

GREENHOUSE GAS EMISSIONS, ABATEMENT AND CONTROL: THE ROLE OF COAL

I.M. Smith, K.V. Thambimuthu, IEA Coal Research, London, UK

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ABSTRACT

The basis for quantifying the relative effect of greenhouse gas emissions from coal utilisation is discussed. Emission factors (gC/MJ) need to include greenhouse gas emissions and energy losses throughout the fuel cycle in order to compare the fuels. Nevertheless CO₂ is the most important greenhouse gas from coal. Emission factors have decreased due to improved efficiency of coal use. The scope for further improvements in efficiency of conventional and advanced power generation is assessed. Control of CO₂ emissions is viewed as a less promising option owing to the high cost and energy penalty of most methods.

It is concluded that there is no firm basis for evaluating the effect of reducing emissions on their global warming potential. However it is desirable that available technologies be implemented to reduce emissions by improved efficiency.

INTRODUCTION

Greenhouse gases from coal include methane (CH₄), released during hard coal production, and most important, carbon dioxide (CO₂) as well as nitrous oxide (N₂O) which are emitted when coal is used. Ozone (O₃) is another greenhouse gas formed indirectly from complex reactions with other pollutants in the atmosphere. Here other oxides of nitrogen, nitric oxide and nitrogen dioxide (jointly referred to as NO_x), play a role and are emitted from coal use. The topic of nitrogen oxide emissions from coal combustion was reviewed recently at IEA Coal Research by Sloss (1991). Chlorofluorocarbons (CFC) are important greenhouse gases which are produced in the industrial sector where coal is not involved.

Policy choices over the next few years to reduce greenhouse gas emissions are likely to have a profound effect on the use of coal in many countries. It is therefore essential to examine and monitor the scientific and technical basis for reducing emissions of greenhouse gases from coal use. A major scientific assessment of the greenhouse gas issue is provided by the recent report (Houghton and others, 1990) of Working Group I of the Intergovernmental Panel on Climate Change (IPCC), set up in 1988 by the World Meteorological Organization and the United Nations Environment Programme. The IPCC considered that a reduction in CO₂ emissions >60% would be required to stabilise CO₂ concentrations in the atmosphere. IEA Coal Research has been keeping a watching brief on this issue since 1977 (Smith, 1978, 1982, 1988; Vernon, 1990). This paper examines the basis of the quantitative evaluations which are being commissioned by policy makers in attempting to deal with the greenhouse gas issue and assesses the state-of-the-art of abatement and control technologies as they relate to coal use. Information is drawn from a new draft report on this topic (Smith and others, 1991).

GREENHOUSE GAS EMISSIONS

The contributions (%) of trace gases to the greenhouse effect are estimated for the IPCC by Shine and others (1990) over the past decade (based on increased concentrations in the atmosphere) and integrated over the next 100 y (in terms of emissions from human activities in 1990) as follows:

	1980-90	100 y
CO ₂	56	61
CH ₄	15	15
N ₂ O	6	4
CFC	24	12
others	-	8
	101	100

The indirect effects of CH₄ oxidation (the production of CO₂, stratospheric water vapour and

tropospheric O₃) are potentially significant but difficult to quantify. This applies also to the indirect effects from other trace gases: CO (1%), NO_x (6%) and non-methane hydrocarbons (0.5%). Shine and others emphasise that the quantification of these indirect effects needs further revision and evaluation and does not include some important chemical reactions. Victor (1990) points out that the indirect effects vary spatially as well as with time.

Further uncertainties arise from different ways of estimating the effective residence time for CO₂ in the atmosphere. The uptake of CO₂ into the various storage sinks of the global carbon cycle can take a short time, for example into non-woody vegetation or a much longer time into the deep ocean. The IPCC adopted a range of 50-200 y for the effective residence time of CO₂ in the atmosphere (Watson and others, 1990). There are uncertainties in accounting for all the CO₂ emissions which do not remain in the atmosphere. Other potential long term carbon sinks (Tans and others, 1990) have not been quantified but would shorten the effective residence time for CO₂.

The contribution to the greenhouse effect of CH₄ relative to CO₂ is important when considering the merits of fuel substitution from coal to natural gas or a carbon tax. The global warming potential of one mole of CH₄ relative to that of CO₂ ranges from 20-35 or more depending on the assumptions of different authors (Selzer, 1989; Zittel and Selzer, 1990). This uncertainty is compounded by differing values for the effective residence time of CO₂, resulting in a wide variety of numbers for the relative global warming potential of CH₄ : CO₂ (see Table 1). The estimates in Table 1 are ranked from the simplest (no consideration of the differences in residence times for CO₂ and CH₄ and a molar global warming potential of 27) to the most sophisticated by Lashof and Ahuja (1990) and Shine and others (1990). The latter use oceanic models for estimating the residence time of CO₂, more complex chemistry for the indirect effects and include the concept of integrating over the short or long term. In the long term, CO₂ assumes greater importance relative to CH₄ than in the short term. Despite current limitations, the concept of applying global warming potentials over different time horizons is the best available means of evaluating emission abatement scenarios but requires further validation.

The contribution of global coal use to the enhanced greenhouse effect is evaluated from CO₂ emissions in 1988 for the low and high estimates of the contribution from deforestation and land use adopted by the IPCC (see Table 2). Shine and others (1990) assume 7.1 GtC/y for the total CO₂ emissions from human activities in 1990. This lies within the range for total CO₂ shown in Table 2 but implies a low value for deforestation and land use if the 1988 CO₂ emissions of 5.7 GtC/y for fossil fuel are extrapolated to 1990. There is little difference between the contributions for one year or over 100 y. Coal, oil and gas would contribute about 20%, 20% and 8% respectively. There would be an additional 1% and 3% for CH₄ from hard coal mining and gas pipeline leakage respectively, assuming these sources contributed 6.3% and 20.8% of CH₄ emissions from human activities (World Resources Institute, 1990). There would also be small contributions from N₂O and NO_x emissions but these have not been quantified reliably.

Average CO₂ emission factors for bituminous coal, crude oil and natural gas, based on the higher heating value (HHV), are 24.1, 19.9 and 13.8 gC/MJ (Marland, 1983; Marland and Rotty, 1984). Those for the brown coals assessed by Couch (1988) averaged 25.2 gC/MJ. Anthracites have CO₂ emission factors of about 26 gC/MJ. When allowance is made for the effect of CH₄, in terms of its CO₂ equivalent, the emission factor for natural gas increases relative to that of coal and oil due to CH₄ leakage from natural gas distribution systems. Mitchell and Sweet (1990) applied the concept of global warming potentials and estimated that coal and natural gas would have the same emission factors at a CH₄ leakage rate of 11.5% over a 100 y time horizon. Over 20 y, the breakeven point would occur at a CH₄ leakage rate of about 5%. Such CH₄ leakage rates are not uncommon in some systems. However, it is unlikely that leakage from new gas supplies for large scale use would exceed 1% (James, 1990).

Similar evaluations including hard and brown coals in the FRG (Zittel and Selzer, 1990) conclude that, over short time horizons, brown coal has a lower effective CO₂ emission factor than hard coal if most of the CH₄ from hard coal mining is vented to the atmosphere. The two fuels would be equal over the 100 y time horizon.

Energy consumption or emission penalties are incurred when coal is upgraded. For example, a coke from a bituminous coal with a CO₂ emission factor of 24.1 gC/MJ (HHV) had an effective emission factor of 31.8 gC/MJ when coal production overheads were included (Thurlow, 1990). Synthetic fuels

from coal generally have much higher CO₂ emission factors than the original coal - even where gasoline is produced at a high thermal efficiency of 65% or more, the CO₂ emission factor is 38 gC/MJ. However this penalty will be offset by the lower CO₂ emission factor and improved combustion efficiency of the resulting synthetic fuels.

ABATEMENT

The proportion of coal used in power generation is about 73% in OECD countries (IEA, 1990) but worldwide it is probably around 50% (Matthews and Gregory, 1989). This section will therefore concentrate on technologies which decrease CO₂ emissions per unit of useful energy in the large scale use of coal for power generation.

The efficiency of coal use in steam power plants has already improved greatly this century. For example, in the FRG increasing operating pressures and temperatures and the use of steam reheat in conventional power plants have resulted in a reduction in the heat rate from 35 MJ/kWhe in the early 1900s to about 9 MJ/kWhe in the 1980s (Schilling, 1990). Emissions and waste heat losses are now only about 25% of what they were in the early steam based power plants.

Current trends show that further improvements are achievable, both on conventional plants and using more advanced technologies (see Table 3). Hence the use of supercritical steam conditions (Riedle and others, 1990) should reduce CO₂ emissions by 20% compared to a conventional 500 MWe pulverised coal (PC) plant with wet limestone flue gas desulphurisation (FGD) and sub-critical steam conditions (US DOE, 1990). Co-firing with natural gas or oil also results in reductions in CO₂ emissions due to a lower emission factor of the blending fuels. The use of flue gas recycling (Wolsky and Brooks, 1989) or selective H₂ combustion (Steinberg and Grohse, 1990) appears to offer 100% reductions of CO₂ emissions but at considerable energy costs for the separation and disposal of CO₂ or carbon.

The use of combined cycles with gasification, pressurised pulverised coal or fluidised bed combustion (PFBC) should achieve CO₂ reductions of 13-26%. At the upper end of this range are the hybrid PFBC gasification topping cycle developed by British Coal (Dawes and others, 1990) and a new scheme for pressurised pulverised coal combustion (Weinzierl, 1990). In the latter, pulverised coal is burnt under pressure in an ash slugging combustor with gas expansion through a gas turbine. Pulverised coal-natural gas combined cycles with supercritical steam conditions are expected to achieve a reduction in CO₂ emissions of about 37% (Hebel and Kotschenreuther, 1990).

Commercial MHD generators could reduce CO₂ emissions by up to 27% in the near term and even more in future with a greater efficiency of heat recovery (Morrison, 1988). The development of molten carbonate and solid oxide fuel cell technology is currently in its infancy but is potentially capable of reducing CO₂ emissions by up to 44% when used with gas/steam turbine combined cycles (Kinoshita and others, 1988).

Finally, where waste heat can be used in cogeneration or combined heat and power such as in Denmark (Mortensen, 1989), CO₂ reductions approaching 60% are achievable even with conventional coal combustion technologies.

CONTROL TECHNOLOGIES

In contrast to abatement measures, the control of CO₂ emissions by recovery and disposal is generally regarded as a last resort owing to the high energy costs involved. A recent study by the US Electric Power Research Institute (Smelser and Booras, 1990) concluded that 90% CO₂ recovery by MEA scrubbing, solvent regeneration, compression and removal for disposal in the ocean at a depth of 457 m would incur an energy penalty of 370-374 kWhe/t CO₂. The busbar cost of electricity would increase by 159-178% relative to a coal-fired power plant without CO₂ control. These results lie within a range of 222-988 kWhe/t CO₂ for the energy penalty estimated by several authors for control technologies using absorption or cryogenic separation at 90% CO₂ removal or membrane separation at 80% removal. The estimates of energy use are in the range of 21-95% of the energy released from coal combustion (Smith and others, 1991).

Disposal options include the oceans or sites on land such as salt domes and depleted natural gas or oil

fields. For disposal in the oceans, the transfer of CO₂ as solid blocks of dry ice or hydrate was found to be less practical and more costly than gas or liquid injection owing to the tonnage involved. It is desirable to inject the CO₂ into the ocean at depths >1,000 m and preferably at 3-4,000 m in order to minimise the transfer of CO₂ from the ocean to the atmosphere (Hoffert and others, 1979). More research is required on the long term effects of macromixing in the oceans on CO₂ retention in the deep ocean. On land there is potential for storage of liquid CO₂ in salt domes. For example in the USA, the existing storage capacity of strategic crude oil reserves could accommodate about 15 GtC of CO₂ emissions. Global 1980 natural gas production values suggested that the storage capacity of depleted gas reservoirs could increase at about 0.7 GtC/y with an overall capacity as large as that of past and present reserves of natural gas (Baes and others, 1980). Storage of CO₂ in depleted oil fields can be combined with its use as a solvent for enhanced oil recovery by miscible flooding. In the USA it is estimated that this use could only take up 7.7 MtC/y of CO₂ (Abel and others, 1989). However, there would be a substantial release or recycling of injected gas at active production wells.

Alternative means of controlling CO₂ emissions include its use or recycle by natural or industrial processes. A recent study by Martin and others (1990) of essential growth nutrients in the Antarctic ocean shows that the correction of an iron deficiency could promote a thirty fold increase in phytoplankton growth in the outer continental sea. Estimates indicate that increased growth by iron seeding could sequester up to 1.6 Gt C/y of CO₂ over a 50 y period but such an action is undesirable because of unknown ecological effects (Baum, 1990). On land, commercially managed forests in temperate ecosystems could sequester 2.9-5.4 Gt C/y but securing the necessary land areas of 465-733 Mha (Marland, 1989; Sedjo and Solomon, 1989) would pose problems. Unused land in tropical ecosystems (865 Mha) that previously supported forests might however be used to accumulate up to 1.5 Gt C/y over a 100 y period (Houghton, 1990). Two tropical reforestation projects by US and Dutch utilities are to offset the CO₂ emissions from a new 180 MWe coal-fired power plant in the USA and two 600 MWe coal-fired power plants in the Netherlands (Flavin, 1989; EER, 1990). The reuse of CO₂ in fuel or chemical synthesis is economically viable only if the total energy used can be produced at a lower cost than the fuel or chemical value of the product. Here, biofuels, relying on solar radiation as a 'free' energy source for direct removal of CO₂ from the atmosphere, offer a means to slow the growth of fossil fuel use whilst simultaneously reducing the net accumulation of CO₂ in the atmosphere. The present consumption of CO₂ for process use and the synthesis of industrial chemicals suggests that this sector is unlikely to make a significant contribution to reducing the overall global emissions of CO₂.

CONCLUSIONS

The contributions of the greenhouse gas emissions to the enhanced greenhouse effect are expressed in terms of the equivalent global warming potential of CO₂ when policies to reduce emissions are evaluated. This exercise is however complicated by indirect effects from some, as yet, unquantifiable chemical reactions and by uncertainties regarding the effective residence time of CO₂ in the atmosphere. Thus the concept of applying global warming potentials of greenhouse gases over different time horizons is the best available means but requires further revision and evaluation. It is clear that CO₂ is the most important greenhouse gas from coal. However, consideration of CH₄ affects the relative ranking of different fossil fuels as greenhouse gas emitters. Hence high CH₄ leakage rates of 5-10%, such as occur in some natural gas distribution systems, would virtually offset the advantage of the lower CO₂ emission factor for natural gas over coal; although the leakage rates of <1% claimed for new gas distribution systems would make little difference. Coal use worldwide is responsible for about 20% of the enhanced greenhouse effect, half of which is attributable to coal-fired power generation.

There are many options for the abatement of emissions from coal use in power generation. Apart from reducing the overall demand for energy by conservation, there are technologies which will reduce emissions from an improved efficiency of coal use. Existing technologies based on supercritical steam cycles can achieve CO₂ emission reductions of up to 20%. Over the next decade, technologies such as PFBC and gasification combined cycle offer improvements up to 25% or 37% with the use of pulverised coal-natural gas combined cycles. For the future, MHD and fuel cells should reduce CO₂ emissions by 17-44%. All of these technologies could be improved further with co-generation for CO₂ emission reductions approaching 60% - close to that required to stabilise concentrations of CO₂ in the atmosphere.

The control of CO₂ emissions by recovery and disposal appears to incur too high an energy penalty with uncertain environmental consequences for a practical solution. However systems which offer the possibility of the combined removal of CO₂, SO_x and NO_x might have some role in future in conjunction with energy savings. Reafforestation and recycling of CO₂ in fuels potentially have more scope for reducing the concentration of CO₂ in the atmosphere but probably not on the scale required to stabilise it.

Considerable progress has been made to improve efficiency for economic reasons in the past. Now there is an added impetus to achieve more for both economic and environmental benefits. There is scope for reducing emissions from coal use by both abatement and control measures but their success depends on how quickly they can be implemented.

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Table 1 Summary of estimates of CH₄: CO₂ global warming potential

Global warming potential CH ₄ : CO ₂ (molar)	Effective residence time, y		Allowing for indirect effects	Reference
	CO ₂	CH ₄		
27	(10)	10		
3.5	100	10	CO ₂	(Selzer, 1989)
6	60	10	yes	(Pearman, 1989)
10	120	10	O ₃ , CO ₂	(Rohde, 1990)
3.7	230	14.4	O ₃ , H ₂ O, CO = CO ₂	(Lashof and Ahuja, 1990)
12 (1% discount of future)	45			
17 (20 y)*	120	10	O ₃ , H ₂ O, CO, NO _x , NMHC	(Shine and others, 1990)
5.7 (100 y)*				
2.5 (500 y)*				

* integration time horizons NMHC = non-methane hydrocarbons

Table 2 Contributions to the greenhouse effect (Boden and others, 1990; Shine and others, 1990; Watson and others, 1990)

	CO ₂ emissions, 1988		Greenhouse effect, %	
	Gt C/y	%	over 1 y	over 100 y
Coal	2.4	37-28	21-16	23-17
Oil	2.4	37-28	21-16	23-17
Gas	0.9	14-11	8-6	9-7
Fossil fuel	5.7	88-68	50-38	54-41
Cement manufacture	0.2	2.3-1.8	1.3-1.0	1.4-1.1
Deforestation and land use	0.6-2.6	9-31	5-17	6-19
Total CO ₂	6.5-8.5	100	56	61

Table 3 Summary of CO₂ abatement measures for power generation (Smith and others, 1991)

Technology	Steam conditions	Net power plant efficiency (LHV), %	CO ₂ emissions, gC/kWh	CO ₂ reduction, %	Comments
Conventional					
PC + FGD	sub-critical	35	262.1	0	reference plant for CO ₂ emissions
PFBC	sub-critical	37	257	1.95	in-bed desulphurisation, demo _x
PC + FGD, demo _x	supercritical (250 bar)	41.2	228.1	13	540-560°C, 0.065 bar condenser
PC + FGD, demo _x	supercritical (300 bar)	45	209.4	20	600°C, 0.03 bar condenser
PC-natural gas cofiring	sub-critical	36-37.5	233.3-242.1	7.4-11	15% natural gas input
PC design - coal oil mixture	sub-critical	35	251.2	4.2	40% fuel oil input
PC-CO ₂ flue recycle	sub-critical	27.6-28.6	325.9-337.5	(100)	additional energy use for CO ₂ gas disposal
PC design, H ₂ combustion	sub-critical	8.4	-	(100)	energy use for H ₂ separation 76% of coal heating value, additional energy use for carbon disposal
Combined cycles					
IGCC	sub-critical	43	212.7	18.9	low temperature gas cleaning
PFBC	sub-critical	42	226.7	13.5	high temperature gas cleaning
PFBC-gasification cycle	supercritical (250 bar)	48-49	195.6-199.5	23.9-25.4	high temperature gas cleaning
Pressurised pulverised coal	sub-critical	48	194.2	26	additional energy used for gas cleaning, CO ₂ emissions from desulphurisation
PC-natural gas + FGD, demo _x	sub-critical	40	202.1	22.1	33% natural gas input
PC-natural gas + FGD, demo _x	supercritical (300 bar)	49	166.1	36.6	33% natural gas input
MHD	sub-critical	40-45*	192.5-216.5	17-27	additional CO ₂ emissions from desulphurisation
Fuel cells	sub-critical	45-58*	147.1-192.5	26-44	additional CO ₂ emissions from desulphurisation
Cogeneration					
Combined heat and power (CHP)	sub-critical	77-84	108.9-118.5	54-59	range for PC + FGD, PFBC, and PFBC-gasification cycle

* HHV