in OIC Countries: The Possible Contribution of Renewable Energy Resources", Energy Policy, December, 1989, pp. 577-590.

[38] E. Terrado et al., op. cit.

could reduce electricity generation costs by 30%. Many biomass generating options currently promoted for developing countries, including dendrothermal power systems (a wood burning power plant and a dedicated plantation of short-rotation trees), 'bagasse' systems (a sugar mill power plant burning the fibrous residue from cane crushing) and biomass power gasifiers (wood, charcoal, rice husks or coconut husks), are also severely sensitive to prevailing diesel and fuel oil prices. Feedstock prices, which can vary significantly, also tend to be an important determinant of economic viability. For example, estimates from Thailand indicate that quadrupling wood fuel prices up to typical plantation costs of US$20 per tonne (wet weight) results in wood generation systems that are no longer competitive with coal or oil plants.[39] On the other hand, small-scale rural applications of these and other renewable energy technologies, including wind and photovoltaic water pumping, may continue to be economically viable because of the scarcity and unreliability of fossil fuels and their relatively high prices.

The role of nuclear energy as a substitution option illustrates the technical and financial difficulties facing developing countries. For example, for developing countries to replace coal with nuclear power generation by 2025 would require them to extend their existing capacity of 14 GW today and 38 GW projected for 1999 to 2330 GW by 2025.[40] This would require an annual capital cost of US$64 billion and electricity generation costs of US$170 billion each year (US$ 1987). Such a financial commitment is infeasible for most developing countries, as many countries would not have the access to capital to finance nuclear reactors, technology transfers, imported fuel and expertise and investments in infrastructure and training. Many major developing countries with nuclear programmes have already been forced to reduce or phase them out because nuclear plants have been too costly or slow to build.

4.1.2 Building/Industrial and Other Stationary Uses

Fossil fuels are widely used for space and water heating in commercial and residential buildings. In industry, fossil fuels provide heat process energy and feedstock materials. In this section we will be mainly concerned with substitution options for space and water heating and industrial process heat. For these applications, the reduction technologies would involve changing the fuel mix, e.g. introducing combined heat and power (CHP) and switching from coal and oil to gas or biomass. The main replacement technologies are the various renewable energy options for both space and water heating and industrial process heat, passive and active solar heating systems, geothermal processes and solar thermal energy.

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[39] Gowen, op. cit.

[40] B. Keepin and G. Kats, op. cit.

OECD

Table 9 indicates that the industrial and residential/commercial sectors in the OECD accounted for approximately 44% of total CO_2 emissions in 1987. This combined share is expected to fall to around 32% by 2005, with an absolute decline in the residential/commercial sector. However, this will still amount to about the same level of emissions as power generation (ca. 1.2 GtC), which will represent about 13% of total global CO_2 emissions in 2005.

The applications and economics of space/water heating and industrial process heat vary significantly from country to country. Table 21 illustrates these differences by examining the costs per unit of greenhouse gas saved for fuel-switching in heat generation for selected OECD countries.

In Canada, coal is a relatively cheap source of energy for industrial process heat, which makes switching to oil or gas expensive options. The most attractive options would be to switch to gas boilers, kilns and dryers (ca. US$40-120/tC equivalent saved). However, in the residential and commercial building sector, the substitution of gas for oil can lead to some reductions in greenhouse gas emissions with substantial economic gains (i.e. negative additional costs of around - US$750 to-US$2300/tC saved). In Germany, some reductions in greenhouse gas emissions from industrial process heat could be achieved through switching from coal to oil, but the cost would also be high (around US$300-470/tC saved). However, in Germany's residential and commercial sector, switching from coal to oil would produce CO_2 savings with economic gains (i.e. negative additional costs of around - US$145 to - US$160/tC saved). In Italy, the best options for both the industrial and residential/commercial sectors would be to switch from coal to gas, although the additional costs in the industrial sector would be high (around US$150-425/tC saved). The additional costs per greenhouse gas saved for the residential and commerical sectors would also be significant (ca. US$65-95/tC saved).

In Japan coal is a relatively cheap source of energy, which makes switching to oil or gas expensive options for industrial process heat. Gas is the cheapest option for reducing greenhouse gas emissions from boilers and dryers, (i.e., with additional costs of US$473/tC saved for gas boilers and US$635/tC saved for gas dryers). However, as a substitution option for coal cement kilns, oil is marginally less expensive per tonne of greenhouse gas emissions saved than gas. The additional costs of switching from oil to gas in the residential/commercial sector in Japan are high, from US$878 to US$2675/tC saved. In the UK, switching from coal to gas in both the industrial sector and the residential/commercial sector incurs substantially lower costs per unit of greenhouse gas saved (US$45-195/tC saved) than switching from coal to oil. In the USA, gas is again the least expensive substitution option. In the industrial sector costs of switching from coal to gas are low, ranging from US$124-340/tC saved. Switching from oil to gas in the residential sector is an

Table 21: COSTS OF REDUCING CO2 EQUIVALENT EMISSIONS OF GHG THROUGH FUEL SWITCHING IN HEAT PROCESSES, OECD (1989US$)

Technology	Real Generation Costs US$/MBtu 1/	Additional Costs Compared to Base US$/MBtu	GHG Intensity kgCO2/MBtu 2/	GHG Saved kgCO2/MBtu	Additional Costs of GHG Savings US$/tCO2	Additional Costs of GHG Savings US$/tC
CANADA						
1. Industrial						
Coal Boilers	2.94	BASE	139.88	BASE	BASE	BASE
Coal Cement Kilns	2.94	BASE	338.87	BASE	BASE	BASE
Coal Dryers	2.94	BASE	212.32	BASE	BASE	BASE
Oil Boilers	12.46	9.52	91.06	48.82	195.09	716.00
Oil Cement Kilns	12.46	9.52	295.54	43.33	219.82	806.73
Oil Dryers	12.46	9.52	146.19	66.13	144.03	528.58
Gas Boilers	4.33	1.39	57.08	82.80	15.62	57.33
Gas Cement Kilns	4.33	1.39	298.35	40.52	31.84	116.85
Gas Dryers	4.33	1.39	101.13	111.19	11.63	42.59
2. Residential/Commercial						
Oil Furnaces	12.35	BASE	96.29	BASE	BASE	BASE
Oil Boilers	12.35	BASE	107.02	BASE	BASE	BASE
Oil Heaters	12.35	BASE	89.98	BASE	BASE	BASE
Gas Furnaces	6.59	-5.76	87.09	9.20	-626.56	-2299.49
Gas Boilers	6.59	-5.76	79.02	28.00	-205.78	-755.22
Gas Heaters	6.59	-5.76	79.02	10.96	-525.71	-1929.34
GERMANY						
1. Industrial						
Coal Boilers	5.29	BASE	139.88	BASE	BASE	BASE
Coal Cement Kilns	5.29	BASE	338.87	BASE	BASE	BASE
Coal Dryers	5.29	BASE	212.32	BASE	BASE	BASE
Oil Boilers	10.82	5.53	91.06	48.82	113.20	415.46
Oil Cement Kilns	10.82	5.53	295.54	43.33	127.66	468.10
Oil Dryers	10.82	5.53	146.19	66.13	83.57	306.71
2. Residential/Commercial						
Coal Furnaces	13.88	BASE	131.77	BASE	BASE	BASE
Coal Boilers	13.88	BASE	145.61	BASE	BASE	BASE
Coal Heaters	13.88	BASE	126.83	BASE	BASE	BASE
Oil Furnaces	12.35	-1.53	96.29	35.48	-43.09	-158.15
Oil Boilers	12.35	-1.53	107.02	38.58	-39.52	-145.01
Oil Heaters	12.35	-1.53	89.92	36.91	-41.42	-152.03

Table 21: COSTS OF REDUCING CO2 EQUIVALENT EMISSIONS OF GHG THROUGH FUEL SWITCHING IN HEAT PROCESSES, OECD (1989US$)

Technology	Heat Generation Costs US$/MBtu 1/	Additional Costs Compared to Base US$/MBtu	GHG Intensity kgCO2/MBtu 2/	GHG Saved kgCO2/MBtu	Additional Costs of GHG Savings US$/tCO2	Additional Costs of GHG Savings US$/tC
ITALY						
1. Industrial						
Coal Boilers	2.70	BASE	139.88	BASE	BASE	BASE
Coal Cement Kilns	2.70	BASE	338.87	BASE	BASE	BASE
Coal Dryers	2.70	BASE	212.32	BASE	BASE	BASE
Oil Boilers	12.45	9.75	91.06	48.82	199.91	733.68
Oil Cement Kilns	12.46	9.76	395.54	43.33	225.25	826.65
Oil Dryers	12.46	9.76	146.19	66.13	147.58	541.63
Gas Boilers	7.41	4.70	57.08	82.80	56.80	208.49
Gas Cement Kilns	7.41	4.70	298.25	40.62	115.79	424.95
Gas Dryers	7.41	4.70	101.13	111.19	42.30	155.25
2. Residential/Commercial						
Coal Furnaces	9.76	BASE	131.77	BASE	BASE	BASE
Coal Boilers	9.76	BASE	145.61	BASE	BASE	BASE
Coal Heaters	9.76	BASE	126.89	BASE	BASE	BASE
Oil Furnaces	15.99	6.23	96.29	35.48	175.68	644.75
Oil Boilers	15.99	6.23	107.02	38.58	161.54	592.84
Oil Heaters	15.99	6.23	89.98	36.91	168.85	619.59
Gas Furnaces	10.94	1.18	87.09	44.67	26.32	96.61
Gas Boilers	10.94	1.18	79.02	66.58	17.65	64.82
Gas Heaters	10.94	1.18	79.02	47.87	24.56	90.15
JAPAN						
1. Industrial						
Coal Boilers	3.05	BASE	139.88	BASE	BASE	BASE
Coal Cement Kilns	3.06	BASE	338.87	BASE	BASE	BASE
Coal Dryers	3.06	BASE	212.32	BASE	BASE	BASE
Oil Boilers	16.35	13.29	91.06	48.82	272.17	998.86
Oil Cement Kilns	16.35	13.29	395.54	43.33	306.66	1125.44
Oil Dryers	16.35	13.29	146.19	66.13	200.93	737.40
Gas Boilers	17.40	14.35	57.08	82.80	173.27	635.89
Gas Cement Kilns	17.40	14.35	298.25	40.62	353.16	1296.03
Gas Dryers	17.40	14.35	101.13	111.19	129.01	473.53

Table 21: COSTS OF REDUCING CO2 EQUIVALENT EMISSIONS OF GHG THROUGH FUEL SWITCHING IN HEAT PROCESSES, OECD (1989US$)

Technology	Heat Generation Costs US$/MBtu 1/	Additional Costs Compared to Base US$/MBtu	GHG Intensity kgCO2/MBtu 2/	GHG Saved kgCO2/MBtu	Additional Costs of GHG Savings US$/tCO2	Additional Costs of GHG Savings US$/tC
2. Residential/Commercial						
Oil Furnaces	18.46	BASE	96.29	BASE	BASE	BASE
Oil Boilers	18.46	BASE	107.02	BASE	BASE	BASE
Oil Heaters	18.46	BASE	89.98	BASE	BASE	BASE
Gas Furnaces	25.16	6.70	87.09	9.20	728.83	2674.31
Gas Boilers	25.16	6.70	79.02	28.00	239.38	878.52
Gas Heaters	25.16	6.70	79.02	10.96	611.54	2244.34
UK						
1. Industrial						
Coal Boilers	3.88	BASE	139.88	BASE	BASE	BASE
Coal Cement Kilns	3.88	BASE	338.87	BASE	BASE	BASE
Coal Dryers	3.88	BASE	212.32	BASE	BASE	BASE
Oil Boilers	10.23	6.35	91.06	48.82	130.06	477.33
Oil Cement Kilns	10.23	6.35	295.54	43.33	146.55	537.52
Oil Dryers	10.23	6.35	146.19	66.13	96.02	352.39
Gas Boilers	5.29	1.41	57.08	82.80	17.04	62.55
Gas Cement Kilns	5.29	1.41	298.25	40.62	34.74	127.45
Gas Dryers	5.29	1.41	101.13	111.19	12.69	46.58
2. Residential/Commercial						
Coal Furnaces	7.17	BASE	131.77	BASE	BASE	BASE
Coal Boilers	7.17	BASE	145.61	BASE	BASE	BASE
Coal Heaters	7.17	BASE	126.89	BASE	BASE	BASE
Oil Furnaces	12.23	5.06	96.29	35.48	142.53	523.10
Oil Boilers	12.23	5.06	107.02	38.58	131.06	480.98
Oil Heaters	12.23	5.06	89.98	36.91	136.99	502.77
Gas Furnaces	9.52	2.35	87.09	44.67	52.65	193.21
Gas Boilers	9.52	2.35	79.02	66.58	35.32	129.53
Gas Heaters	9.52	2.35	79.02	47.87	49.13	180.30

Table 21: COSTS OF REDUCING CO2 EQUIVALENT EMISSIONS OF GHG THROUGH FUEL SWITCHING IN HEAT PROCESSES, OECD (1989US$)

Technology	Heat Generation Costs US$/MBtu 1/	Additional Costs Compared to Base US$/MBtu	GHG Intensity kgCO2/MBtu 2/	GHG Saved kgCO2/MBtu	Additional Costs of GHG Savings US$/tCO2	Additional Costs of GHG Savings US$/tC
USA						
1. Industrial						
Coal Boilers	2.47	BASE	139.88	BASE	BASE	BASE
Coal Cement Kilns	2.47	BASE	338.87	BASE	BASE	BASE
Coal Dryers	2.47	BASE	212.32	BASE	BASE	BASE
Oil Boilers	10.58	8.11	91.06	48.82	166.19	609.92
Oil Cement Kilns	10.58	8.11	295.54	43.33	187.25	687.22
Oil Dryers	10.58	8.11	146.19	66.13	122.69	450.27
Gas Boilers	6.23	3.76	57.08	82.80	45.45	166.79
Gas Cement Kilns	6.23	3.76	298.25	40.62	92.63	339.96
Gas Dryers	6.23	3.76	101.13	111.19	33.84	124.20
2. Residential/Commercial						
Oil Furnaces	13.05	BASE	96.29	BASE	BASE	BASE
Oil Boilers	13.05	BASE	107.02	BASE	BASE	BASE
Oil Heaters	13.05	BASE	89.98	BASE	BASE	BASE
Gas Furnaces	9.17	-3.88	87.09	9.20	-421.95	-1548.57
Gas Boilers	9.17	-3.88	79.02	28.00	-138.59	-508.63
Gas Heaters	9.17	-3.88	79.02	10.96	-354.05	-1299.35

Notes: 1/ Heat costs taken from OECD/IEA. "Renewable Sources of Energy". OECD. Paris. March 1987. Table 42.

2/ Industrial emission factors taken from S. Piccot, J. Buzun and H.C. Frey. "Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NOx, N2O, CH4, CO and CO2". United States Environmental Protection Agency, Washington DC. May 1990. Residental emission factors taken from IEA/OECD. "Greenhouse Gas Emissions: The Energy Dimension". IEA. Paris. 1990. Table E-1.2.3.

especially attractive option, as gas is both a cheaper and cleaner means of generating heat, with negative additional costs of reducing CO_2 emissions from -US$508 to -US$1548/tC saved.

Other substitution options for greenhouse gas emissions from the industrial and residential/commercial sectors in the OECD would come from applications of renewable energy and combined heat and power. Specific examples from selected OECD countries are discussed below.

United States

In the USA, CO_2 emissions from the residential/commercial and industrial sector accounted for a third of total emissions in 1985 (0.81 GtC/year from a total of 1.25 GtC/year). This share is expected to fall in absolute and relative terms by 2005, but still remain highly significant with CO_2 emissions of 0.50 GtC/annum.[41] The renewable energy alternatives to conventional fossil fuels for industrial process heat include biomass fuels, geothermal systems and solar thermal energy sources (see Table 22). As wood-fired boilers actually emit more greenhouse gases per unit of heat generated than convential coal boilers, they are not considered further as a means of reducing greenhouse gases. However, as has been noted earlier, this level of emissions may be an overestimate of the total contribution of burning wood fuels to the levels of greenhouse gases in the atmosphere, due to the uptake of carbon during biomass growth.

Of the replacement renewable options for industrial heat processes in Table 22, geothermal technologies currently incur relatively low additional costs for reducing greenhouse gas emissions (i.e., minimum costs from US$41-100/tC equivalent saved). These costs are expected to fall further in the future. However, applications of geothermal energy to industrial heat processes are limited because sufficient resource sites may not be located near main industrial demand centres. At present, solar thermal industrial process heat is an expensive substitute for conventional coal technologies, with costs ranging from US$190 to US$725/tC equivalent saved. However, future applications of solar thermal power to industrial processes may benefit from developments in parabolic dishes and solar trough systems for solar thermal electricity generation. The main constraints on industrial applications of solar thermal energy remain the need for high direct insolation, storage capacity for photolytic detoxification and durable collectors that track the sun.[42]

In the US residential/commercial sector reduction of greenhouse gases by geothermal energy is currently economically attractive.

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[41] J.A. Edmunds et.al, op.cit.

[42] Idaho National Engineering Laboratory et al., op. cit., Appendix H.

Table 22: COSTS OF SUBSTITUTING FOR GHG EMISSIONS IN HEAT PROCESSES. USA (1989 US$)

Technology	Heat Generation Costs US$/MBtu		Additional Costs Compared to Base US$/MBtu		GHG Intensity kgCO2/MBtu		GHG Saved kgCO2/MBtu		Additional Costs of GHG Savings US$/tCO2		Additional Costs of GHG Savings US$/tC	
1. Industrial												
Coal Boilers	2.47		BASE		139.88		BASE		BASE		BASE	
Coal Cement Kilns	2.47		BASE		338.87		BASE		BASE		BASE	
Coal Dryers	2.47		BASE		212.32		BASE		BASE		BASE	
REDUCTION - BIOMASS FUELS												
	min	max	min	max	min	max	min	max	min	max	min	max
Wood-Fired Boilers	12.84	16.50	10.37	14.03	145.92	145.92	-6.04	-6.04	NA	NA	NA	NA
REPLACEMENT - RENEWABLES												
Geothermal (c)	min	max	min	max	min	max	min	max	min	max	min	max
- boilers	6.26	10.43	3.79	7.96	0.00	0.00	139.88	139.88	27.08	56.90	99.37	208.82
- cement kilns	6.26	10.43	3.79	7.96	0.00	0.00	338.87	338.87	11.18	23.49	41.02	86.19
- dryers	6.26	10.43	3.79	7.96	0.00	0.00	212.32	212.32	17.84	37.48	65.47	137.57
Geothermal (f)	min	max	min	max	min	max	min	max	min	max	min	max
- boilers	3.86	8.34	1.39	5.87	0.00	0.00	139.88	139.88	9.93	41.99	36.44	154.09
- cement kilns	3.86	8.34	1.39	5.87	0.00	0.00	338.87	338.87	4.10	17.33	15.04	63.61
- dryers	3.86	8.34	1.39	5.87	0.00	0.00	212.32	212.32	6.54	27.66	24.01	101.52
Solar thermal IPH	min	max	min	max	min	max	min	max	min	max	min	max
- boilers	20.00	30.00	17.53	27.53	0.00	0.00	139.88	139.88	125.33	196.83	459.94	722.11
- cement kilns	20.00	30.00	17.53	27.53	0.00	0.00	338.87	338.87	51.73	81.24	189.86	298.16
- dryers	20.00	30.00	17.53	27.53	0.00	0.00	212.32	212.32	82.57	129.67	303.02	475.87

Table 22: COSTS OF SUBSTITUTING FOR GHG EMISSIONS IN HEAT PROCESSES, USA (1989 US$)

Technology	Heat Generation Costs US$/MBtu		Additional Costs Compared to Base US$/MBtu		GHG Intensity kgCO2/MBtu		GHG Saved kgCO2/MBtu		Additional Costs of GHG Savings US$/tCO2		Additional Costs of GHG Savings US$/tC	
2. Residential/Commercial												
Oil Furnaces	13.05		BASE		96.29		BASE		BASE		BASE	
Oil Boilers	13.05		BASE		107.02		BASE		BASE		BASE	
Oil Heaters	13.05		BASE		89.98		BASE		BASE		BASE	
REPLACEMENT - RENEWABLES												
Geothermal (c)	min	max	min	max	min	max	min	max	min	max	min	max
- furnaces	6.26	10.43	-6.80	-2.62	0.00	0.00	96.29	96.29	-70.58	-27.26	-259.02	-100.04
- boilers	6.26	10.43	-6.80	-2.62	0.00	0.00	107.02	107.02	-63.50	-24.52	-233.04	-90.00
- heaters	6.26	10.43	-6.80	-2.62	0.00	0.00	89.98	89.98	-75.52	-29.17	-277.17	-107.05
Geothermal (f)	min	max	min	max	min	max	min	max	min	max	min	max
- furnaces	3.86	8.34	-9.19	-4.71	0.00	0.00	96.29	96.29	-95.49	-48.92	-350.43	-179.53
- boilers	3.86	8.34	-9.19	-4.71	0.00	0.00	107.02	107.02	-85.91	-44.01	-315.29	-161.52
- heaters	3.86	8.34	-9.19	-4.71	0.00	0.00	89.98	89.98	-102.18	-52.35	-374.99	-192.11
Active solar (c)	min	max	min	max	min	max	min	max	min	max	min	max
- space/water heat	15.12	41.71	2.07	28.66	0.00	0.00	89.98	89.98	22.98	318.49	84.34	1168.87
- cooling	17.21	41.71	4.15	28.66	0.00	0.00	89.98	89.98	46.16	318.49	169.40	1168.87
Active solar (f)	min	max	min	max	min	max	min	max	min	max	min	max
- space/water heat	5.63	11.47	-7.42	-1.58	0.00	0.00	89.98	89.98	-82.48	-17.58	-302.69	-64.52
- cooling	5.63	13.03	-7.42	-0.02	0.00	0.00	89.98	89.98	-82.48	-0.20	-302.69	-0.72
Passive solar	min	max	min	max	min	max	min	max	min	max	min	max
- heat/cooling	0.00	10.43	-13.05	-2.62	0.00	0.00	89.98	89.98	-145.06	-29.17	-532.35	-107.05

Notes: c = current, f = future, IPH = industrial process heat.

Sources: Table 21; S. Piccot, J. Buzun and H.C. Frey, Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NOx, N2O, CH4, CO and CO2, Prepared for US Environmental Protection Agency, Washington DC, May 1990; Idaho National Engineering Laboratory et al., The Potential of Renewable Energy: An Interlaboratory White Paper, Solar Energy Research Institute Golden, Colorado, March 1990; and N. Rader et al., Power Surge: The Status and Near Term Potential of Renewable Energy Technologies, Public Citizen, Washington DC, May 1989.

Switching from oil to geothermal heat resources leads to substantial savings, that is, negative additional costs from- US$90 to - US$280/tC saved. Stationary thermal use of geothermal in the residential/commercial building sector shows much promise; however, reservoir temperatures and flow rates, as well as depths of the resource, vary greatly among geographic locations, thus affecting regional costs. Greater development is expected initially in the Northeast, followed by the West, with the South and North Central regions providing only minimal contributions by 2030. A significant proportion of this development is expected to be heat pumps, with an annual increase of 10-18% in their use during the next 20 years.[43]

Around 37% of total US energy consumption is used in residential and commercial buildings. Because solar building technologies have the potential to provide up to 80% of typical new building heating, cooling and lighting requirements, the potential to reduce energy use in this area is enormous.[44] There are two types of solar building technologies: passive and active. Passive solar systems rely entirely on the design of the building structure, whilst active solar systems make use of mechanical components, such as pumps and fans, to tap or regulate the sun's energy.

Some passive solar designs can be incorporated into building design at little or no added cost. The negative additional costs of replacing oil heating/cooling systems by passive solar heating/cooling technologies range from - US$533 to - US$107/tC equivalent saved (see Table 22). However, passive heating technologies do face some constraints, including greatest heat requirements in northern latitudes and winter months when insolation is lowest, and limited availability of south-facing potential glazing area. Further research into advanced windows with reduced thermal loss, improved ventilation, incorporating thermal storage into building materials and integrating passive with active solar systems may improve the use of passive solar in residential/commercial buildings in the future.[45]

Active solar heating and cooling systems use pumps or fans for heat distribution and solar collectors that are distinct from the building structure. Currently, these are more expensive technologies for heating and cooling than conventional oil fired systems in residential/commercial buildings. Table 22 indicates that the minimum additional costs of reducing greenhouse gas emissions for space water heating is US$84/tC equivalent saved, and for cooling US$169/tC saved. However, the maximum costs of these systems are considerably greater, US$1168/tC saved, reflecting the wide range in heat/cooling generation costs of active solar systems.

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[43] _Ibid_., Appendix C.

[44] N. Rader _et.al_. _op.cit._.

[45] Idaho National Engineering Laboratory _et.al_, _op.cit._.

Active heating shares similar constraints to passive heating, in that the greatest heat requirement is in northern locations and winter months where insolation levels are lowest. Active solar technology also suffers high heat losses when the load is the greatest. Active cooling systems are constrained by the need for cooling subsystems and higher operational temperatures that reduce collector efficiency, and by competition from efficient conventional chillers/heat pumps. Improving construction materials, such as glazers, absorbers and desiccant materials, and developing central storage systems and integrated heating and cooling systems will make active solar systems more attractive.[46] As shown in Table 22, active solar heat/cooling systems are expected to be economically competitive with conventional oil fired systems in the future, with negative additional costs ranging from - US$0.72 to - US$302.69/tC equivalent removed.

United Kingdom

In the UK, CO_2 emissions from the domestic and industrial sector amounted to 65Mt of carbon in 1987, that is 40% of total UK emissions. Emissions from the industrial sector have declined from over 90MtC in 1960 to 40Mt in 1987, resulting from fuel switching, a decline in the total manufacturing output of 'heavy industry', and marked structural changes and efficiency gains elsewhere in the sector.[47] In contrast, emissions of CO_2 from the domestic sector have remained remarkably static over the same period. However, the constancy of the level of emissions has hidden large changes in structure and fuel use. Whilst the number of open coal fires has declined substantially, central heating systems are now commonplace in most homes in the UK. Although the widespread switching from oil to gas in residential/commercial heating has lowered the levels of CO_2 emissions from heating systems, this has been offset by improvements in heating and comfort standards, and increases in the number of households.

Substitution options for industrial and residential/commercial heat processes in the UK are given in Table 23. Combined heat and power (CHP) systems can make substantial savings in fuel use compared to the usual combination of boiler plant for heating and conventional thermal generation for electricity. The thermal output that is harnessed from an electricity generating plant in a CHP can replace fuels that would otherwise be consumed in heat-only boilers. When allowance is made for heat recovery, CHP systems can run at an efficiency of at least 80% given good utilization of the thermal output. Conventional coal-fired electrical power stations currently operate at 33% efficiency. The costs and emission levels of small-scale combined heat and power systems (40-60 kW capacities) are compared to conventional systems in Table 23, although viable installations could range

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[46] Idaho National Engineering Laboratory, et. al, op. cit..

[47] UK Department of Energy, op.cit..

Table 23: COSTS OF SUBSTITUTING FOR CO2 EQUIVALENT EMISSIONS OF GHG IN HEAT PROCESSES, UK (1989 UK£)

1. Power/Heat	Generation Costs UKp/kWh	Additional Costs Compared to Base UKp/kWh	GHG Intensity tCO2/GWh 1/	GHG Saved tCO2/GWh	Additional Costs of GHG Savings UK£/tCO2	Additional Costs of GHG Savings UK£/tC
Coal power	4.75	BASE	1362.73	BASE	BASE	BASE
Coal/oil boiler	--	BASE	435.38	BASE	BASE	BASE
Gas boiler	--	BASE	238.49	BASE	BASE	BASE
REDUCTION - CHP						
Small-scale CHP 2/	3.01	-1.73	812.55	1420.94	-12.20	-44.77
Small-scale CHP 3/	3.01	-1.73	812.55	1027.17	-16.87	-61.93

2. Res./Com.	Generation Costs UK£/MBtu	Additional Costs Compared to Base UK£/MBtu	GHG Intensity kgCO2/MBtu	GHG Saved kgCO2/MBtu	Additional Costs of GHG Savings UK£/tCO2	Additional Costs of GHG Savings UK£/tC
Coal Heaters	7.17	BASE	126.89	BASE	BASE	BASE
REPLACEMENT - PASSIVE SOLAR						
Orientation	0.00	-7.17	0.00	126.89	-56.53	-207.46
South windows	1.57	-5.60	0.00	126.89	-44.13	-161.95
Roof collector/fan	9.05	1.87	0.00	126.89	14.77	54.20
S. windows (max.)	10.75	3.58	0.00	126.89	28.20	103.50
Conservatory	14.82	7.64	0.00	126.89	60.23	221.06
Double-glazed wall	20.72	13.54	0.00	126.89	106.73	391.73

Notes:
1/ Emissions from generation only and excludes N2O.
2/ Replaces coal power plus heat from coal/oil boilers.
3/ Replaces coal power plus heat from gas boilers.

Sources: R.D. Evans, Environmental and Economic Implications of Small Scale CHP, Energy and Environment Paper 3, ETSU, Harwell Laboratory, Oxford, March 1990; IEA/OECD, Renewable Sources of Energy, IEA, Paris, 1987; and Table 13.

from 15 kW in small commercial buildings to over 50 MW on large industrial sites.

Gas fueled combined heat and power stations save 1027tCO_2 equivalent emissions per GWh when replacing coal powered electricity generation and gas boilers, and 1420tCO_2/GWh when replacing coal generated electricity with coal or oil boilers. The additional costs of reducing greenhouse gas emissions by this substitution option are negative, ranging from - UK£45 to-UK£62/tC equivalent emissions saved.

In the residential/commercial sectors in the UK passive solar heat systems compete with conventional coal heaters. There is a wide variety of passive solar technologies that are available, some of which are less expensive than coal heaters, others that are more costly. Of the cheaper passive solar options, building orientation and south facing windows incur negative additional costs for reducing greenhouse gas emissions, from - UK£162 to-UK£207/tC equivalent saved. The most expensive option is double glazed walls, with additional costs of UK£392/tC saved.

Developing Countries

As in the case of electricity generation, domestic/commercial and industrial use of space and water heating/cooling in developing countries will continue to rise in the future. The ability of developing countries to reduce these emissions from replacement and reduction technologies will again depend on the transfer of technologies from more developed countries, domestic and international factors, including the price of oil, government intervention in fuel prices and specific site conditions.

China is distinct among developing countries in that it has significant heating loads over much of the country. Total consumption of energy in China has been growing rapidly from 293 million tonnes of coal equivalent (mtce) in 1970 to 845 mtce in 1987 and is expected to increase to between 1.3-2.4 billion tce by 2000.[40] China is currently the third largest energy consuming country in the world and up to 75% of its primary energy requirement is derived from coal. Around 60% of primary energy in China is consumed by the industrial sector. At present, space heating use, excluding that for hotels and offices catering for foreigners, is constrained by mandated coal allocations resulting in partially heated buildings with indoor temperatures significantly below design conditions.

Inefficiencies are also caused by a pricing structure that does not reflect the true costs of energy production in China. Distortions in energy pricing may impact severely upon the choice

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[40] Yu Joe Huang, "Potentials For and Barriers to Building Energy Conservation in China", Contemporary Policy Issues, Vol. VIII, July 1990, pp.1-18.

of substitution options in heat generation. For example, switching from conventional boiler generation in Beijing to cogeneration or the use of clean coal in boilers reduces annual coal consumption by 110,000 and 74, 130 tonnes respectively. The additional costs per kg of greenhouse gas emissions reduced range from Yuan (Y) - 5.67 to Y4.78/kgC equivalent saved for cogeneration and around Y31/kgC equivalent saved for clean coal (The official exchange rate in 1989 was Y3.73 = US$1.00).[49] However, large government subsidies for coal consumption are making both substitution options less financially attractive, although they also hide the opportunity costs of the electricity output forgone from cogeneration. For example, in 1984 electricity prices in China were only 58% of the long-run marginal cost of electricity supply.[50]

A recent study of the potential for energy conservation in residential/commercial buildings in China also includes estimates of some 'passive solar' technologies in terms of the cost of coal conservation (the ratio of the annualised cost of investment to amount of coal saved annually).[51] For insulating the north walls of buildings this cost was Yuan (Y) 1.40/tonne of coal saved, for insulating south walls the cost was Y4.99/tonne saved and for double glazing Y2.71/tonne saved. Translated into tonnes of carbon saved, the costs of these substitution options amount to Y2.12/tC and Y7.56/tC saved for north and south wall insulation respectively, and Y4.11/tC saved for double glazing.

Biomass heat gasifiers are used widely for industrial and commercial process heat applications in Brazil, Southeast Asia and the South Pacific. In large scale industrial processes biomass heat gasifiers (100kW-10MW capacity) are substitutes for fuel oil to provide process heat for drying (e.g., tea, grain, lumber), manufacturing glass, tiles and bricks, producing cement, processing food and so on. Smaller biomass heat gasifiers are used for crop drying, baking and similar applications. These systems are extremely sensitive to oil prices, wood fuel prices and gasifier capital cost estimates. For example, with a drop in fuel oil prices from US$30 to US$15 per barrel (bbl) (1986 prices) the break even fuel wood price for a moderately priced heat gasifier system (US$ 25000/GJ/hr) drops from US$ 30/tonne to

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[49] Derived from estimates by W.O. Spofford, "Least-Cost Alternative of Space Heating Alternatives in Beijing: The Case of Cogeneration at Shijingshan Power Plant", Working draft, Resources for the Future, Washington D.C., USA, March 1990.

[50] M. Kosmo, "Commercial Energy Subsidies in Developing Countries: Opportunity for Reform", Energy Policy, June 1989, pp 244-253.

[51] Yu Joe Huang, op.cit.

near zero.[52] The economic feasibility of large scale biomass gasifiers tends to be more constrained by high oil, biomass and capital costs than the smaller, remote, rural systems.

Active residential and small commercial solar water heating systems operate in many developing countries. Large industrial applications of solar water heating are more constrained by economic costs, and are highly sensitive to the price of oil based substitute systems. For example, Kenyan residential solar heating installations remained economically attractive even when fuel oil prices fell from US¢5.5/kWh to US¢4.4/kWh (1986 prices) between 1985 and 1986.[53] However, if the economic price of displaced fuel oil remains above US$ 150/tonne of oil equivalent (toe), (i.e., US$ 25/bbl fuel oil, 4¢/kWh or US$50/mt wood - 1986 prices), existing solar water heaters in high insolation areas may be cost-effective for industrial process heat in Kenya. As the price of fuel imports have dropped well below US$ 25/bbl many industrial solar water heating systems are no longer viable alternatives to oil based heating systems. Given that in Kenya electrical power costs range from US¢3 to US¢10/kWh for hydropower to US¢5-US¢20/kWh for thermal generation, solar water heating systems in high insolation areas are often more economical than conventional electric systems for heating water. Similar factors are likely to affect solar cooling systems for buildings in the industrial, commercial and residential sectors of developing countries.

4.1.3 Transport

There are essentially three options available for controlling greenhouse gas emissions from fossil fuel use in transportation:

i. improvements in the fuel efficiency of vehicles and transport systems;
ii. switching to more energy efficient means of travel; and,
iii. converting to alternative fuels that produce little or no greenhouse gases.

This paper will consider only the third option of fuel substitution. Although transportation contributes only 16% of global CO_2 emissions, emissions of NOx and CO from this sector are highly significant. On a world scale, transport accounts for 42% of total NO_x emissions and 60% of total CO emissions (see Table 8). Emissions from the transport sector in OECD countries are even more significant, and account for as much as 22% of CO_2 emissions, 52% of NO_x emissions and 90% of CO emissions (see Table 9). Although the share of emissions from the transport sector in developing countries is currently less significant, they are expected to grow rapidly in future years.

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[52] E. Terrado, M. Mendis and K. Fitzgerald, "Impact of Lower Oil Prices on Renewable Energy Technologies", Industry and Energy Department Working Paper, Energy Series No. 5, The World Bank, Washington D.C., USA, May 1989.

[53] _ibid._.

The clean fuel substitution options for replacing greenhouse emissions from the transport sector include biomass-based fuels (e.g., ethanol, methanol, gasoline), hydrogen (H_2) and electricity from non-fossil fuel sources. Although progress has been made to develop cost-effective clean fuels, technological and financial constraints often undermine their economic attractiveness. For example, electric cars are currently constrained by their limited range and dependence upon fossil fuel generated electrical power. The remaining alternative fuels are reduction substitutes; that is, they reduce rather than replace greenhouse gas emissions per unit of energy substituted.

Table 24 compares the level of CO_2 equivalent greenhouse gas emissions from gasoline and diesel from crude oil with clean-fuel and other substitutes. The effect of efficiency improvements in vehicles is also included as a benchmark. In some cases, such as switching from gasoline to methanol derived from natural gas, the reduction in emissions may be relatively small (3%). In comparison, methanol derived from coal almost doubles CO_2 equivalent emissions. Similarly, electric vehicles from the current fossil fuel power mix would only marginally reduce emissions. Although compressed natural gas (CNG) and liquified natural gas (LNG) could lead to 19% and 15% reductions respectively in greenhouse gas emissions when substituted for gasoline, problems of fuel storage as well as the limited range of natural gas fueled vehicles constrain their potential.

Hydrogen and electric vehicles from non-fossil fuel sources are a long-term substitution option. Problems with hydrogen include the weight of storage tanks, which are currently 15-20 times the weight of the stored hydrogen, complications in production from nuclear and photovoltaic sources and difficulties with leakage and safety. However, a study in the United States has shown that, if the production cost of amorphous silicon PV modules are reduced from their current cost of US1.50-1.60 per peak Watt (W_p) to US\$0.2-0.4/W_p, then PV hydrogen could become comparable in cost to other liquid synthetic fuels. The levelized life-cycle costs for owning and operating cars on PV hydrogen compared to other fuels also show that, assuming storage and range limits are solved, PV hydrogen cars could become an economic option.[54]

Electric powered vehicles are constrained by range limitations and development of sufficiently light, compact and powerful batteries at a low cost. The most promising option in the near term is a 'hybrid' car, which combines an electric engine with a conventional internal combustion engine. The electric engine could be used in short trips in urban areas, as it is more

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[54] J.M. Ogden and R.H. Williams, "New Prospects for Solar Hydrogen Energy: Implications of Advances in Thin-Film Solar Cell Technology", IEA/OECD Expert Seminar on Energy Technologies to Reduce Emissions of Greenhouse Gases, OECD, Paris, 12-14 April 1989.

Table 24

Greenhouse Gas Emissions for Alternative Fuels for Vehicles

FUEL/FEEDSTOCK	TOTAL CO_2-Equivalent Emissions (GT/yr)	%CHANGE per Mile, Relative to Petroleum
Hydrogen, non-fossil power	0	- 100
EVs, non-fossil power 1/	0	- 100
Methanol from biomass	0	- 100
Ethanol from biomass	0	- 100
Gasoline from biomass	0	- 100
Double Fleet Efficiency	0.668	- 50
CNG from natural gas 2/	1.081	- 19
LNG from natural gas 3/	1.135	- 15
Methanol from natural gas	1.293	- 3
EVs, current power mix	NA 4/	- 1
Gasoline/diesel from crude oil	1.336	BASE
Methanol from coal	2.639	+ 98
Liquid Hydrogen from coal	3.240	+ 143

Notes: 1/ EV = electric vehicles
2/ CNG = compressed natural gas
3/ LNG = liquified natural gas
4/ Depends upon the level penetration assumed possible for electric vehicles.

Total CO_2 equivalent emissions include production, distribution and end-use emissions of the fuels. Greenhouse gas emissions included in calculation are CO_2, CH_4 and N_2O. The CO_2 equivalent weighting used for CH_4 is 11.6 and for N_2O is 175 (75 year time horizon assumed).

Source: D. Sperling and M.A. DeLuchi, "Transportation Energy Strategies and the Greenhouse Effect", IEA/OECD Expert Seminar on Energy Technologies for Reducing Emissions of Greenhouse Gases, OECD, Paris, 12-14 April 1989.

efficient and less polluting, and the conventional engine could be used for longer journeys and recharging.[55]
Considerable attention has been given to biofuels - the liquid fuels for transportation produced from biomass feedstocks - as the most attractive clean fuel substitution option in the near term. Ethanol can be produced from sugar, starch or cellulose feedstocks (wood, energy crops and municipal and other wastes). Methanol is made from biomass by first gasifying the feedstock to form a 'syngas' mixture of CO, H_2, CO_2, higher hydrocarbons and tar. Gasoline can also be produced from biomass by either producing first an intermediate biocrude liquid product or by isolating the hydrocarbon portion of oils derived from rape seed, sunflowers, oil palms or even aquatic plants. In the United States, it is estimated that through intensive research and development biofuels could increase their present contribution of 0.07 quads (1 quad = 10^9 x MBtus) to 2.4 quads in 2010 (over 2% of total US energy demand) and to 8.4 quads in 2030 (almost 6% of total energy demand).[56]

However, given current relative fuel prices, wide-scale adoption of biofuels is still limited. Unless the recent oil price rises are sustained, environmental standards are changed, biofuel subsidies and/or petroleum taxes imposed, or significant cost reductions occur for biofuel technologies, then petroleum gasoline and diesel fuel will remain the only transport fuels available on a large scale and at low prices. Table 25 indicates the current competitiveness of biofuels in the United States, the United Kingdom and West Germany. In none of the countries are the prices of these fuels comparable with those of petroleum gasoline.

However, perhaps the best lessons to date on the economics of biofuel development comes from Brazil's sugarcane-to-ethanol programme. Since 1975, Brazil has been committed to increasing its use of ethanol as an extender for petoleum derived gasoline. Ethanol production costs in the mid 1980s were estimated to be US$0.18 to US$0.48 per litre. However, these costs have been highly subsidised in the past - through a guaranteed floor price of US$0.25 per litre, by providing large ethanol investment loans at negative real interest rates and by subsidising the industry's capital costs. The rationale for subsidies stems from low international prices for sugar, high unemployment in agricultural areas and vulnerability to world oil price fluctuations. Although the ethanol programme has enabled Brazil's sugarcane industry to expand and strengthen, the programme still provides only 3% of agricultural jobs in Brazil, mainly through temporary and seasonal labour demand. Moreover, domestic price distortions bias the competitiveness of the ethanol programme. If the savings from the recent declines in world oil prices were passed on to the Brazilian economy, the ethanol programme would be

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[55] OECD/IEA Expert Panel on Low Consumption/Low Emission Automobile, Summary Report, OECD, Paris, 14-15 February 1990.

[56] Idaho National Engineering Laboratory <u>et al.</u>, <u>op. cit.</u>

Table 25

Gasoline and Biofuel Prices in US, UK and West Germany

1. United States

Fuel Type	US$ per US Gallon
Gasoline, from biomass	1.60
Ethanol, from corn	1.28
Ethanol, from cellulose	1.25 - 1.35
Methanol, from biomass	0.60 - 1.70
Gasoline, from petroleum	0.59

2. United Kingdom

Fuel Type	UK£ per Litre
Ethanol, from beet	0.39
Ethanol, from wheat	0.28
Gasoline, from petroleum	0.09

3. West Germany

Fuel Type	DM per kWh
Gasoline, from rape seed	0.20 - 0.22
Ethanol, from biomass	0.21
Methanol, from natural gas	0.07
Gasoline, from petroleum	0.06

Notes: All prices are ex-refinery.

Source: Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories and Solar Energy Research Institute, The Potential of Renewable Energy: An Interlaboratory White Paper, Solar Energy Research Institute, Golden, Colorado, March 1990, Appendix B; J.E. Marrow, J. Coombs and E.W. Lees, An Assessment of Bio-Ethanol as a Transport Fuel in the UK, Energy Technology Support Unit, HMSO, October, 1987; and, G. Klob, G. Eickhoff, M. Kleemann, N. Krzikalla, M. Pohlmann and H.J. Wagner, "CO_2 Reduction Potential Through Rational Energy Utilization and Use of Renewable Sources in the Federal Republic of Germany", KFA, Julich, West Germany, May 1989.

economically infeasible on a production cost basis at 1987 oil prices.[57]

Based on US data, it is possible to indicate the cost-effectiveness of biofuels and PV hydrogen as substitutes for petroleum derived gasoline (see Table 26). Of the three replacement biofuel options, ethanol is currently the most expensive substitute for gasoline and incurs additional costs of US$ 350/tC equivalent of greenhouse gas emissions saved. Gasoline derived from cellulose feedstock is marginally less expensive than ethanol, and in turn methanol is marginally less expensive than gasoline. However, the costs of ethanol and gasoline are projected to fall more rapidly in the future than the costs of methane. The future additional costs of saving greenhouse gas emissions may range from a maximum of US$ 73/tC equivalent for methane to - US$42 and - US$ 50/tC equivalent greenhouse gases saved by ethanol and biomass gasoline respectively. The latter two options, at least in the United States, may be the most attractive.

A major constraint for biofuels is that the economic reliability of feedstock production must be demonstrated if farmers and land owners are to commit large land areas to long-term production of energy crops. Monoculture herbaceous and woody energy crops must be produced on a large scale over an extended time to demonstrate the economic viability of several species under a variety of climatic conditions, exposure to pests and diseases and responsivenes to inputs. In countries where there is surplus arable land, such as the United States, the opportunity costs of diverting land to biofuel feedstock production may be low. However, in the more densely populated European economies, such as the UK, these costs may increase. In developing countries, the impact on agricultural production, particularly food, must be examined. For example, even in land-abundant Brazil the price incentives for the sugarcane ethanol programme may have displaced food production.[58] Also, the net impact of biofuel feedstocks on greenhouse gas emissions will depend on the previous land use. If biofuel crops replace a forest, the difference between the amount of forest carbon released from forest clearance and the proportionately smaller amount of carbon fixing crops results in a one-time net emission of CO_2. In addition, there would be a release of CO_2 from the cleared soil, and a large release of N_2O.[59] On the other hand, the national economic benefits of

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[57] M.M. Gowen, <u>op. cit.</u> Despite the poor economics suggested by the Brazilian ethanol programme, other developing countries such as Argentina, Costa Rica, Kenya, Malawi, Swaziland and Zimbabwe have also committed themselves to ethanol production.

[58] M. Gowen, <u>op. cit.</u>

[59] D. Sperling and M.A. DeLuchi, "Transportation Energy Strategies and the Greenhouse Effect", IEA/OECD Expert Seminar on Energy Technologies for Reducing Emissions of Greenhouse Gases, OECD, Paris, 12-14 April 1989.

Table 26: COSTS OF SUBSTITUTING FOR CO2 EQUIVALENT EMISSIONS OF GHG IN TRANSPORT FUELS, US (1989 US$)

FUEL TYPE	Fuel Costs US$/MBtu		Additional Costs Compared to Base US$/MBtu		GHG intensity kgCO2/MBtu		GHG Saved kgCO2/MBtu		Additional Costs of GHG Savings US$/tCO2		Additional Costs of GHG Savings US$/tC	
Gasoline, petroleum	8.66		BASE		99.28		BASE		BASE		BASE	
REPLACEMENT - BIOFUELS 1/												
	min	max	min	max	min	max	min	max	min	max	min	max
Ethanol (c)	18.15		9.49		0.00		99.28		95.58		350.78	
Ethanol (f)	7.51	10.43	-1.15	1.77	0.00	0.00	99.28	99.26	-11.55	17.86	-42.40	65.53
Methanol (c)	14.39		5.74		0.00		99.28		57.77		212.01	
Methanol (f)	10.64		1.98		0.00		99.28		19.96		73.24	
Gasoline (c)	16.16		7.51		0.00		99.26		75.62		277.54	
Gasoline (f)	7.30	8.86	-1.36	0.21	0.00	0.00	99.28	99.28	-13.65	2.10	-50.11	7.71
REPLACEMENT - PV HYDROGEN 2/												
	min	max	min	max	min	max	min	max	min	max	min	max
Fuel (f)	9.61	14.78	0.95	6.13	0.00	0.00	99.26	99.28	9.60	61.71	35.23	226.47

Notes: c = current (1990) f = future (2010)

1/ Idaho National Engineering Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Sandia National Laboratories, Solar Energy Research Institute, The Potenetial of Renewable Energy: An Interlaboratory White Paper, Solar Energy Research Institute, Golden, Colorado, USA. March 1990, Appendix B.

2/ S. Piccot, J.A. Buzun and H.C. Frey, Emissions and Cost Estimates for Globally Significant Anthropogenic Combustion Sources of NOx, N2O, CH4, CO and CO2, Prepared for US Environmental Protection Agency, Washington DC, May 1990.

expanded biofuel use include the development of new domestic fuel and agro-industry markets, more efficient utilization of basic commodity byproduct markets, rural employment generation and foreign exchange savings through imported fuel displacement.

The future substitution of PV hydrogen for gasoline could be a relatively cost-effective way of reducing greenhouse gas emissions, with additional costs ranging from US$ 35-61/tC saved (see Table 26). As noted above, however, these low additional costs require substantial breakthroughs on the costs of this substitute technology.

4.1.4 Switching to a Hydrogen/Methane Economy

The role of advanced non-fossil fuel technologies, such as PV hydrogen, as the means for controlling greenhouse gas emissions raises long-term issues over the evolution of energy-economic systems. Such technologies may be the beginning of a 'new wave' of fundamental changes in the basic energy sources we use.

For example, Figure 3 indicates that the long-term evolution of the world energy system has been away from low ratio hydrogen to carbon energy sources, such as wood, coal and oil, towards an increasing ratio of hydrogen to carbon energy sources, such as natural gas (methane). From this perspective, methane could be the transitional hydrocarbon. Future progress may focus on the production of hydrogen from lower carbon content fuels, such as gas, and ultimately from non-carbon energy sources, such as solar and nuclear energy sources, with hydrogen evolving as the primary energy carrier.

New markets for natural gas appear to be opening in electricity generation and in transportation, for example as feedstock for methanol fuel. One report estimates that by the turn of the century, the share of gas in the world primary energy demand could exceed the shares of coal and oil, peaking at close to 70% of world primary energy supply, and gas could remain the primary source of world energy for 50 years.[60] Natural gas emits only about 40% as much greenhouse gases per unit energy as coal (see Table 13), and because natural gas is more efficient than coal for many applications, this emission ratio may be even lower. Switching to a methane based economy has important implications for global warming.

It is also suggested that the use of hydrogen in the economy may grow significantly in the future. Total demand for hydrogen is estimated to increase by 12-17% between 1985 and 2025, with the

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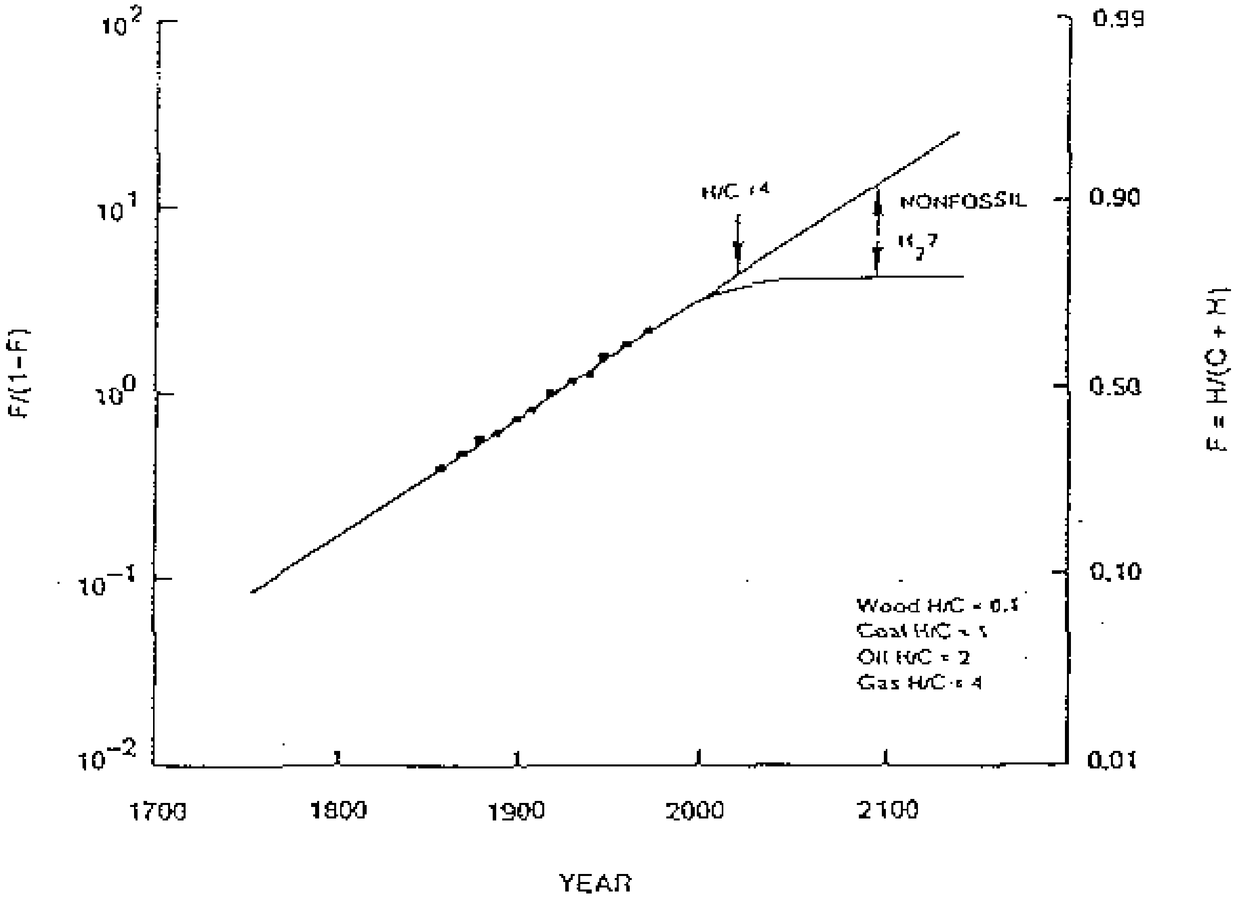
[60] J.H. Ausubel, A. Grubler, N. Nakicenovic, "Carbon Dioxide Emissions in a Methane Economy", Climatic Change, Vol.12, pp 245-263, 1988.

Figure 3

The Ratio of Hydrogen to Carbon in the World Fuel Mix



Notes: Evolution of the ratio hydrogen (H) to carbon (C) in the world fuel mix. The figure for wood refers to dry wood suitable for energy generation. If the progression is to continue beyond methane, production of large amounts of hydrogen fuel without fossil energy is required.

Source: J.H. Ausubel, A. Grubler, N. Nakicenovic, "Carbon Dioxide Emissions in a Methane Economy", Climate Change, Volume 12, pp. 245-263, 1988.

majority of this growth from indirect energy demand.[61] Currently the main uses of hydrogen in the economy are in ammonia synthetics, methanol synthetics and oil refining. In the petroleum and coal industries hydrogen is increasingly required to improve yields through upgrading the hydrogen-carbon ratio of the fuels. The demand for hydrogen as a fuel for domestic and commercial heating is likely to emerge and become significant in the future. For example, in Denmark, hydrogen has been added to natural gas supplies, up to about 10% of volume, without the need for major modifications to existing appliances. Hydrogen may also have an important role in the future as an energy carrier as it can be stored and transported relatively easily and may have a lower transmission cost than electricity. However, if the electricity first has to be converted into hydrogen for tranmission and then back to electricity for end use, the total costs of this system may make hydrogen economically unattractive as an energy carrier.

Compared to other energy use sectors, such as space heating and industrial process heat, transport is particuarly dependant upon liquid fuels. The use of liquid hydrogen in aircraft may be economically attractive as it is likely to have superior technical characteristics over conventional fuels which result in lower direct operating costs for aircrafts. Any new infrastructure required to accomodate hydrogen fuelled planes may offset reductions in operating costs. As noted above, hydrogen can also be used as a vehicle fuel in most conventional internal combustion engines with only minor modifications, and could become competitive with alternative synthetic fuels in the future (see Section 4.1.3 and Table 26).[62]

Hydrogen can be produced from a range of sources, including hydrocarbons, electrolysis of water, direct use of nuclear heat by thermochemical cycles and catalytic photolysis using solar energy. As noted in Section 4.1.3, electrolytic hydrogen produced from photovoltaic (PV) electricity has environmental advantages over fossil fuel-based energy supply options. When hydrogen is burned in the air the primary combustion product is water vapour with traces of NO_x. If hydrogen is produced via electrolysis from PV electricity no carbon dioxide gases would be emitted in its production or combustion. Therefore, hydrogen from PV electrolysis is an energy substitute option that <u>replaces</u> greenhouse gas emissions per unit of energy consumed. Given advances in thin-film solar technology, the cost of producing

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[61] K. F. Langely, "The Future Role of Hydrogen in the UK Energy Economy", Energy Technology Support Unit, Harwell, Oxford.

[62] J. Ogden and R. Williams, "New Prospects for Solar Hydrogen Energy: Implications of Advances in Thin Film Solar Cell Technology", Centre for Energy and Environmental Studies, Princeton University, New Jersey, USA, IEA/OECD Expert Seminar on Energy Technologies to Reduce Greenhouse Gases, OECD, Paris, April 12-14, 1989.

hydrogen from PV (US$10.1-15.5/GJ, 1990US$) is cheaper than from nuclear-based electrolytic hydrogen (US$26.7/GJ), from hydroelectric sources (US$23.4-28.9/GJ) and from wind sources (US$18.9-22.3/GJ).[63] If these technological advances are realised, then PV hydrogen could potentially become a cost-effective economy-wide way of controlling greenhouse gas emissions.

4.2 CFC Substitution Options

4.2.1 Introduction

Under the terms of the Montreal Protocol, signatories have agreed to reduce the consumption of five major chlorofluorocarbons (CFCs) and three important halons with effect from January 1989. The consumption, defined as production plus imports minus exports, is to be progressively reduced, so that by 1998 it will be only 15% of its July 1986 level. These terms apply to signatories which are generally regarded as developed countries, with separate terms applying to 'developing countries'. The latter are defined as those having a per capita consumption of CFCs of 0.3 kg. They are permitted ten years to arrive at the same reduction in consumption.[64]

The reasons for seeking controls on the use of CFCs are well known - damage to the ozone layer results in increased incidence of skin melanomas, cataracts and related diseases. Furthermore, it damages the tropospheric ozone layer, with attendant damage to agriculture. Finally, as has been shown in Section 2, CFCs are a major contributor to global warming and climate change. Although this is generally accepted, and a convention has been reached, which was signed by 36 countries, accounting for as much as 80% of the consumption of the regulated substances, a proper benefit cost analysis was never carried out, comparing costs and benefits on a global scale. In the United States, however, such studies were carried out. One major study was that of the Environmental Protection Agency, which showed benefits of control to be massively in excess of potential costs - by a factor of over 150 in many scenarios.[65] On this basis, it was decided by the Economic Panel of the United Nations Environment Programme (UNEP) that a global study could be avoided. In any event, the data required to carry it out were simply not available. Part of the relevant information has been collected, at least on the cost

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[63] J. Ogden et.al, op.cit..

[64] In addition, developing countries have a few other concessions - such as production above the 1986 level being permitted in the interim phase.

[65] See Environmental Protection Agency, Regulatory Impact Analysis Protection of Stratospheric Ozone, Vols I-III, Washington DC., 1987.

side in the last year or so but it is still inadequate to conduct a proper benefit cost exercise for all countries (or even a majority of them).

In this section, the issues involved in the estimation of the costs are discussed and some illustrative figures presented. As has been stated above, no full scale cost estimation exercise exists. The key issues that need to be addressed are:

a) how does one deal with uncertainty regarding the costs of substitution? Much of the substitute substances and technology are only just being developed and their costs are uncertain;

b) how does one address the question of efficiency in substitution? As the process of substitution takes place, will private incentives ensure that the least costly dynamic path is chosen, and if not what instruments are needed to ensure such a path;

c) there is a distinction, at least at the political level, between the costs of substitution in developing countries and those in developed countries. The former are claiming some assistance with technology transfer and arguing that the process of substitution imposes broader costs of retarded development upon them. How far is this true and what policies can one implement to reduce such costs to a minimum?

4.2.2 Major Categories of Costs

To reduce the use of CFCs over a period of time, costs will be incurred in the following areas:

* costs of using higher cost substitutes;
* costs of adjustments in the industries using CFCs and halons as inputs;
* differential costs of operating equipment with the substitutes;
* costs of amortising existing CFC production capacity faster than would otherwise be the case; and
* the costs of information collection in this area.

Each of these is discussed in greater detail below.

Costs of Using Higher Cost Substitutes

Chemical companies are actively involved in developing substitutes to CFCs at the present time. In some applications (e.g. aerosols), the substitutes are already there and are cheaper than the CFCs they replace; in others (e.g. solvents) the substitutes exist but are more expensive than the CFCs; and in some applications such as refrigeration, adequate substitutes have yet to be developed. Table 27 gives the existing costs of substitutes as of last year. Recall that existing CFCs currently cost about $1.5 a kilo for CFC11 and CFC12.

Table 27

Incremental Costs of Substitutes for CFCs and Dates of Availability

	Additional Cost ($/Kg.)	Available Dates
Aerosols	Nil	Available Now
Ind. Refrigerants	0.95	1995
Solvents	1.15	1993
Non-Rigid Foam Blowing Agents	1.75->0.8	1990->1998
Rigid Foam Blowing Agents	1.75->0.8	1990->1998
Comfort Airconditioning	1.45->0.95	1990->1998
Domestic Refrigeration	14.60->11.90	1995->1998
Mobile Airconditioning	13.25->10.95	1994->1998

Source: Mckinsey & Co., Protecting the Global Atmosphere: Funding Mechanisms, Second Interim Report to the Ministerial Conference on Atmospheric Pollution and Climate Change, The Hague, Netherlands, 1989.

Notes: Where more than one figure is given, the cost is expected to fall from the higher to the lower figure. The dates at which the two figures apply are given in the second column.

As with all new chemical products, the price is expected to fall over time as production increases. For CFC11 and CFC12, a learning curve was fitted and a log linear relationship was found to hold, for a large range, between cumulative production and price. The elasticity estimated indicated that for every doubling of cumulative production, price fell by about 20 to 30%. Hence there is an incentive to wait for prices to fall before moving production to the substitute. How this will affect the rate of substitution will depend very much on what the governments, who have signed the agreement, create in the way of incentive structures for users to substitute the new products.

At present these have not fully evolved but there are clearly trade-offs that need to be examined. Assuming: a) a terminal date of 1998 for achieving a given overall reduction in consumption of 85%, b) different substitution costs in each of the uses, c) given demand profiles for each of the products involved and d) given profiles for the prices of substitutes along the lines indicated above, there is a straightforward dynamic optimisation problem based on minimising expected discounted present value of costs. The solutions to such a problem are being examined, along with the supporting incentive structures.[66] The results of that research are not yet completed, but what emerges is that it is not generally desirable to focus on substituting the cheapest alternatives first, leaving the most expensive to the last. The least cost substitution profile depends, among other factors, on the size of each market, the relative initial cost differentials, and the expected rate of fall in price. In addition, a simple CFC tax will not in general ensure the realisation of the optimal profile. The instruments required include differential taxes/subsidies on different uses.

Costs of Adjustments in the Industries Using CFCs and Halons as Inputs

Table 28 shows the main industries which use CFCs and the technological possibilities for substitution within them. These will necessarily entail costs, arising from changes in maintenance practices, in production processes and in operating costs of the new equipment used (mainly energy costs). At present it is difficult to say how large these costs will be. Some estimates have been made by the EPA[67] for individual products and these are given below:

Aerosols:
Plant relocation or added filling room: $25,000-$750,000 according to plant size

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[66] A. Markandya and M. Pemberton, "Dynamic Optimization and the Control in the Use of CFCs", mimeo, Unviversity College London, 1990.

[67] Environmental Protection Agency, "Capital Costs of CFC Reductions for the First Three Years", mimeo, Washington DC, 1990.

Table 28

Technological Substitution Possibilities with CFCs

SECTOR	SAVINGS POSSIBLE WITH EXISTING EQUIPMENT	PROSPECTS OF SUBSTITUTES TO CFCS	CHANGES USE OF CFC SUBSTITUTES WILL ENTAIL
Domestic Refrigeration	Recycling of CFC'S possible; costs under investigation.	Several alternative refrigerants should be available by 1995. But they will be costly.	New equipment required, will probably reduce energy efficiency.
Commercial Refrigeration	Minor technical adjustments to reduce CFC'S use or emission. Recycling of CFC'S upon disposal of unit. Substitution of CFC'S with alternative refrigerants possible but costly.	Two costly refrigerants should be available by 1995.	New equipment required for optimal use of CFC substitutes. Cost increase for new equipment estimated at 10-20%. Drop in operating costs expected.
Refrigerated Transport	Minor technical adjustments, recycling.	Good. Several alternative refrigerants now in testing. Available late 1990s.	New equipment required. No certain cost estimates available. Effective replacement costs high due to extended lifetime of existing equipment.
Cold Storage	Minor technical adjustments, recycling, use of CFC substitutes.	Good. Several alternative refrigerants now in testing. Available late 1990s.	New equipment will be more energy efficient but costly. Effective replacement costs high, again due to extended lifetime of existing equipment (avg. 15 yrs.)

SECTOR	SAVINGS POSSIBLE WITH EXISTING EQUIPMENT	PROSPECTS OF SUBSTITUTES TO CFCS	CHANGES USE OF CFC SUBSTITUTES WILL ENTAIL
Comfort Air Conditioning	Recycling. leakage reduction, and use of CFC substitutes possible but costly.	Good. Several alternative coolants now in testing. Available early 1990s.	New equipment required for optimal use of CFC substitutes. No certain cost estimates available.
Industrial Refrigeration	Improved maintenance, recycling, and use of CFC substitutes.	Alternative refrigerants now in testing. Available mid-1990s.	No further information available.
Heat Pumps Used For Heating	Improved maintenance.	Good CFC substitutes should be available by 1993.	New equipment required. No cost estimates available.
Mobile Air Conditioning	Technical adjustments (some major), use of CFC substitutes (some options very costly).	Good. CFC substitutes should be available by 1995.	New equipment required for optimal use of CFC substitutes. Added cost $30-100 per vehicle.
Rigid and Flexible Foams	Use of CFC substitutes (including water).	Good. CFC substitutes should be available by early 1990s.	New equipment required for total elimination of CFC'S.
Electronic Degreasing and Dry Cleaning Solvents	Recovery of solvent losses, use of CFC substitutes (including water).	Good. Many alternative cleaning solutions already in use.	New equipment required for some industrial uses (i.e. dry cleaning). Costs significant but not specified.

SECTOR	SAVINGS POSSIBLE WITH EXISTING EQUIPMENT	PROSPECTS OF SUBSTITUTES TO CFCS	CHANGES USE OF CFC SUBSTITUTES WILL ENTAIL
Aerosols	Use of CFC substitutes	Excellent. Many non-CFC gas propellants or pumps now available with few technical impediments.	New equipment required in many instances, but not significantly costly; Cost of final aerosol product generally less than corresponding CFC-using product.
Sterilants	Use of CFC substitutes, technical adjustments.	Excellent. Many CFC substitutes now available, others in development.	Few changes required, total CFC replacement feasible using already existing technology.

Source: Markandya, A. (1990), The Costs to Developing Countries of Joining the Montreal Protocol, UNEP, Nairobi.

Facilities for use of compressed gas as propellant: $45,000-$125,000 according to plant size

Foams:
Packaging Facilities: $50,000-$150,000 according to plant size

Household Refrigeration:
Costs of new compressors etc.: $50,000 per plant

Mobile Air-Conditioning:
Per machine retrofitted: $1,000-$2,500

Solvents:
Use of Aqueous cleaning systems: $10,000-$130,000 per machine
Replacement of Engineering Controls: $1,900-$60,000 per machine

Halons:
Recycling of portable and wheeled units: $1,000-$3,000 per machine

The key point to note about these costs is that they need not all be incurred initially, and that the optimisation problem of replacing CFCs with substitutes extends to replacing existing CFC-using production processes with those using substitute technology. For example, there would not normally be any need to retrofit much of the airconditioning or refrigeration equipment, if new equipment operating on substitutes could be brought into use quickly enough. This would imply higher costs in new manufacturing and faster amortisation of existing equipment, but lower costs on retrofitting. The issue is one of optimisation which has not been carried out.

Differential Costs of Operating Equipment with the Substitutes

In some of the earlier research it was argued that equipment using substitutes, particularly in refrigeration, would involve higher energy costs of operation.[68] However, this view has been challenged and the current consensus is that there probably would not be much in the way of additional energy costs involved in the transfer. In fact some of the prototype refrigerators are more energy efficient than the ones they replace.

Costs of Amortising Existing CFC Production Capacity Faster than Would Otherwise be the Case

In developed countries with manufacturing facilities for CFCs (principally France, Germany, Italy, UK, USA), the lead time in arriving at the Montreal Protocol has been long enough for there

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[68] See for example, United Nations Environment Programme, Economic Panel Report: Pursuant to Article 6 of the Montreal Protocol on Substances that Deplete the Ozone Layer, Vols. 1-3, Nairobi, 1990. Also, U.S. Congress, An Analysis of the Montreal Protocol on Substances that Deplete the Ozone Layer, Office of Technology Assessment, Washington DC, 1988.

not to be a need to amortise plants faster than would otherwise have been the case. In any event many of the new plants are 'swing plants' capable of switching to the production of non-banned materials. This is also the case with some of the new facilities set up in India and China. In other developing countries with such facilities, there may be a need for earlier closedown, but it is not likely to amount to a large figure. If plants have an economic life of 25 years, and the terms of the agreement would allow them production for the next 18 years, the maximum shortening of the life could be 7 years. As substitutes develop and become cheaper, the economic life will be shortened by more than that anyway.

The Costs of Information Collection

From the discussion so far, it is clear that there is a great need for information collection in this area. The costs of that should properly be attributed to the substitution. From recent discussion of the Parties to the Montreal Protocol, a budget for such information gathering has been established at around $10 million over the next three years.

4.2.3 Costs to Developing Countries

As part of the attempt to encourage non-signatories to the Montreal Protocol (notably India, China and Brazil), the Parties to the Protocol attempted to estimate the costs of meeting the terms and reducing their use of CFCs by 2008 in the prescribed manner. Initially this exercise was carried out for all developing countries in the aggregate, and subsequently a number of country case studies were commissioned for key and 'typical' countries. The results of these studies showed the following:[69]

a) for all developing countries, the discounted present value of costs of the more expensive substitutes would amount to around $1.8 billion. However it is possible that the total cost would be much less than this;

b) for the next three years the costs of restructuring industry and training personnel in the use of alternative technologies would amount to between $210 million and $280 million.

It is important to emphasise that such cost calculations are very approximate. The figure of $1.8 billion was based on some limited optimisation of the shift to substitutes over the permitted interval. However, the parameters of such optimisation

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[69] These figures are taken from A. Markandya, The Costs to Developing Countries of Joining the Montreal Protocol, UNEP and EPA, Nairobi, 1990. Individual country case studies are still being reviewed and their results are not as yet available.

are complex and a number of parameters were not included, such as the rate of retrofitting and the scope for recycling.
One issue which divides the position of developing countries and the need to minimise costs of substitution is that of importing the substitute products versus manufacturing them domestically in the developing countries. Cost considerations would suggest that they be imported - there are significant economies of scale and the pharmaceutical companies would not release their patents without substantial payment. However, the pressure not to increase imports, and the fears of technological dominance lead developing countries to demand that the technology be transferred and the 'assistance' package be based on the costs of manufacturing the products in their countries. Clearly this would raise the cost considerably. The figures referred to above are not based on such domestic production, but on importation from the cheapest source.

4.3 Methane Substitution Options

Sources of methane emissions are shown in Table 29. As with carbon, there are sinks corresponding to emissions, but emissions levels currently exceed absorptions so that methane is increasing in net terms. Globally, the dominant sources are anaerobic processes in wetlands and rice paddies, which account for over 40% of emissions. Enteric fermentation in animals accounts for a further 15%, with gas drilling, biomass burning, termites, landfills and coalmines being of roughly equal importance at around 7-9% each of total emissions.

The picture within a single industrialised nation is rather different. Table 30 shows sources for the United Kingdom. Methane from coal mines accounts for one quarter of emissions, and livestock and other animals account for some 36%. Landfill accounts for a further 22%. In terms of <u>substitution</u> technologies, it is evident that the following measures need to be evaluated:

i. waste recycling and reduction to reduce landfill waste disposal;

ii. recovery of methane gas from landfill sites;

iii. extraction and recovery of methane from coalmines;

iv. more efficient use of animal feed;

v. reduced gas pipe leakages;

vi. gas recovery as opposed to flaring at drilling sites;

vii. switching from coal, oil and gas to renewable energy technolgies;

At the more pervasive level, major reductions in methane emissions would require changes in agricultural practice and in

Table 29

Estimated Sources and Sinks of Methane

	Annual Release (Tg CH4)		Range (Tq CH4)
Source			
Natural Wetlands (bogs, swamps, tundra, etc)	115	(22%)	100-200
Rice Paddies	110	(21%)	25-170
Enteric Fermentation (animals)	80	(15%)	65-100
Gas Drilling, venting, transmission	45	(9%)	25- 50
Biomass Burning	40	(8%)	20- 80
Termites	40	(8%)	10-100
Landfills	40	(8%)	20- 70
Coal Mining	35	(7%)	17- 50
Oceans	10		5- 20
Freshwaters	5		1- 25
CH4 Hydrate Destabilization	5		0-100
Total	525		400-600
Sink			
Removal by soils	?		?
Reaction with hydroxyl radicals in the atmosphere	500		400-600
Atmospheric Increases	44		40- 48

Source: IPCC, Working Group 1, 1990.

Table 30

UK Anthropogenic Emissions of Methane

Source	Emissions MT as methane	
Landfill	0.716	22%
Cattle	0.792	25%
Other Animals	0.348	11%
Coal Mines	0.830	25%
Flaring and Venting	0.219	7%
Gas Leakage	0.345	11%
Road Transport	0.021	<1%
Other	0.002	negligible
Total	3.273	

Source: G. Thurlow (ed), Technological Reponses to the Greenhouse Effect, Rooster Books Ltd, Royston, 1990.

the output mix, notably away from meat and paddy rice. The prospects for this are, predictably, fairly small once cultural, institutional and political factors are considered. However, greater scope exists for changing agricultural practices since methane emissions from rice paddies are sensitive to levels of fertiliser use and management of irrigation water flows. But the exact scope for change is unknown given that rice paddy methane emission data have so far not been obtained from Asia which has around 90% of the world's rice paddy harvest.[70]

Preliminary economic analyses in the UK suggest that landfill waste can be reduced at zero incremental cost given that recycling rates are, in any event, judged to be below their economic optimum. Landfill gas recovery can be obtained at fairly modest cost, but recovery of methane from coal mines is thought to be severly limited in scope, i.e. there are technical barriers to recovery.

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[70]. See IPCC, Working Group 1, 1990, para 1.3.3.2.

5. CONCLUSIONS AND POLICY RECOMMENDATIONS

5.1 Cost Curves and Cost Analysis

Cost analysis of greenhouse gas control options is a prerequisite of a rational approach to global warming and stratospheric ozone depletion. Two broad philosophies of control have tended to emerge. The first is the cost-benefit approach and the second is what might be termed the 'critical loads' approach. In the former case, costs of controlling greenhouse gas emissions, and costs of adapting to global warming, are compared to the avoided damage. Policy choices should then centre on the point where net global benefits are maximised, subject to other social goals such as distributional incidence. In the cost-benefit approach, the determination of control costs - including substitution costs- is self-evidently important.

In the critical loads approach, thresholds in the warming-damage function are identified and policy aims for levels of warming below thresholds which are marked by quantam changes in damage, together with a safety margin. Critical loads approaches therefore tend to identify either dicontinuities in the damage function, or 'knees' where a continuous damage function shows a marked change in the rate of change. Economists are typically suspicious of critical loads because of the general absence of anything that seeks to identify net benefit functions. Scientists, especially ecologists, tend to be suspicious of the economists' belief that damage functions are continous, particularly in the context of environmental change of which the world has no prior experience. This is of course especially true of global warming. However, even with the critical loads approach, it is essential to identify cost functions and to seek the minimum cost combination of ameliorative measures. Even if the critical loads approach risks inefficiency, there is little point in adding to it by a failure to identify minimum abatement costs ('X-inefficiency').

A further reason for cost determination is that policy-makers seek guidance not just on targets (which is what the cost-benefit and critical loads approaches are primarily designed to identify) but also on the <u>sequencing</u> of control measures. The minimum cost requirement can be stated more formally as one of minimising the present value of the costs of achieving target reductions, although the present value formulation raises issues of intergenerational fairness.[71] The general requirement for policy makers, then, is to determine a cost function of the form shown

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[71] Thus, under the present value approach, costs borne by future generations are discounted back to the present. By adopting low cost measures first, future generations will face possible high cost solutions to further contain global warming. Offsetting this, technological change should keep future costs down and, of course, future generations are the primary beneficiaries of current policies to contain global warming.

in Figure 4. CO_2-equivalents are shown on the horizontal axis and dollar costs on the vertical axis. Each 'block' on the cost function represents a CO_2-reducing technology and the dollar cost per unit greenhouse gas saved is then calculated as:

$$\frac{\text{PV Cost Substitute} - \text{PV Cost Greenhouse Gas Technology}}{\text{Change in Greenhouse Gas Emissions}}$$

The scale of the blocks is determined by the extent to which the relevant technology can be introduced. Typically, we would expect technology penetration to be limited by various factors-geographical (e.g. for wind and wave energy), institutional (acceptability of nuclear power, for example), market factors (e.g. scale of base load electricity market) and so on. *Within* the blocks costs will vary so that the 'tops' of the blocks are at best an average of varying marginal costs.

Figure 5 highlights one of the features of the greenhouse gas debate which is, in fact, highly reminiscent of the energy conservation debate of the 1970s. Some authorities believe that there are widespread measures that can be undertaken to reduce greenhouse gases at negative cost, i.e. expenditures would be more than offset by purely *private* returns. Greenhouse gas reduction tends then to be a further benefit. If this is correct, curve B would be relevant to policy-making. But if negative cost functions exist it is pertinent to ask why such measures have not automatically been undertaken in the context of pure market forces. Views differ between the camps. Advocates of the negative cost view tend to argue that the negative cost technologies are generally energy conservation measures, and that energy conservation markets are in disequilibrium. Alternatively, or in addition, they argue that market imperfections, e.g. information deficiencies, inhibit conservation measures. Disbelievers argue that the shaded area in Figure 5 is imaginary and that true cost functions are more like A. The shaded area is imaginary because there are in fact hidden costs not being accounted for in the cost function A.

It seems likely that the debate over the nature of the cost curve directly concerns conservation measures more that substitutes. But in another respect the debate re-emerges in the context of substitutes. As noted in previous sections, the costs surveyed in this report have been the direct resource costs. Yet the substitute technologies themsleves have social costs, e.g. the perceived risks of nuclear power, impact of tidal barrages on wildlife habitats, and so on. Technically, the relevant cost function neeeds to be defined in terms of *social* costs, not resource costs alone. A final feature of focussing on resource costs alone is that it ignores second and third-order cost impacts on other sectors of the economy. Strictly what is required is a multi-sectoral general equilibrium model in which it is possible to identify cost impacts beyond the immediate resource costs of technology substitution. Such models exist and

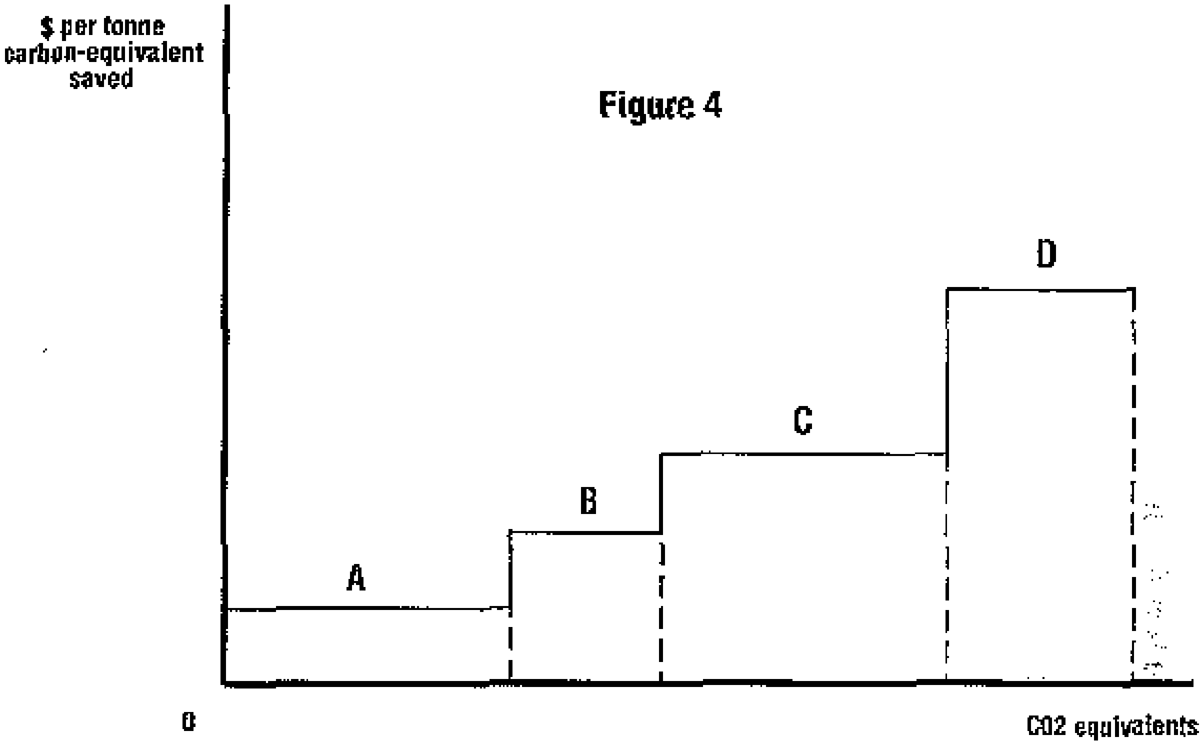
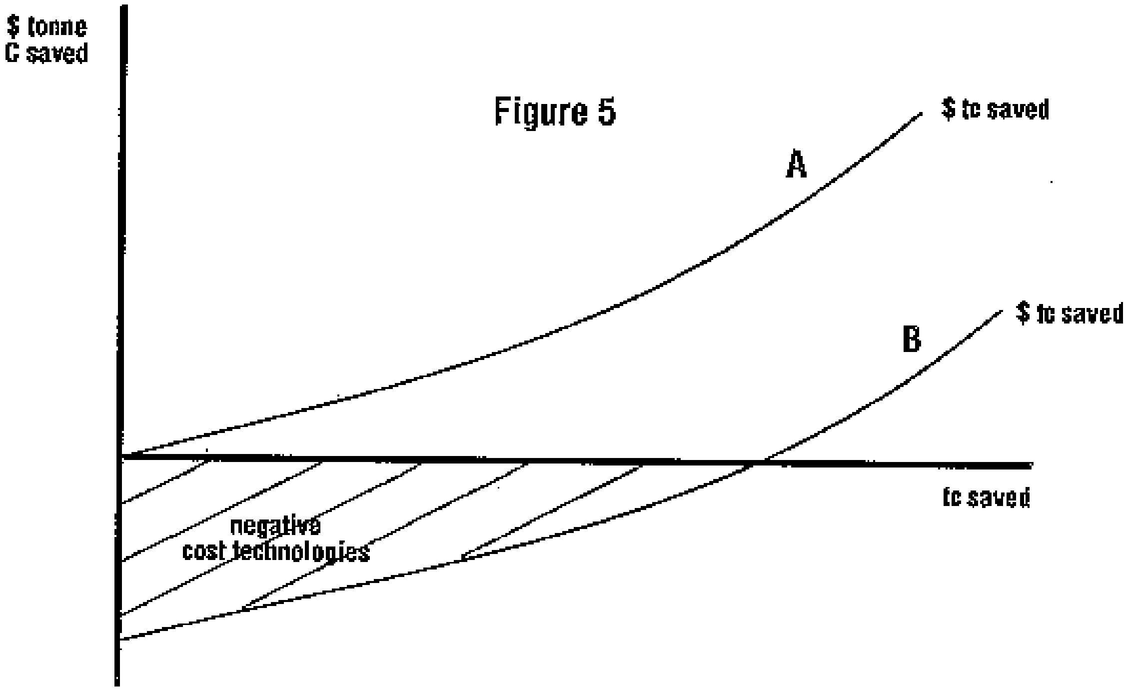


Figure 4


$ tonne
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negative
cost technologies

Figure 5

some have been supplemented by environmental benefit estimates.[72] As far as we know , however, no model has yet been 'run' with technology substitution scenarios, although this would seem to be feasible.

Some fairly simplistic attempts have been made to estimate cost functions of the form shown in Figures 4 and 5. Figures 6-8 provide indicative examples for OECD, Eastern Europe and the 'rest of the world'.[73] The curves shown tend to suggest that energy conservation measures are likely to be more cost-effective than technology substitution for initial CO_2 reduction measures, and this is borne out by other studies. CFC substitution also appears as a low cost 'solution', at least for a great many uses of CFCs. Beyond these observations, available data make specification of credible marginal cost functions extremely difficult. Figures 6-8 are regarded by their authors as indicative only. Two UK cost functions are shown if Figures 9 and 10. Figure 9 represents a government viewpoint, and Figure 10 an environmentalist group's viewpoint.[74] Clearly, as might be expected, official and environmentalist estimates diverge markedly. The official view on nuclear power has changed, however, and the marked preference for nuclear technology is perhaps not as strong as is shown in Figure 9. Note also that Figure 10 contains energy conservation technologies in considerable detail, whereas Figure 9 has energy conservation in general (at an agreed negative cost) but with substantial uncertainty about cost and scale of potential penetration.

5.2 Conclusions on Greenhouse Gas Substitution Options

The results of this study confirm that technology substitution options for greenhouse gas abatement are likely to remain relatively expensive in the near term. The exceptions may be fossil-fuel switching, e.g. from coal to advanced gas technologies, passive solar and CFC substitution. Indeed, our findings suggest that some of these options may actually yield economic savings. What is more, given the rapid changes in the technology and costs of various substitution options, a wide

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[72] See, for example, S. Glomsrad et al, 'Stabilization of Emissions of CO2: a Computable General Equilibrium Assessment', Norwegian Central Bureau of Statistics, Oslo, Discussion paper No. 48, April 1990.

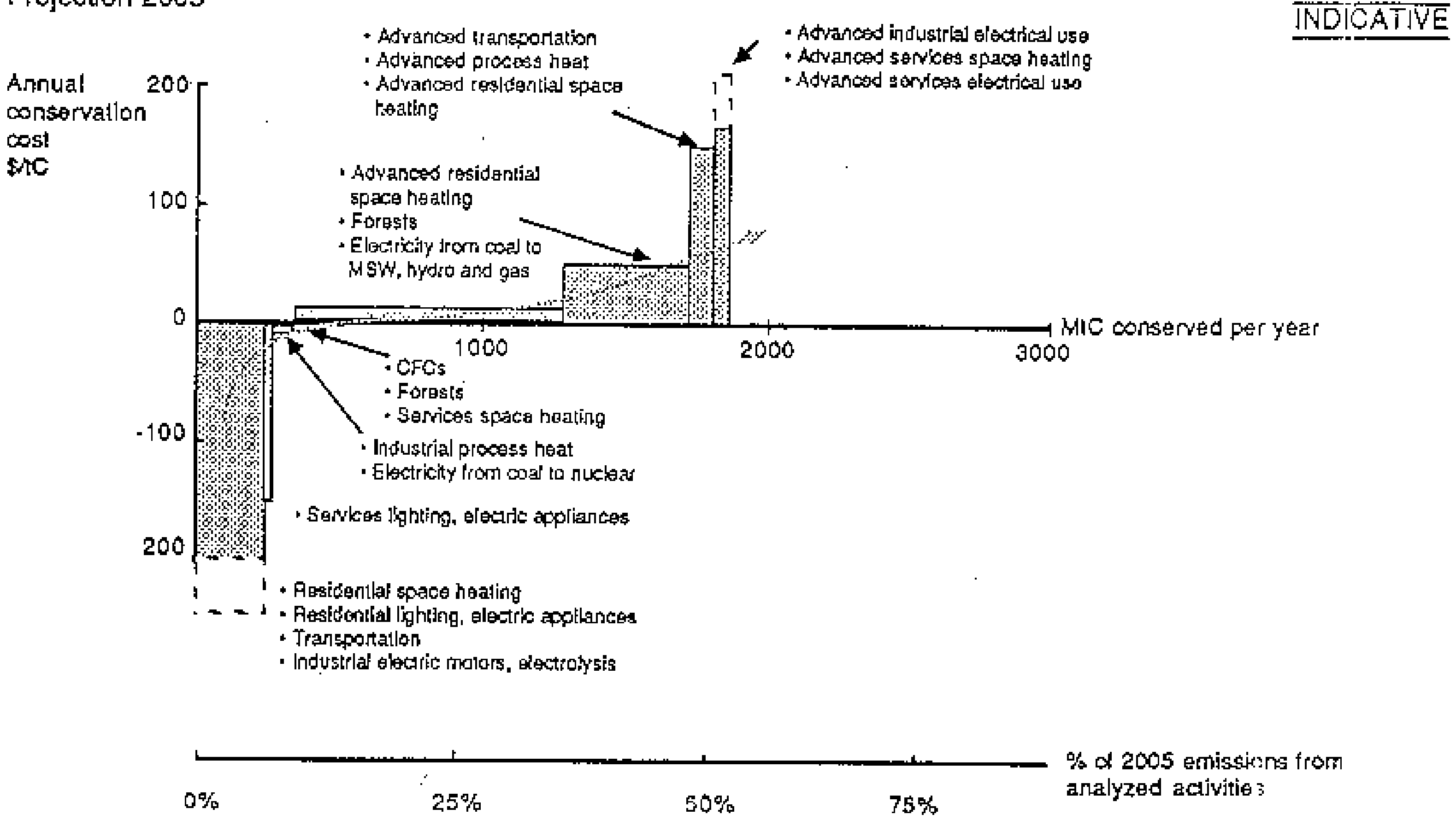
[73] Figures 6-8 are taken from Mckinsey and Co, Protecting the Global Environment: Funding Mechanisms, Prepared for the Ministerial Conference on Atmospheric Pollution and Climatic Change, Noordwijk, the Netherlands, November 1989.

[74] Figure 9 is derived from data in UK Department of Energy, An Evaluation of Energy Related Greenhouse Gas Emissions and Measures to Ameliorate Them, Energy Paper 58, HMSO, London 1989. Figure 10 is taken from T. Jackson and S. Roberts, Getting Out of the Greenhouse, Friends of the Earth, London, December 1989.

FIGURE 6

COST CURVE OECD

Projection 2005



Note: Based on available research material

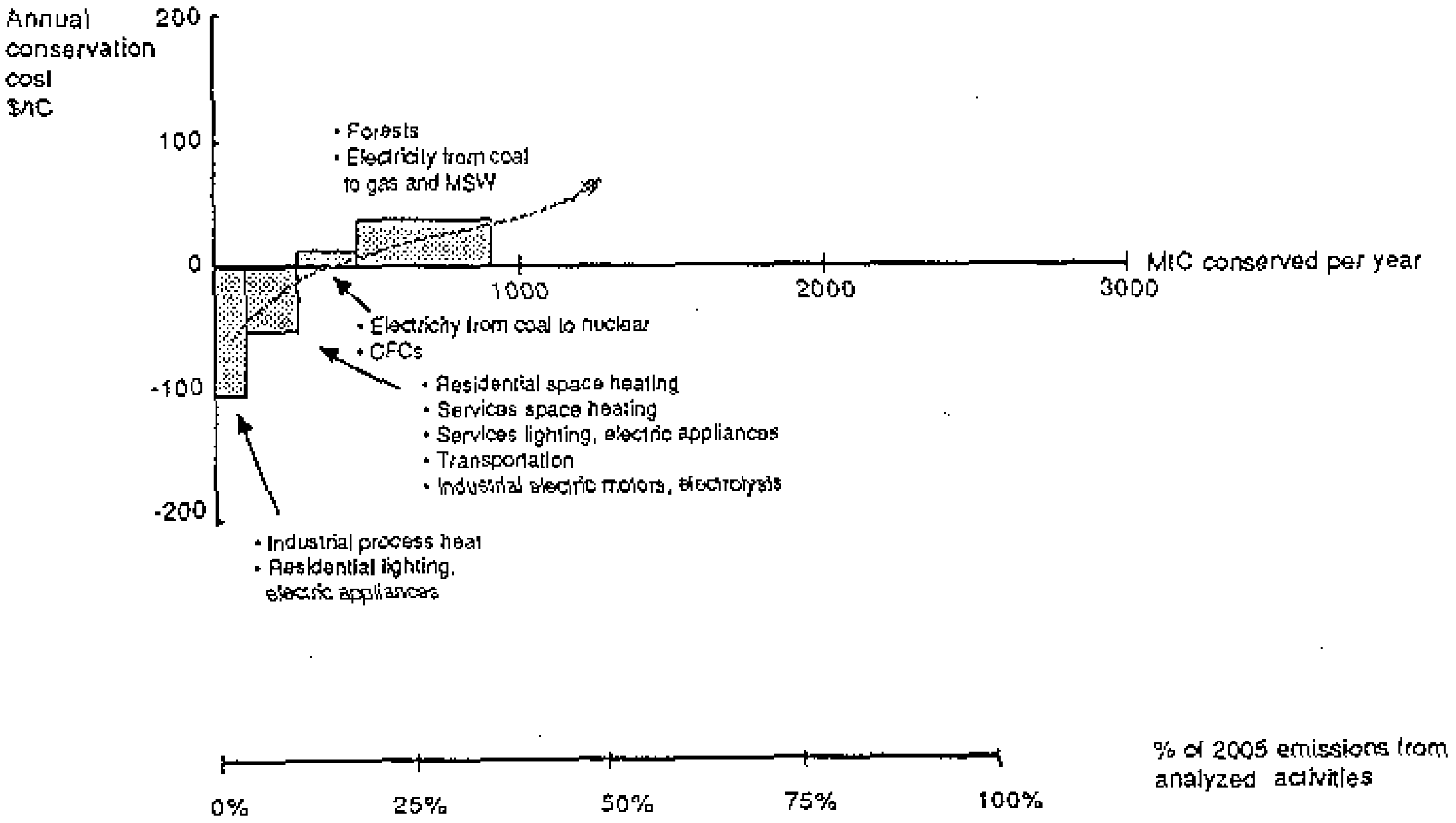
Source: International energy consultants; McKinsey analysis

FIGURE 7

COST CURVE EASTERN EUROPE

Projection 2005

INDICATIVE



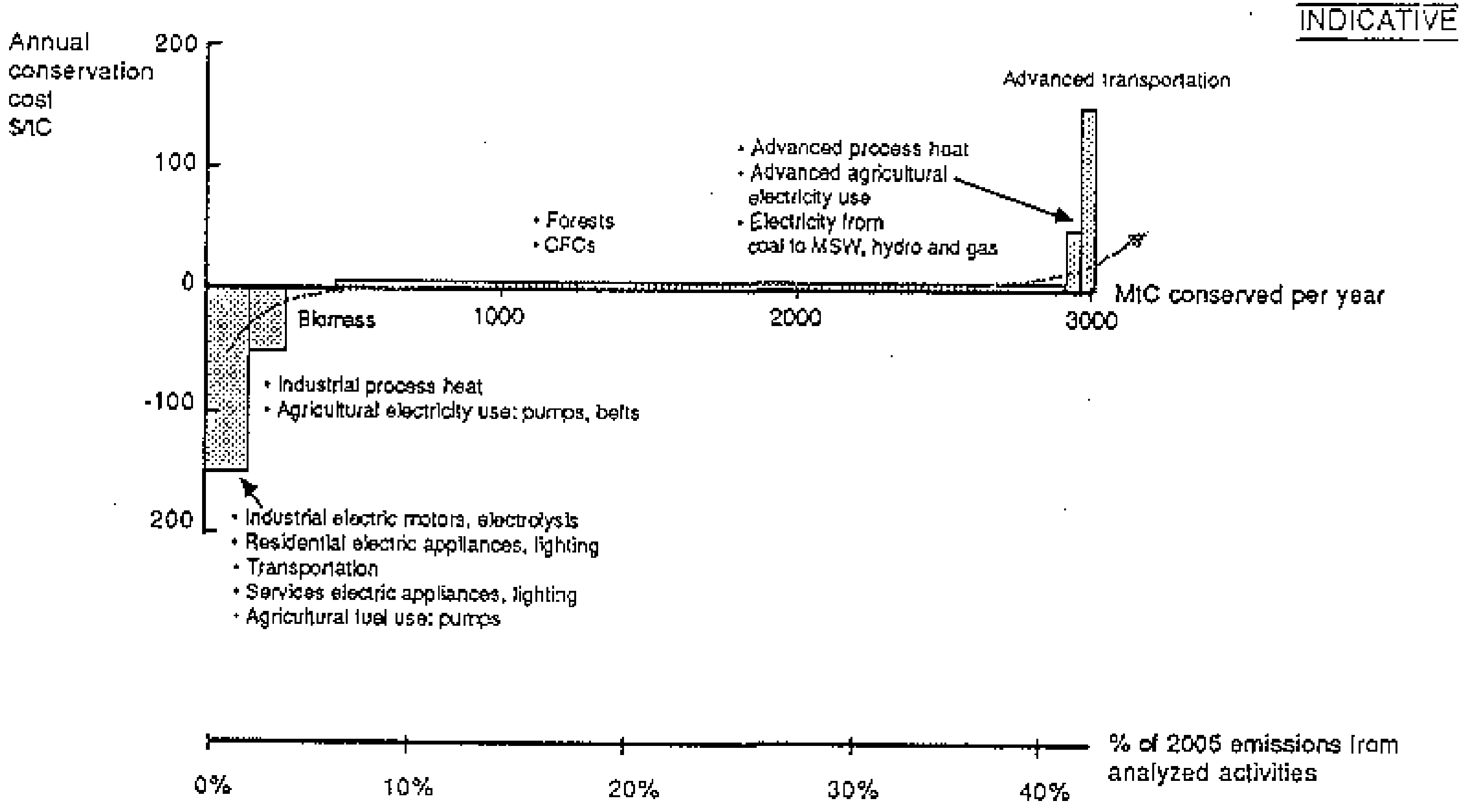
Note: Based on available research material

Source: International energy consultants; McKinsey analysis

FIGURE 8

COST CURVE REST OF WORLD

Projection 2005



Note: Based on available research material

Source: International energy consultants; McKinsey analysis

Figure 9

An Official View of GHG Substitution Costs: UK

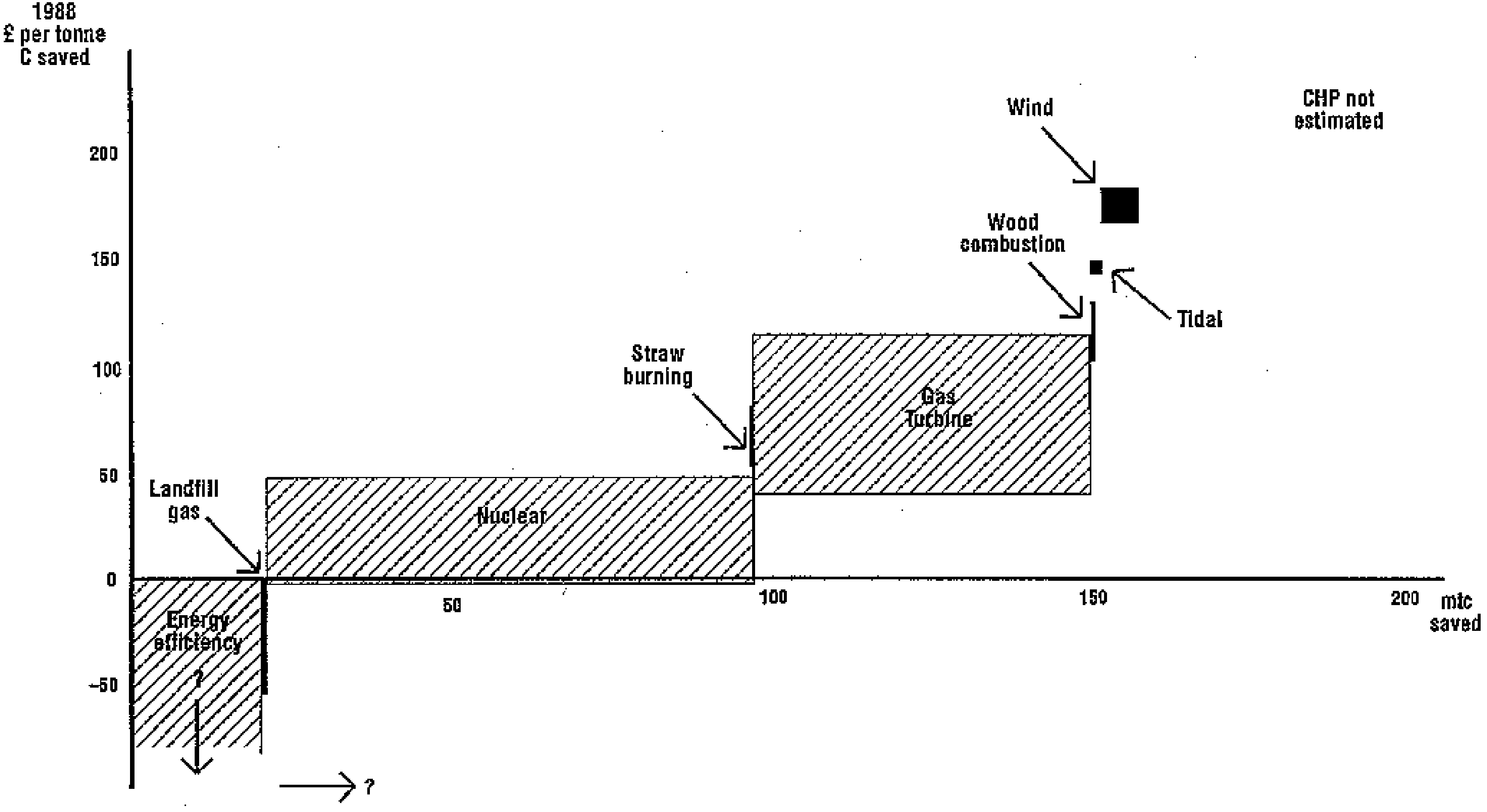
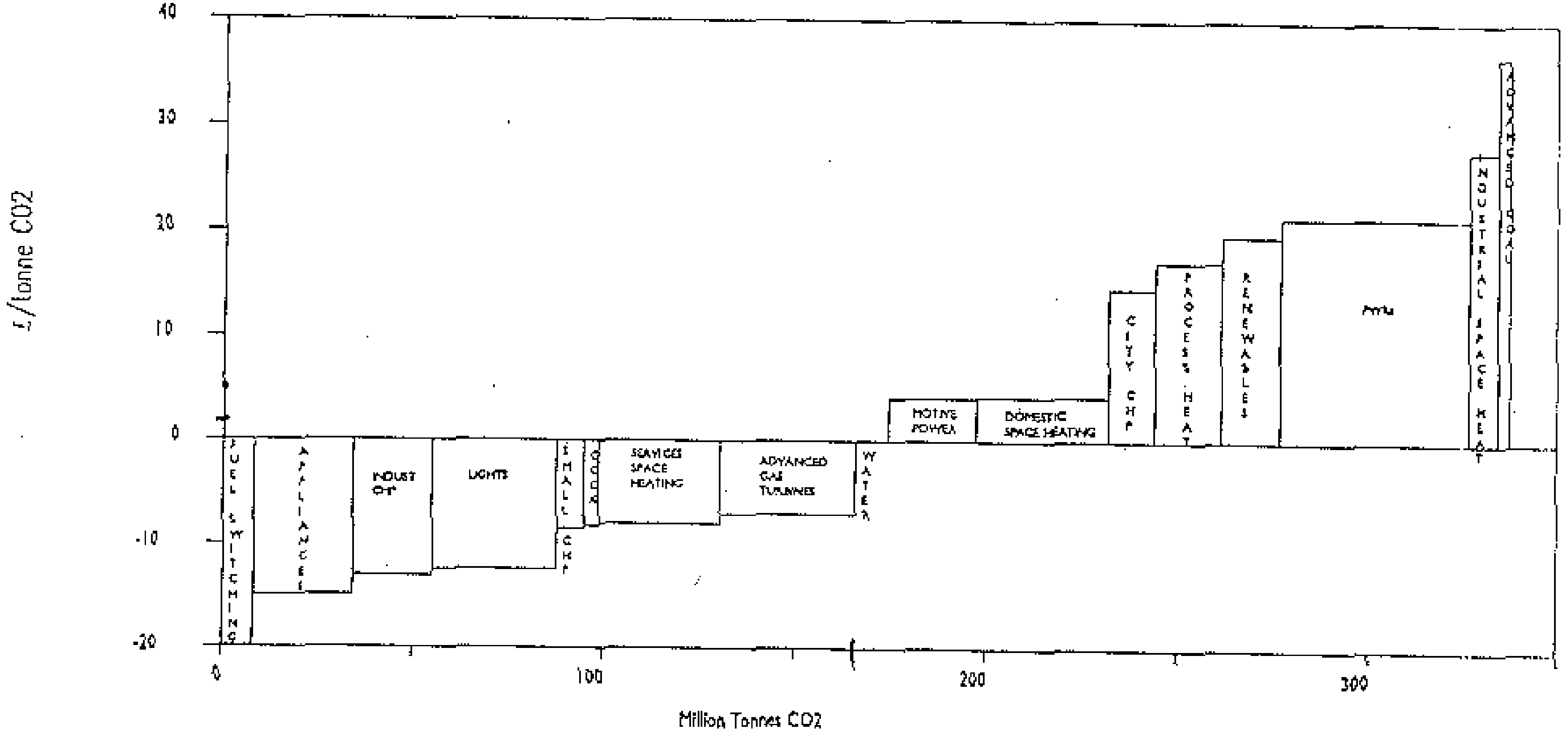


FIGURE 10

AN ENVIRONMENTALIST VIEW OF GREENHOUSE GAS SUBSTITUTION COSTS: UNITED KINGDOM



spectrum of greenhouse gas substitution options may become economically attractive abatement strategy in the long run. There are several factors pointing to this trend:

i. We are clearly at an important watershed for most technological developments. Significant substitution technologies are beginning to achieve market penetration on a large scale. For example, as indicated in Figure 1, many critical renewable energy technologies for replacing fossil fuels are at a critical transition phase of development between proven capability and future supplies.

ii. Once market penetration is assured, both economies of scale and improved reliability may lead to substantial cost reductions in many advanced technologies at a rapid rate.[75] However, technologies with high social costs, such as nuclear power and possibly tidal energy, will benefit less from economies of scale, as these obviously only impact on direct resource costs. Suitable land availability is another factor affecting some technologies, such as photovoltaic power, biomass and wind energy.[76]

iii. Costs will vary significantly from country to country and even from region to region within countries. Therefore, some substitution options may be more cost-effective in certain countries or locations rather than in others. Rational greenhouse gas abatement strategies should take advantage of geographic-specific potentials for substitution.

iv. Current cost estimates for substitution technologies are necessarily based on projections of future prices and policy interventions. Most projections are conservative. For example, for the energy sector, future fossil fuel prices are assumed to remain constant in real terms, or rise slightly, and current energy policies are assumed to continue. However, in the long run, future scarcity or market imperfections for fossil fuels - or political events

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[75] For example, D. Anderson, "Photovoltaics: A Review of Costs", Draft paper, University College, London, June 1990 notes that, in addition to the technical advances in manufacturing processes, materials, cell design and conversion efficiency, future costs of photovoltaics should also be significantly reduced by improvements in the reliability of the technology, especially increases in the expected lifetime of units, and scale economies.

[76] An appropriate indicator for the land intensity of each technology might be generated kWh per square metre (kWh/m^2). D. Anderson, op. cit., indicates that photovoltaic generation may be less constrained by land availability than previously thought. Less than 0.5% of the land surface in areas with high insolation is in theory required to meet the world's energy demands, assuming 15% photovoltaic conversion efficiency.

market imperfections for fossil fuels - or political events like the current 'Gulf Crisis' - may lead to more substantial price rises.

v. Although substitutions will phase in gradually as the long run marginal cost of substitutes declines relative to fossil fuel costs, market forces alone are unlikely to secure the 'optimal' rate of substitution given environmental costs. The imposition of a carbon tax or of significant quantitative restrictions on the use of fossil fuels may be necessary to change relative prices to favour substitution and conservation.

Greenhouse gas substitution options must consequently be considered a necessary component of any strategy for controlling global warming. Moreover, the cost-effectiveness of these options will invariably be affected by any resulting policy interventions - carbon taxes and emission permits, phased reductions in greenhouse gas emissions and subsidies for the research, development and deployment of the substitution technologies. Further research is therefore required to:

i. improve estimates of the current and future cost-effectiveness of the relevant substitution options for different regions of the world;

ii. extend these estimates to include not just the direct resource costs but all the economic and social costs (and benefits) of the various options;

iii. incorporate this 'micro' analysis into multi-sectoral general equilibrium models to examine the impact of appropriate policy instruments in abating greenhouse gas emissions; and

iv. based on the above analyses, design incentive structures to encourage the appropriate level of research, development and deployment of greenhouse gas substitution technologies.

Further consideration must be given to the capital and technology constraints facing developing countries. For example, an upper estimate of the cost to these countries for implementing the Montreal Protocol for CFC substitution is US$1800 million in 1990, falling to zero over the next 18 years. The additional cost of faster amortization of existing CFC producing equipment may be as much as US$155 million. Thus, to assist developing countries in meeting these costs of CFC substitution, a technical assistance fund with an initial allocation of US$10 million for the first two years has been recommended. In addition, the fund would loan US$200 million over three years to increase manufacturing capability using new technologies with CFC substitutes. US$10 million would also be required for systemic collection of information on the production, consumption and use of CFCs and their substitutes by country.[77]

Similar financial assistance will most likely be required for a wide spectrum of greenhouse gas substitution options. Given the rapid increases in developing country emissions, any international agreements and policy measures must include assistance to the Third World for substitution technologies.

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[77] A. Markandya, "The Costs to Developing Countries of Joining the Montreal Protocol", UNEP and EPA, Nairobi, 1990.

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David W Pearce, Edward B Barbier and Anil Markandya,
Sustainable Development: Economics and
Environment in the Third World, Edward Elgar
Publishing Limited, London 1989.

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David W Pearce, Anil Markandya and Edward B Barbier
Blueprint for a Green Economy, Earthscan,
September 1989, £6.95 (third printing)

This book by the London Environmental Economics Centre was prepared as a report for the Department of Environment, as a follow up to the UK government's response to the Brundtland Report. Here it stated that: '...the UK fully intends to continue building on this approach (environmental improvement) and further to develop policies consistent with the concept of sustainable development.'
The book attempts to assist that process.

Gordon R. Conway and Edward B. Barbier
After the Green Revolution:
Sustainable Agriculture for Development
Earthscan, London 1990 £8.95

The Green Revolution has been successful in greatly improving agricultural productivity in many parts of the developing world. But these successes may be limited to specific favourable agro-ecological and economic conditions. This book discusses how more sustainable and equitable forms of agricultural development need to be promoted. The key is developing appropriate techniques and participatory approaches at the local level, advocating complementary policy reforms at the national level and working within the constraints imposed by the international economic system.

David W. Pearce and R. Kerry Turner

** Economics of Natural Resources and the Environment, Harvester-Wheatsheaf, London and Johns Hopkins University Press, Baltimore, 1989.

This is a major textbook covering the elements of environmental economics in theory and practice. It is aimed at undergraduates and includes chapters on sustainable development, environmental ethics, pollution taxes and permits, environmental policy in the West and East, recycling, and optimal resource use.

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