SUBSTITUTION OF NATURAL GAS FOR COAL: CLIMATIC EFFECTS OF UTILITY SECTOR EMISSIONS

KATHARINE HAYHOE [1], HAROON S. KHESHGI [2], ATUL K. JAIN [1] and DONALD J. WUEBBLES [1]

[1] *Department of Atmospheric Sciences, University of Illinois, 105 S. Gregory St., Urbana, IL 61801, U.S.A.*
E-mail: hayhoe@atmos.uiuc.edu
[2] *Corporate Strategic Research, ExxonMobil Research and Engineering Company, Annandale, NJ 08801, U.S.A.*

Abstract. Substitution of natural gas for coal is one means of reducing carbon dioxide (CO_2) emissions. However, natural gas and coal use also results in emissions of other radiatively active substances including methane (CH_4), sulfur dioxide (SO_2), a sulfate aerosol precursor, and black carbon (BC) particles. Will switching from coal to gas reduce the net impact of fossil fuel use on global climate? Using the electric utility sector as an example, changes in emissions of CO_2, CH_4, SO_2 and BC resulting from the replacement of coal by natural gas are evaluated, and their modeled net effect on global mean-annual temperature calculated. Coal-to-gas substitution initially produces higher temperatures relative to continued coal use. This warming is due to reduced SO_2 emissions and possible increases in CH_4 emissions, and can last from 1 to 30 years, depending on the sulfur controls assumed. This is followed by a net decrease in temperature relative to continued coal use, resulting from lower emissions of CO_2 and BC. The length of this period and the extent of the warming or cooling expected from coal-to-gas substitution is found to depend on key uncertainties and characteristics of the substitutions, especially those related to: (1) SO_2 emissions and consequent sulphate aerosol forcing; and (2) the relative efficiencies of the power plants involved in the switch.

1. Introduction

Since the beginning of the industrial age, emissions of carbon dioxide, methane and other greenhouse gases, as well as aerosols and their precursors, have increased rapidly. Much of the increase in carbon dioxide and other emissions is attributed to intensified human activity in agriculture, biomass burning, and fossil fuel consumption. This increase has caused a corresponding change in atmospheric composition, which is projected to lead to increases in global temperature (IPCC, 2001). Limiting carbon dioxide emissions is thought to be essential to the long-term mitigation of climate change because carbon dioxide is expected to continue as the dominant anthropogenic greenhouse gas well into the future (e.g., Hansen et al., 2000; IPCC, 2001). Since energy use is the primary source of anthropogenic emissions of carbon dioxide, many strategies for greenhouse gas abatement focus on energy-related emissions.

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Fuel switching, or the substitution of low-carbon fuels for fossil fuels with higher carbon contents, is one of the principal methods suggested to reduce carbon dioxide emissions from energy consumption in the near future (e.g., E7, 2000; Nakicenovic, 2000; Audus, 1999; ORNL, 1997; Watson et al., 1996). In this study, we use the replacement of coal use by natural gas in the electric power generation sector* as a case study to evaluate the net effect of such a fuel substitution on climate. This sector was chosen because the potential for replacing coal-powered facilities by natural gas is well-defined in terms of existing technology and infrastructure, cost, centralized sources, and consequent effect on carbon dioxide emissions. In conjunction with industry, utilities have been identified as one of the main sectors of the economy in which fuel switching could be expected to have a significant impact on GHG emission reductions in the near future, both globally and on a national basis (e.g., Moomaw and Moreira, 2001; IGPO, 2000; Logan and Luo, 1999; Freedman, 1996, 1990; IPCC, 1996c; Johansson et al., 1996).

To assess the effectiveness of an emission reduction strategy as a means of mitigating the *net* impact of human activities on climate, all substantial changes in emissions of radiatively active substances must be included. For the substitution of gas for coal, these include at least four key substances. First, carbon dioxide (CO_2) and black carbon (BC) emissions are expected to decrease with coal-to-gas substitution, thus reducing warming. In addition, methane (CH_4) emissions from coal mining could decrease; however, this decrease may be offset by increased CH_4 emissions from natural gas processing and transportation. Finally, reduction of sulfur dioxide (SO_2) emissions associated with coal use has the potential to warm climate through elimination of the cooling effect of sulfate aerosols, as well as eliminating other environmental effects not related to climate.**

We use the Integrated Science Assessment Model (ISAM) of Jain et al. (1994) to project the impact of substituting natural gas for coal, and the subsequent change in emissions, on global mean-annual near-surface temperature. Using ISAM, we conduct an analysis of the sensitivity of projected temperature change from CO_2, CH_4, SO_2 and BC emissions associated with coal and natural gas use to key factors that affect emission rates and global temperature effects. Four uncertain factors are considered: CH_4 emissions from (1) natural gas use and (2) coal mining, and the radiative forcing associated with (3) sulfate and (4) black carbon aerosols. In these cases we examine the effect of the range of uncertainty in each factor on the temperature change projected from fuel substitution. Three additional factors that are characteristics of the switch are considered: (1) the relative efficiency of coal to natural gas power generation, and emissions of (2) sulfur, and (3) black carbon

* This study only addresses the replacement of coal by gas in order to generate electricity. It does not evaluate the substitution of gas for electricity (e.g., replacing electric heaters with a gas-fired furnace).

** SO_2 produces acidic compounds and sulfate aerosols reponsible for visibility degradation, human health impacts and acid rain, which in turn acidifies lakes and streams, endangers ecosystems, and damages soils, forests and buildings (EPA, 2000b).

from coal combustion that depend on fuel characteristics, technologies applied, and emission controls. We examine how these factors affect the timing and magnitude of temperature change projected to result from coal-to-gas fuel substitution.

Finally, we evaluate the effect of gas-for-coal substitution on future climate change in the context of energy consumption and emissions projected by the Intergovernmental Panel on Climate Change (IPCC, 2000) A1 Balanced (A1b) scenario. Analyses of various fuel substitution scenarios, in terms of extent and scheduling, show the potential range of fuel substitution impacts on the timing and magnitude of projected global temperature change.

2. Calculating the Climate Impact of Coal vs. Gas-Fired Power Generation

2.1. PROJECTIONS OF GLOBAL TEMPERATURE CHANGE

The Integrated Science Assessment Model (ISAM) of Jain et al. (1994) is used together with energy-related greenhouse gas emission data to project and compare the global mean-annual temperature effects of coal and natural gas-related CO_2, CH_4, SO_2 and BC emissions. The ISAM is an integrated climate system model containing gas cycle models to convert emissions of major greenhouse gases to concentrations, an atmosphere and ocean energy balance climate model to calculate temperature change, and a sea level rise model.

ISAM's global carbon cycle component simulates CO_2 exchange between the atmosphere, carbon reservoirs in the terrestrial biosphere, and the ocean column and mixed layer (Jain et al., 1994, 1995, 1996; Kheshgi et al., 1996, 1999a). The model consists of a homogeneous atmosphere, an ocean mixed layer and land biosphere boxes, and a vertically-resolved upwelling-diffusion deep ocean.

In its reduced form as used in this study, atmospheric CH_4 concentrations are calculated by simulating the main atmospheric chemical processes influencing the global concentrations of CH_4, CO, and OH, using a global CH_4–CO–OH cycle model (Kheshgi et al., 1999b). Carbon cycle components are coupled to each other through the atmosphere, and in turn are coupled to a reduced-form energy-balance climate model of the type used in the 1990 IPCC assessment (e.g., Harvey et al., 1997). Thermohaline circulation is schematically represented by polar bottom-water formation, with the return flow upwelling through the 1-D water column to the surface ocean, from where it is returned to the bottom of the ocean column as bottom water through the polar sea. In this study, the updated seasonal and latitudinal GHG radiative forcing analyses of Jain et al. (2000) have been used.

The global temperature change projected by the model is used as an index of climate change. Changes in temperature that are expected to result from fuel switching over various time scales are calculated for an impulse of greenhouse gas, sulfur or black carbon emissions emitted in 2000. In contrast to other calculations that use a background of constant atmospheric composition (global warming potentials, for example), here the unit pulse of each substance decays over the background concentrations resulting from the A1b emissions scenario (IPCC, 2000). Using the changing atmospheric composition modeled from the A1b emissions scenario as background is a more realistic approach than a constant background for several reasons: (1) it includes the impact of increasing concentrations on atmospheric absorption lines, and changing temperatures on atmospheric chemistry; (2) it reveals the growing importance of CO_2 relative to other greenhouse gases and aerosols as CO_2 accumulates in the atmosphere, and (3) it includes the effects of CH_4 and CO emissions on CH_4 lifetime.

One of the key factors relating radiative forcing change to global temperature change in the ISAM model is the equilibrium climate sensitivity parameter. Equilibrium climate sensitivity parameterizes the positive and negative feedback responses of the earth-atmosphere system to radiative forcing. It is a factor used to account for the uncertainty in future global climate projections, even though the full characterization of uncertainty of climate projections is not well established (e.g., NRC, 2001). The value of equilibrium climate sensitivity is quite uncertain (e.g., Morgan and Keith, 1995). Here, we use a reference estimate value of 2.5 °C for a radiative forcing increase produced by a doubling of CO_2 concentration (IPCC, 1996a, 2001). Although a range of climate sensitivity from 1.5 °C to 4.5 °C is commonly considered, the value used does not change the relative effectiveness of coal-to-gas switching, nor the proportion of climate change mitigation relative to baseline. However, the magnitude of the effect does scale with climate sensitivity, as shown in Section 5.

There are other factors responsible for current and future climate variability. These include solar fluctuations, volcanic eruptions, ocean current changes, and their interactions with large-scale atmospheric dynamic patterns, as discussed by NRC (1998). Future climate change will be the result of a combination of human-induced and natural forcings. Since the magnitude of climate variability may well exceed the magnitude of the climate effects from the limited changes estimated from fuel substitution in the power sector considered here, the climate effects of a coal-to-gas substitution may not be directly detectable. However, emissions from the power sector add uniformly to global anthropogenic emissions, and the total anthropogenic effect on climate is projected to far exceed past climate variability (IPCC, 2001). Projections of future climate change due to the effects of fuel substitution are, of course, subject to the many limitations of projections of anthropogenic climate change in general, as discussed in NRC (2001) and Hansen et al. (1998).

2.2. GAS-FOR-COAL SUBSTITUTION UNDER SUSTAINED ENERGY USE

Previous calculations of global temperature change from a one-time emissions pulse from coal and natural gas use (Hayhoe et al., 1998) have shown that, despite a short-term warming caused by sulfate aerosol reductions, the replacement of coal by natural gas at one point in time will result in a net long-term reduction in the rate of temperature rise due to energy-related emissions. Continuous replacement of coal by gas-fired generation, however, is likely to involve a longer period of time before temperature reductions from gas relative to coal use become evident. The delay would primarily be caused by continual aerosol production from coal use, producing a net cooling effect, as opposed to negligible aerosol production from gas use. This offset is similar to the initial decadal- to century-scale warming following the fossil fuel abatement scenarios considered by West et al. (1997) and Wigley (1991). To examine this hypothesis, we conduct a detailed analysis of the climatic impact of substituting gas for coal for continuous operation over 100 years.

A time-dependent normalized index for the mitigation of global temperature change due to electrical power production from natural gas versus coal can be obtained from the ratio of the temperature change projected to occur per unit coal-produced electricity after a given time period to that of natural gas over the same time period. This is given by:

$$R = \frac{\Delta T_{\mathrm{coal}}}{\Delta T_{\mathrm{gas}}}, \tag{1}$$

where ΔT_{coal} is the change in temperature from emissions associated with the generation of a certain amount of electrical power from coal, here taken to be °C per GJ_e of electricity produced from coal, and ΔT_{gas} is the temperature change resulting from the gas-fired generation of the same amount of electricity (1 GJ_e). R is the ratio of the projected global mean temperature effects of coal to natural gas use. Implicit in these values are the different emissions associated with each fuel's use as well as the higher efficiency of natural gas as compared to coal generation. The ratio R is insensitive to the magnitude of fuel substitution considered, and the value of climate sensitivity assumed. As such, these results are applicable over a wide range of spatial scales, from global to regional and even individual cases.

Using global average emission factors and efficiencies given in Tables I and II, the derivation of which are described in detail in the following sections, produces the base case curve that lies in the middle of Figures 1 and 2. In the first 15 years, aerosol emissions from coal use produce a large decrease in global-mean temperature that would be mitigated by the substitution of natural gas; therefore, continued use of coal over 15 years or less leads to a net cooling whereas natural gas use leads to warming, as indicated by $R < 0$. Continued coal use for approximately 15 to 25 years leads to warming, although to a lesser projected extent than with natural gas, with $0 < R < +1$. Considering only global temperature change over this period, substituting gas for coal will not mitigate projected temperature increase. For continuous use beyond 25 years, $R > 1$, indicating that substituting gas for coal will reduce projected temperature increase with long-term use. Note that the length of time before $R > 1$ decreases from 25 to 3 years if aerosol direct forcing alone is considered.

3. Sensitivity to Key Uncertainties

It is clear that these findings are dependent on the uncertainties in estimates of emission factors and radiative forcing associated with CO_2, CH_4, SO_2 and BC. Using the ratio approach described above, we examine the time-dependent sensitivity of the benefits of fuel switching to four uncertain factors: (1) the natural gas loss rate, (2) methane emissions from coal mining, (3) direct and indirect sulfate aerosol forcing, and (4) black carbon direct radiative forcing.

3.1. CO_2 EMISSIONS FROM COAL AND GAS COMBUSTION

Emission factors from a number of sources have been compiled to assess the relative climatic effect of a shift in electricity generation from coal to natural gas (Table I). Fuel substitution in the electric power sector has the potential for significant CO_2 reductions, as it is currently responsible for almost 2100 MtC/yr or 37.5% of global CO_2 emissions from fossil fuels (Moomaw and Moreira, 2001). CO_2 emission factors per unit primary energy are given in terms of the Lower Heating Value* (LHV), which is the convention used by the IPCC in calculations of its emission scenarios (IPCC, 2000, 1996b; Watson et al., 1996).

Carbon emissions from coal depend on the proportion of carbon to hydrogen and oxygen in the coal, as well as the presence of other substances such as sulfur. Carbon emissions increase with coal rank, from bituminous coal through sub-bituminous up to lignite or brown coal (Hong and Slatick, 1994), producing emission factors that range from 16.5 to 29.5 kgC/GJ, depending on coal type. An emission factor of 25.0 kgC/GJ is representative of the global average coal mix used for electricity generation (Table I). For natural gas, carbon emissions depend on the proportion of methane to other substances. Natural gas is generally 90% to 98% pure methane, leading to a relatively small spread around the 'best guess' value of 15.0 kgC/GJ used here (Table I). For both coal and natural gas, the 'best guess' values (Table I) are used throughout, as the sensitivity of the results of this study to the range in CO_2 emission factors is of secondary importance relative to other factors examined here.

The carbon content of natural gas is only 60% that of coal per unit of primary energy content (Table I). Taking into account the higher efficiency of state-of-the-art electricity production from natural gas turbines over the average efficiency for coal power generation, CO_2 emissions per unit gas-fired electricity are at least an additional 30% lower than emissions from coal-fired power (Table II). However, the ability of coal-to-gas switching to mitigate the impact of human activities on global mean temperature does not depend solely on its effect on CO_2 emissions.

* LHV does not include the additional energy from the condensation of water vapor contained in the combustion process.

Table I

Global average emission factors from coal and natural gas use, based on region- and country-specific coal sulfur content, heat content, coal type, and sulfur and particulate controls. Regional maxima and minima determine the range.

Source	Emissions per unit primary energy (kg/GJ [a])	Range
CO_2 (kgC/GJ)		
Coal combustion	25	16.5–29.5 [b]
Natural gas combustion	15	14.8–15.3
CH_4 ($kgCH_4$/GJ)		
Coal mining	0.57	0.02–2.0
Natural gas extraction and transportation – current	0.76 [c]	0.33–2.2 [d]
Natural gas extraction and transportation – future	0.58 [c]	0.33–2.2 [d]
SO_2 (kgS/GJ)		
Coal combustion	0.24	0.02–1.2
Natural gas combustion	0.0003	–
Black Carbon (kgBC/GJ)		
Coal combustion	0.04	0.013–0.18
Natural gas combustion	2.2×10^{-7}	–

[a] Lower Heating Value (LHV) is used after the convention of IEA and IPCC. Higher Heating Value (HHV) decreases emissions per unit energy by approximately 1 kg/GJ, and increases the efficiencies considered by several percent. However, this difference is well within the range of factors affecting the results of fuel switching considered in Section 3.

[b] Range covers carbon emission factors from bituminous, sub-bituminous and lignite coal. Anthracite is excluded as it is primarily used for home heating.

[c] Based on a natural gas methane content of 90%, with 0.5% of total natural gas production assumed to be lost during production and 2.5% during transportation and use. The natural gas loss rate during transportation decreases to 1.5% for current additional and future natural gas use, after GRI (1997).

[d] Corresponds to a natural gas loss rate during transportation ranging from 0.2% to 10% and a loss rate of 0.5% during production.

Sources: Alexandrova, 2000; Barns and Edmonds, 1990; Beck, 1993; Beck et al., 1993; Benkovitz et al., 1996; Creedy, 1993; Coconea et al., 2000; Cooke and Wilson, 1996; Cooke et al., 1999; Energy Information Administration (EIA), 1999, 2000a–d, 2001; Environmental Protection Agency (EPA), 1993a,b, 1996; Gale and Freund, 2000; Gas Research Institute (GRI), 1997; Hargreaves et al., 1994; Harrison et al., 1995; Intergovernmental Panel on Climate Change (IPCC), 1996b,c; International Energy Agency (IEA), 1991a,b,c, 1996, 1998, 2001; Kirchgessner et al., 1993; Kirchgessner, 2000; Lefohn et al., 1999; Liousse et al., 1996; Mitchell, 1993; Saghafi et al., 1997; Slanina et al., 1994; Xueyi, 2000.

Table II

Global average emission factors for coal and natural gas use per gigajoule electricity (GJ_e). Range of emission factors calculated from range in efficiencies only, given in parenthesis.

	Efficiency LHV	Emission per unit electricity			
		CO_2 (kgC/GJ_e)	CH_4 (kgCH_4/GJ_e)	SO_2 (kgS/GJ_e)	BC (kgBC/GJ_e)
Coal	32% (25–43%)	78.1 (62–100)	1.78 (1.3–2.3)	0.75 (0.56–0.96)	0.13 (0.1–0.16)
Natural gas [a]	60% (50–90%)	25 (17–30)	0.97 (0.64–1.2)	5.0×10^{-4} (3.3–6.0×10^{-4})	3.7×10^{-7} (2.4–4.4×10^{-7})

[a] CH_4 emission factors are for natural gas in addition to current use, with a global average loss rate of 1.5%.

Sources: Brown et al., 1998; Casten, 1998; U.S. Department of Energy (DOE), 2000; Energy Information Administration (EIA), 2000c, 2001; Freedman, 1996; Hay, 1990; International Energy Agency (IEA), 1991a,b,c; IEA Greenhouse Gas Research and Development (GHG R&D), 1999; Intergovernmental Panel on Climate Change (IPCC), 1996c, 2000; Johansson et al., 1996; Malek, 1997; Moomaw and Moreira, 2001; Oak Ridges National Laboratory (ORNL), 1997; Watson et al., 1996.

3.2. CH_4 EMISSIONS FROM COAL MINING AND NATURAL GAS LOSS

Processing and consumption of coal and natural gas releases methane, the second most important greenhouse gas emitted by human activities. Changes in absolute methane emissions are small compared to the carbon emission reductions that accompany switching from coal to natural gas. Moreover, the response time of methane in the atmosphere to a given perturbation is approximately 12 years, which is short compared to the hundreds of years over which CO_2 emissions are expected to affect its atmospheric concentration (IPCC, 2001). However, an increase in the atmospheric concentration of CH_4 leads to an absorption of infrared radiation that is 24 times stronger per unit mass than an equivalent increase in CO_2 concentration over 100 years (WMO, 1999). Methane is also responsible for indirect forcing effects that result from the production of other greenhouse gases: tropospheric O_3, stratospheric water vapor, and CO_2. We add 30% to the direct radiative forcing for CH_4 in order to account for these indirect effects (Wuebbles et al., 2000; Lelieveld et al. 1998, 1993; Fuglestvedt et al., 1996; IPCC, 1995; Brühl, 1993).

The net change in methane emissions incurred by an increase in natural gas use and a decrease in coal use is an important factor determining the effectiveness of replacing coal by natural gas. Despite the significance of gas and coal-related CH_4 emissions to atmospheric concentrations (e.g., Law and Nisbet, 1996; Lelieveld et al., 1993; Tie and Mroz, 1993), considerable debate exists concerning the magnitude of the CH_4 emission factors. This debate is due to issues such as measurement difficulties and large regional variations in sources. For CH_4 emissions, we have chosen to examine a range in emission factors spanning regional variations rather than the smaller uncertainty in global average values in order to explore the full potential impact of CH_4 emission factors on fuel substitution. In terms of regionally-dependent emission factors, methane emissions could be a design criteria for an individual power generating facility, coal mine, or pipeline. However, emissions assessments of the entire system contain uncertainty (±40% for the U.S. national estimate alone (EIA, 2000d)) and are therefore considered in this section rather than with the other design criteria considered in Section 4.

During coal extraction, methane trapped in and around coal is released to the atmosphere. Global and regional estimates of CH_4 emissions from coal and mines depend on many factors: type of coal, depth of the mine, mining practices, methane content of the coal seams, whether methane is flared or released, and other environmental conditions. In this analysis, a global average emission factor of 0.57 kgCH_4 per GJ of coal produced has been taken to be representative of emissions from underground, surface, and post-mining operations. This value was calculated based on the latest consistent, region-specific estimates of methane emission factors, coal heat content, and coal production (EIA, 2000b; IEA, 1998; Saghafi et al., 1997). However, estimates of methane emission factors from individual underground mines can range from 0.02 kgCH_4/GJ to over 2.0 kgCH_4/GJ (Gale and Freund, 2000; Kirchgessner, 2000, and references therein; Xueyi, 2000; Saghafi et al., 1997; Beck, 1993; Kirchgessner et al., 1993; Barns and Edmonds, 1990). The importance of this range to the effectiveness of fuel switching as a means to reduce climate change is assessed in Figure 1a.

Figure 1a shows that the estimated range in coal mining emissions (see Table I) gives a moderate range of ratio values. Using the highest rather than the lowest emissions estimate accelerates the point at which the substitution of gas for coal begins to reduce temperature change by a decade. After 100 years, coal use results in climate warming that is 2.05 to 2.4 times greater than the climate warming resulting from natural gas, depending on CH_4 emission factors for coal mining. Thus, the emphasis that some literature (e.g., Tie and Mroz, 1993; Lelieveld et al., 1993; GRI, 1997) has placed on the uncertainty in the gas loss rate rather than emissions from coal mining when evaluating coal-to-gas switching may not be justified.

Methane is also emitted when natural gas is lost at any time during its production, transmission, and distribution. Although the global average loss rate for natural gas transmission is likely between 2% and 4% (Kirchgessner, 2000; GRI, 1997; Harrison et al., 1995; Beck, 1993; Beck et al., 1993; EPA, 1993b; Barns and Edmonds, 1990), regional leakage percentages have been estimated to range from 1% to as high as 10% of total natural gas production, depending on the quality of the pipelines, the extraction process, the method used to estimate gas losses, and other factors (e.g., Alexandrova, 2000; Coconea et al., 2000; Kirchgessner, 2000; Mitchell, 1996; Slanina et al., 1994; Beck et al., 1993). Alternatively, the loss rate of additional natural gas could be only 20% to 70% of the present loss rate due to

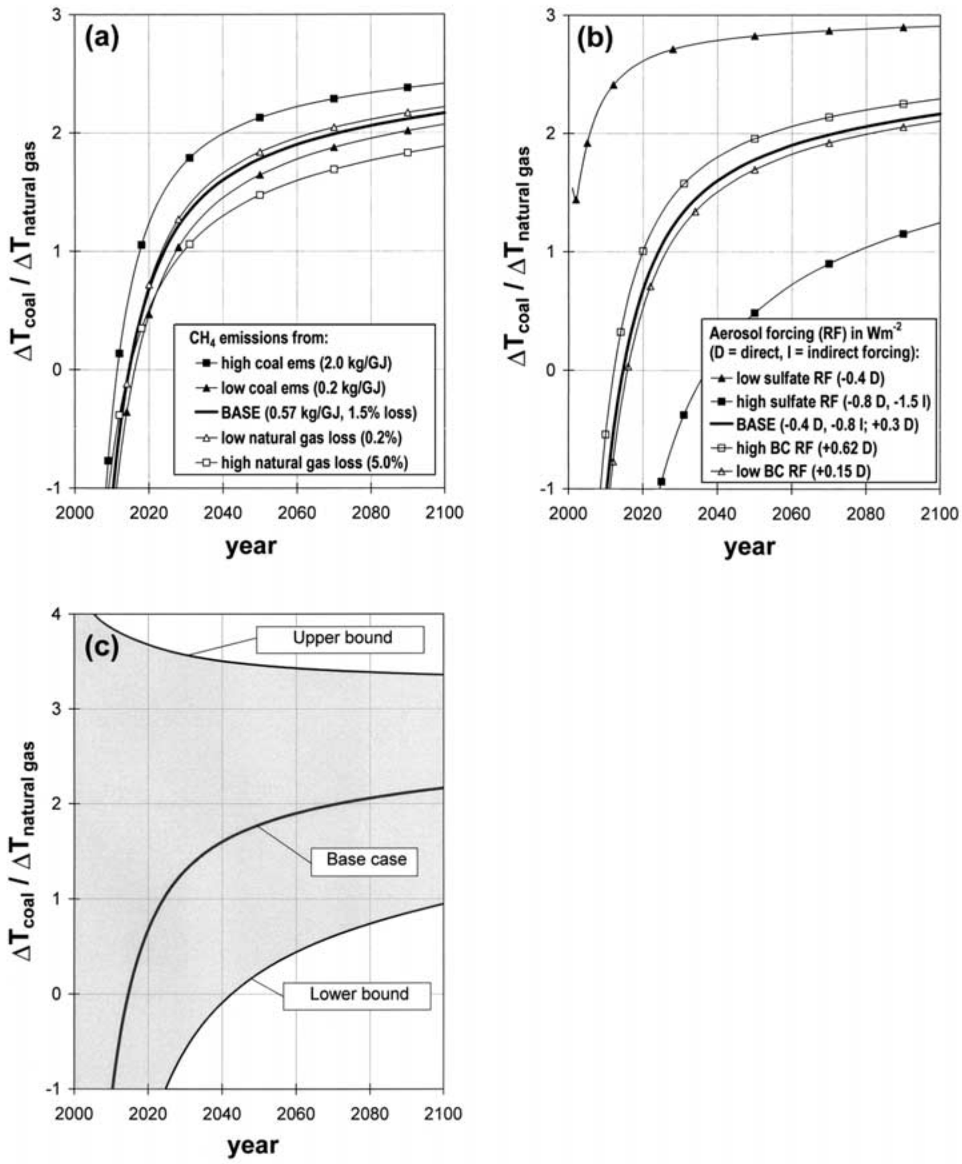

Figure 1. Ratio, R, of temperature change from coal-fired electricity generation to temperature change from natural gas-fired generation, per unit electricity generated. When $R > 1$, projected global temperature increase from coal use is greater than that from natural gas. Switching from coal to natural gas would thereby reduce projected global warming. Results illustrate the sensitivity of temperature projections of fuel switching on the following uncertain factors: (a) CH_4 emissions from coal mining and natural gas loss, (b) direct and indirect radiative forcing due to sulfate aerosols, and direct forcing due to black carbon aerosols, and (c) net range due to combined uncertainties. Ranges shown for each factor are given in Table I, with all other factors held fixed at base case values.

the use of the excess capacity of pre-existing systems as well as the construction of facilities with improved leakage control (GRI, 1997; Harrison et al., 1995). Thus, the relevant loss rates for individual or regional fuel substitution may be anywhere from 0.2% to 10%.

The emission factor of 0.58 kgCH_4/GJ given in Table I is based on a transportation loss rate of 1.5% for the additional increment of natural gas used for fuel switching, while an emission factor of 0.76 kgCH_4/GJ corresponds to a current global average loss rate of 3%. Figure 1a shows that if the average natural gas loss rate involved in a coal-to-gas switch were as large as 2.2 kgCH_4/GJ for a 10% loss rate, a decrease in climate warming would not become apparent until 30 years afterwards. This delay is shortened to 24 or 25 years for emission factors of 0.33 or 0.58 kgCH_4/GJ if the loss rate of the additional natural gas used were 0.2% or 1.5% (base case). These results compare well with the 'break-even' points at which the climatic effects of coal use will equal those of natural gas calculated by GRI (1997) and Lelieveld et al. (1993). It is also interesting to note that the uncertainty in coal mining emissions tended to increase the attractiveness of gas relative to coal, while the range of natural gas loss rates mainly acts to reduce the effectiveness of coal-to-gas substitution.

Whether natural gas or coal emission rates in a given region are low or high, these results project that coal-to-gas switching would reduce projected global temperature increase within a maximum of three decades after its implementation, given a 'best guess' estimate for sulfate aerosol direct and indirect forcing. However, this result changes when the uncertainties in sulfate aerosol radiative forcing are included.

3.3. SULFATE AEROSOL PRODUCTION AND FORCING

Sulfur dioxide (SO_2) emissions result from the combustion of fossil fuels containing sulfur. In the atmosphere, SO_2 is quickly oxidized to sulfuric acid, which in turn condenses onto cloud droplet and aerosol particle surfaces to form sulfate aerosols. Coal-fired electricity generation is one of the most important sources of anthropogenic aerosols, generating two-thirds of SO_2 emissions from U.S. sources (EPA, 1997) and a major portion of global emissions (Benkovitz et al., 1996; IPCC, 1996a).

Due to their lifetime of a few days to weeks, sulfate aerosols are inhomogeneously concentrated over areas such as the Northern Hemisphere continents, downwind of major SO_2 emitters. In contrast, longer-lived GHGs are relatively well-mixed. Because of the strong regional nature of aerosol concentrations, a global-mean annual forcing and a linear sum of the combined effects of aerosols and greenhouse gases may underestimate the climatic effect of aerosol forcing (IPCC, 1996a; Taylor and Penner, 1994). Localized aerosol forcing, however, has been found to create a non-local climate response pattern that resembled that of GHGs (Reader and Boer, 1998). In either case, the magnitude of aerosol forcing is such that it has the potential to counter a large share of the warming from greenhouse gases (IPCC, 2001; Kiehl and Briegleb, 1993). On this basis aerosol forcing effects are included in this study, which examines only global annual-mean temperature, and does not resolve any spatial scales. Their inclusion in this analysis will at least provide an approximate and perhaps conservative estimate of the contribution of aerosols to the climatic impact of switching from coal to natural gas.

It has already been shown in Figure 1a that coal-to-gas substitution results in an initial climate warming due to sulfur emission reductions. This is the result of the direct effect of sulfate aerosols being the scattering, rather than the absorption, of solar radiation. This scattering produces a negative radiative forcing of the opposite sign to the warming effect of greenhouse gases that cools the Earth's surface. In addition, the contribution of aerosols to cloud condensation nuclei is thought to produce an indirect cooling effect which may be more than twice that of the direct effect (Haywood and Boucher, 2000). In contrast to the radiative forcing for well-mixed greenhouse gases such as CO_2 and CH_4, the relationships between SO_2 emissions, sulfate aerosol loading, and radiative forcing contain numerous uncertainties and spatial variations, depending on regional conditions such as atmospheric chemistry, humidity and cloud cover (e.g., Adams et al., 2001; Rasch et al., 2000; Boucher et al., 1998; West et al., 1998; Pan et al., 1997, 1998).

In this study, the current annual global direct and indirect aerosol forcing are the IPCC 'best-guess' estimates of –0.4 W/m^2 and –0.8 W/m^2, respectively (IPCC, 2001). Both the direct and indirect forcing associated with anthropogenic sulfate aerosols is highly uncertain, with a range of at least –0.2 to –1.0 Wm^{-2} for the direct effect, and from zero to more than –1.5 Wm^{-2} for the indirect effect (IPCC, 2001; Adams et al., 2001; Haywood and Boucher, 2000; Kiehl et al., 2000). Global mean-annual temperature change due to direct and indirect forcings is assumed to be equivalent and additive here. This is a simplifying assumption, since the temperature effects of direct forcing are concentrated over Northern Hemisphere continents where maximum emissions occur, while temperature change resulting from the indirect effect has been modelled to be strongest over the Northern Hemisphere oceans (Chuang et al., 1997; Feichter et al., 1997; Erickson et al., 1995). The sensitivity of the coal-to-gas ratio R to this range in aerosol forcing is shown in Figure 1b.

When the 'best guess' estimates of direct and indirect radiative forcing are used in the base case, the benefits of fuel switching are delayed by 25 years. However, for direct radiative forcing coefficients of –0.4 Wm^{-2} or less with a negligible indirect effect, sulfate aerosols will not delay the projected temperature decrease due to fuel switching for any significant length of time. The replacement of coal by natural gas use will reduce projected global temperature change (as indicated by $R > 1$) over all time scales longer than 1 year. For strong negative aerosol forcing, –0.8 Wm^{-2} for the direct effect and –1.5 Wm^{-2} for the indirect effect, continuous coal use for almost 80 years has a mitigative effect on global warming relative to natural gas use (as indicated by $R < 1$) due to the cooling effect of aerosols.

Uncertainty in sulfate aerosol radiative forcing coefficients produces the largest variation in the relative climatic effects of coal and gas use of any of the uncertain factors examined here. Clearly, the effects of a coal-to-gas switch may not be observed over the lifetime of a single power plant if sulfate aerosol forcing lies at the strong end of the range. However, given a long enough time horizon, the warming caused by reducing short-lived SO_2 emissions will be outweighed by the cooling effect of mitigating longer-lived greenhouse gas emissions. Further potential to offset sulfate-induced cooling arises from coal-related emissions of another short-lived aerosol, black carbon.

3.4. BLACK CARBON AEROSOLS AND FORCING

Black carbon (BC) contained in soot forms the nuclei of infrared-absorbing carbonaceous aerosols that have been identified recently as significant contributors to positive radiative forcing. Major anthropogenic sources of BC* are split evenly, with coal and diesel combustion accounting for approximately 50% of emissions, while biomass burning makes up the remainder (Cooke et al., 1999; Cooke and Wilson, 1996; Liousse et al., 1996). Using the latest country- and region-specific statistics for hard and brown coal use and heat content (EIA, 2000b; IEA, 1998) weighted by regional black carbon emission factors from Cooke et al. (1999), a global average emission factor of 0.04 kgBC/GJ was calculated (Table I).

Carbonaceous aerosols have a short lifetime of only 4–8 days (Cooke et al., 1999; Cooke and Wilson, 1996; Liousse et al., 1996), comparable to that of sulfate aerosols. Hence, their radiative forcing and temperature impact were modelled to decay with the same impulse response function as sulfate aerosols, with a current direct radiative forcing of +0.3 Wm^{-2} for externally mixed aerosol particles arising from both fossil fuel use and biomass burning (Cooke et al., 1999; Haywood et al., 1997; Myhre et al., 1998).

The estimated direct forcing of black carbon aerosols has been found to be strongly affected by the mixing state of the aerosol (Haywood and Boucher, 2000). Previous estimates of direct radiative forcing by fossil fuel black carbon range from +0.16 Wm^{-2} for an external mixture to +0.42 Wm^{-2} for black carbon internally mixed with sulfate (Haywood and Boucher, 2000; Haywood et al., 1999; Shine and Forster, 1999; Haywood and Ramaswamy, 1998; Myhre et al., 1998; Penner et al., 1998). However, recent studies by Jacobson (2001a,b) find a global fossil fuel + biomass burning direct forcing ranging from +0.31 Wm^{-2} for an external

* Combustion also results in emissions of organic carbon (OC), with the ratio between black and organic emissions being primarily dependent on the combustion temperature. Since most electricity generating plants operate at very high temperatures, industry is a major source of BC, while domestic fuel use is mainly responsible for OC emissions. For this reason, only BC has been included in this analysis.

mixture, through +0.55 Wm^{-2} for a multiple-distribution coated core, and up to +0.62 Wm^{-2} for internally mixed, coated-core black carbon.

In Figure 1b we examine a range in global annual BC forcings from +0.15 to +0.62 Wm^{-2}. The impact of this range on the coal/gas temperature ratio R is not large in comparison to other uncertainties examined here. Hence, the uncertainty in BC direct forcing, while high, has a limited effect on the outcome of coal-to-gas switching. A doubling of BC radiative forcing will increase the effectiveness of coal-to-gas switching, here reaching a ratio of 2.3 vs. the base case ratio of 2.15 by 2100. It would also decrease the delay before the temperature change mitigation due to natural gas substitution were observed by 5 years, as the stronger forcing from black carbon would offset the cooling effect of sulfate aerosols to a greater degree. This offsetting effect is likely to occur with a similar regional pattern of forcing, due to the similarity in fossil fuel sources and lifetime.

It should be noted that the inclusion of black carbon as the only aerosol with a warming effect might underestimate the absorption of infrared radiation by atmospheric aerosols. Several studies (Adams et al., 2001; Gaffney and Marley, 1998) have shown that sulfate, nitrate and other soluble species dissolved in wet aerosols can be both strong absorbers and reflectors.

3.5. NET UNCERTAINTY

The largest uncertainty considered is that associated with the direct and indirect radiative forcing for sulfate aerosols – but does this uncertainty render the others negligible? A clearer picture is obtained by examining two scenarios that bound all the uncertainty ranges given here (Figure 1c). The case giving a 'lower bound' estimate of R in Figure 1c has CH_4 emissions from coal mining falling at the smallest end of the range while CH_4 emissions from natural gas are at the highest end. Sulfate aerosol forcing is maximized and black carbon forcing minimized. In this case, coal-to-gas switching would not result in temperature change mitigation (as indicated by $R > 1$) until 100 years after implementation. In comparison to the delay with maximum sulfate forcing alone, considering the uncertainty in CH_4 emissions and BC forcing adds over 20 years to the length of time before climate change mitigation is observed.

The case giving an 'upper bound' estimate of R in Figure 1c has the lowest end of the range of CH_4 emissions from natural gas use, high CH_4 emissions from coal mining, and low sulfate and high black carbon aerosol forcings. For the upper bound estimate of R, projected global warming mitigation caused by substituting gas for coal is seen immediately. In this case, coal use produces well over 3 times the temperature change due to natural gas use over all time horizons, exceeding the low sulfate aerosol forcing ratio shown in Figure 1b.

4. Sensitivity to Key Characteristics

These findings are also dependent on the many assumptions that have been made regarding emission controls, relative efficiencies, and fuel characteristics. Estimates of sulfur and black carbon emissions from coal, and the relative efficiencies of coal to gas power generation are characteristics of a fuel switch that can be chosen, and the characteristics of this choice will affect the extent to which fuel switching alters projections of temperature change. Using the same ratio approach, we examine the time-dependent sensitivity of the benefits of fuel switching to key options in a given gas-for-coal substitution.

4.1. RELATIVE EFFICIENCY OF COAL-FIRED TO GAS-FIRED TECHNOLOGY

The difference between the efficiency of coal-fired versus gas-fired electricity generation is a characteristic of a fuel substitution that strongly affects projections of global temperature change. Efficiencies for coal- and gas-fired utilities used in this analysis are given in Table II, along with an emission factor per unit electricity production for each fuel, following from the primary energy emission factors given in Table I.

Figure 2a shows the ratio R for three ratios of coal-to-gas efficiency. The base case value of 0.53 corresponds to the substitution of a natural gas combined-cycle plant with the current average efficiency of 60% for a coal-fired unit with an efficiency of 32%. The base case assumes that the less efficient coal-powered facilities will be replaced by the latest natural gas combined-cycle technology. These values might be considered conservative, as average coal-powered plant efficiencies in a number of countries are lower than 30%. In addition, when natural gas co- or tri-generation is considered, the effective efficiency of the system can rise to over 90% (e.g., Moomaw and Moreira, 2001; Casten, 1998; Malek, 1997), although the energy service provided in such a system is not always directly comparable to that of electricity generation. The low end of our range is a ratio of 0.27 that could represent the substitution of a gas-fired co-generation plant with an efficiency of 90% for a 25% efficient coal-fired plant. Lastly, a ratio of 0.8 could represent the substitution of a 55% efficient gas-fired plant for a coal-fired plant with an efficiency of 40%. In the future, coal gasification has the potential to reach efficiencies of 50% (DOE, 2000); however, substitute gas use efficiencies greater than 63% would keep the coal/gas efficiency ratio within the range examined here.

Assuming the high efficiency ratio of 0.8 rather than the low efficiency ratio of 0.27 delays the reduction in temperature change due to the switch, as indicated by $R > 1$, by 15 years. This may be significant, considering that the average lifetime of a power plant is several decades. In the long term, the lowest efficiency ratio of 0.27 produces the highest ratio of coal-to-gas temperature change of any of the individual variables examined in this sensitivity analysis, reaching a ratio of 4 before 2100. Substitution of high efficiency gas technology (e.g., co- or tri-

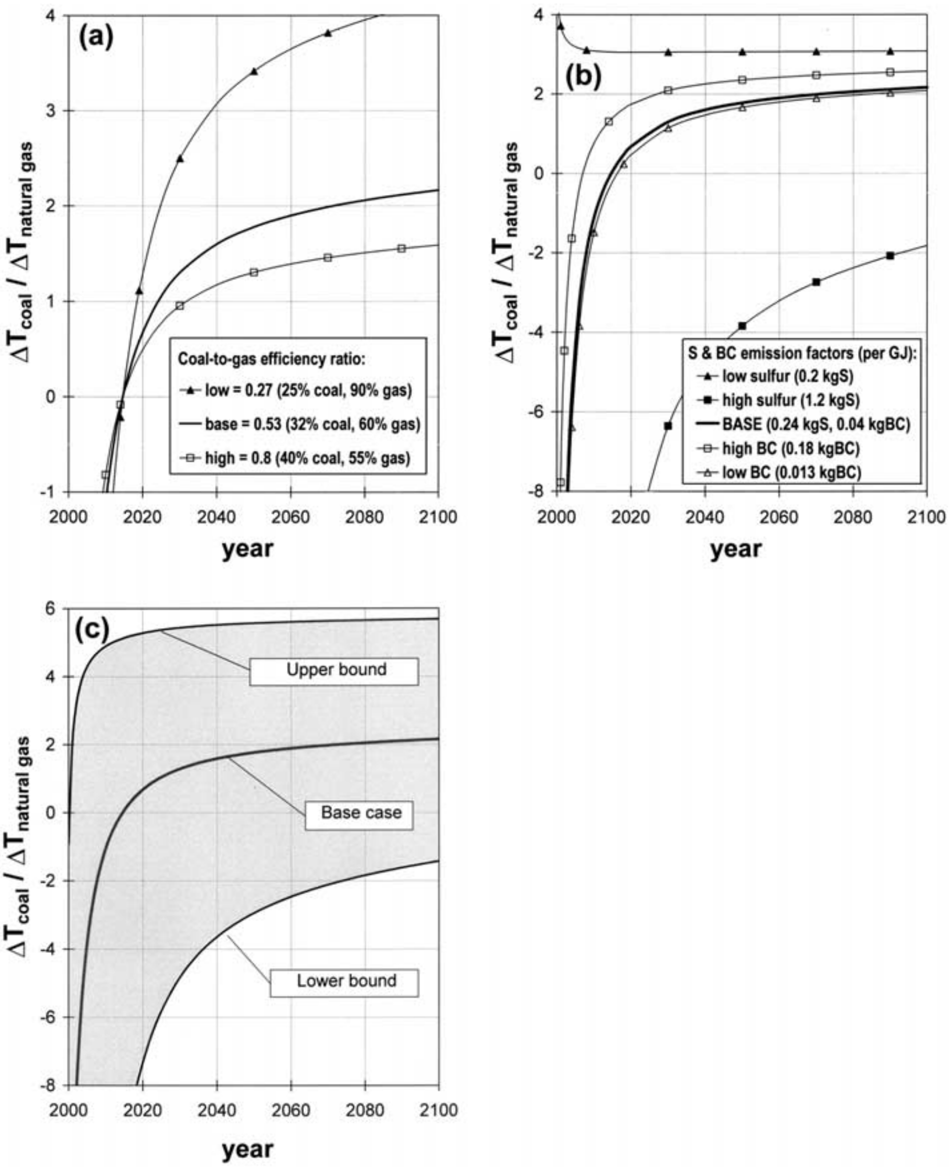

Figure 2. Same ratio as in Figure 1, illustrating the dependence of the climatic effect of fuel switching on the following choices to be made during implementation: (a) the ratio of power generation efficiencies for coal to those for natural gas; (b) the equivalent sulfur content of coal, including both the actual sulfur content and the amount of sulfur removed; black carbon emissions from coal, affected by coal type and particulate controls; and (c) net impact of all options, considered together. Ranges shown for each factor are given in Tables I and II, with all other factors held fixed at base case values.

generation) for low-efficiency coal plants is therefore projected to have the greatest effect on temperature change for all characteristics of coal-to-gas switching.

4.2. SULFUR EMISSIONS FROM COAL USE

Sulfur dioxide emissions from coal vary significantly due to the range in coal sulfur content of different types and from different regions around the world. This affects the outcome of a given fuel substitution: for example, if a high-sulfur-emitting facility rather than low-emitting one is replaced by natural gas, a larger initial warming of climate would be expected due to a reduction in short-lived sulfate aerosols.

The sulfur content of coal can be as low as 0.5% for anthracite and well over 3% for some types of lignite (e.g., Benkovitz et al., 1996; EPA, 1996; Hargreaves et al., 1994). Depending on the energy content of the coal, corresponding uncontrolled sulfur emission factors can range from less than 0.2 to over 1.2 kgS/GJ. In addition, the amount of sulfur emitted during combustion and electricity production can be reduced by technologies such as boiler additives that reduce sulfur emissions by 50–70%, and post-combustion 'scrubbing' that can remove over 95% of SO_2 from flue gas (DOE, 2000; EPA, 1996; Princiotta, 1990). In this analysis, a global average base case emission factor of 0.24 kgS/GJ is used, based on the latest regional and global statistics concerning emissions control technology, sulfur content, heat content, and production data for hard and brown coal (EIA, 2001, 2000b; Lefohn et al., 1999).

In Figure 2b, the impact on the coal-to-gas global temperature ratio of a range of emission factors from 0.02 to 1.2 kgS/GJ is examined. The lowest value of 0.02 kgS/GJ, could correspond to emissions from a facility powered by coal with a sulfur content of 0.8%, for example, and a 95% rate of sulfur removal from flue gas using a lime-based solvent.⋆ The highest emission factor of 1.2 kgS/GJ could correspond to the use of coal with a sulfur content of 3% with no emission controls in place.⋆⋆

In the presence of significant SO_2 emissions controls, the impact of coal-to-gas switching will be positive over all time scales, as indicated by $R > 1$. Any combination of coal sulfur content and emissions controls up to the global average is projected to result in mitigation of global warming with coal-to-gas switching over time horizons greater than 25 years. However, the use of coal with a high sulfur content and no controls has such a large impact on climate, particularly if both

⋆ These conditions exist in the U.S., for example, at the Escalante 1 plant of the Plains Electricity Generation and Transportation Coop, and the Coalstrip 3 and 4 plants of the Montana Power Co. (EIA, 2000c).

⋆⋆ These conditions could apply to a number of locations outside of the U.S. and Western Europe lacking sulfur controls (e.g., Lefohn et al., 1999). Coal with sulfur contents higher than 7% is produced in many locations including the midwest United States (EIA, 2000c). However, average power plant emission factors generally remain below this level by using fuel mixtures or by implementing SO_2 emission controls; hence, we have taken this value as our upper bound.

direct and indirect sulfate aerosol forcing are considered, that switching to gas will have a net warming effect due to the removal of aerosol precursor emissions over time horizons beyond 100 years. When only aerosol direct forcing is considered with high sulfur emissions, however, a reduction in global temperature change is seen after 36 years. Next to the uncertainty in aerosol radiative forcing, which also affects the relative climatic importance of sulfur emissions compared to CO_2 and CH_4, the range of SO_2 emissions produces the greatest variation in the impact of fuel substitution in the electricity sector on the length of time before global temperature change occurs due to the substitution.

These results may suggest a form of climate engineering – allowing SO_2 emissions from coal-fired power plants in order to use the cooling effects of aerosols to offset greenhouse warming. Such options have been the subject of recurring discussion (e.g., Hansen et al., 2000; Dickinson, 1996; Schneider, 1996) as they raise many questions, from ethical and legal issues (Bodansky, 1996; Jamieson, 1996; Schneider, 1996) to practical questions regarding the magnitude of sulfate aerosol loading that would be required to counteract climate warming (Dickinson, 1996). However, due to their impact on local and regional air pollution, SO_2 emissions are already being controlled in some coal-fired plants in North America and Europe. Recent emission scenarios include a decreasing ratio of SO_2 emissions to coal use in the future, regardless of their impact on climate (e.g., IPCC, 2000).

4.3. BLACK CARBON EMISSIONS FROM COAL USE

Black carbon emissions from coal use depend on the type of coal. Lignite or brown coal used for electricity generation in Eastern Europe, for example, has much higher emissions than hard or bituminous coal (EIA, 2000b). Emissions are also affected by the efficiency of the equipment used, as lower efficiency often results in lower combustion temperatures and hence higher black carbon and total particulate emissions. SO_2 and particulate control devices simultaneously remove some black carbon. However, black carbon particles span a wide range of radii, from sub-micron to bulk. The removal efficiency of control devices decreases with decreasing size, so control devices may remove 99% of large particles down to only 10% of sub-micron particles (EPA, 1996). Following Cooke et al. (1999), we assumed an average removal efficiency for BC particles of 50% in developed countries and no controls in developing nations for our base case.

In Figure 2b we examine the sensitivity of our results to a range in black carbon emission factors. At the low end of the range, an emission factor of 0.0126 kgBC/GJ corresponds to the coal type, heat content and emission controls currently existing in Canada and the U.S., where black carbon emissions are low and their contribution to the impact of fuel switching is small. At the high end of the range, an emission factor of 0.18 kgBC/GJ could represent an average coal-fired plant in Eastern Europe or South-East Asia, where coal heat content is low, as lignite is frequently used and emission controls are minimal.

This range in BC emissions results in a wider spread than the uncertainty in BC forcing examined in Figure 1b. For high emissions, coal-to-gas fuel substitution results in a projected reduction in warming after 12 years, as opposed to 25 years for the global average case and 28 years for the low BC emissions case. Again, this is due to black carbon eliminating some of the 'masking' effect caused by reduction in sulfate aerosols. Taken alone, these results would suggest that despite the large uncertainty in forcing, judicious selection when substituting natural gas for coal may enable significant BC emission reductions, thus contributing to the short-term mitigation of climate warming suggested by Hansen et al., 2000. However, SO_2 and other particulate emissions controls simultaneously remove BC, leading to a correlation between BC and SO_2 emissions. Coal-to-gas substitution simultaneously eliminates any warming effect due to BC emissions as well as a significant cooling effect due to sulfate aerosols. Although regional variations in coal sulfur content would make it possible to select some individual power plants with lower-than-global-average SO_2/BC emission ratios, the radiative effect of sulfate aerosols will generally dominate. This will lead to a net warming effect due to reduction in sulfate aerosol formation from a coal-to-gas substitution, despite the concomitant reduction in black carbon.

4.4. NET IMPACT OF FUEL SWITCHING CHOICES

When the full range of options, including efficiency, sulfur and black carbon emissions are combined in Figure 2c, it can be seen that the upper and lower bounds on *R* are broader than the bounds caused by the range of uncertainties shown in Figure 1c. The highest coal-to-gas ratio consists of a low-efficiency coal plant with low SO_2 and BC emissions* being converted to a high-efficiency gas-fired plant. Here, the projected global temperature increase due to coal-fired electricity production rises to almost 6 times that of gas-fired generation. In contrast, for a small coal-to-gas efficiency ratio and high SO_2 and BC emissions, the cooling effect of aerosols is so large that coal use produces an absolute net cooling effect over time scales extending beyond 100 years.

This suggests that although the uncertainties involved in calculating the effect on global temperature of coal-to-gas switching are large, the range of choices that can be made are even more important. Selection of the coal plants to be replaced and the natural gas replacement technology could enhance the potential for this strategy to reduce the net climate impacts of fossil fuels on climate, regardless of uncertainties involved.

* Although low SO_2 and high BC emissions would produce a more favorable scenario for coal-to-gas switching, it is unrealistic to assume SO_2 controls without BC emissions also being controlled.

5. Potential Mitigation of Projected Temperature Change

To compare the absolute projected magnitude of global mean temperature change resulting from the substitution of natural gas for coal use in electricity generation, we use the following index:

$$\delta T\,(^{\circ}\mathrm{C}) = \Delta T_{FS} - \Delta T_{noFS}\,, \tag{2}$$

where ΔT_{noFS} (no fuel switch) is the reference global mean temperature change that would occur for a given amount of electricity produced by coal and gas use as specified by a baseline scenario. ΔT_{FS} (fuel switch) is the change in temperature that would be caused by replacing a specified percentage of electricity production from coal use in the baseline scenario by the equivalent amount of electricity production from natural gas. δT, the difference between the 'coal-to-gas fuel switch' case and the baseline case, represents global temperature change mitigation or enhancement (for a net reduction or increase in global warming) caused by a coal-to-gas switch relative to the baseline case with no switching. Using this representation, the δTs resulting from the replacement of a given percentage of coal-fired electricity production by gas can be evaluated.

5.1. BASELINE EMISSIONS SCENARIO AND ASSUMPTIONS

A baseline energy use scenario is used to illustrate the mitigation potential of fuel switching on future projections of global temperature change. The baseline scenario provides a reference relative to which the projected global temperature effects of fuel substitution as a means of climate change abatement can be compared. Future scenarios of energy use are generally based on assumptions regarding population, economic growth, energy use, end-use efficiency, and the implementation of environmental policies. The baseline scenario chosen for this analysis is the IPCC A1 Balanced scenario (A1b) as calculated by the MiniCam model (IPCC, 2000). The A1b scenario is that of rapid economic growth, the introduction of new and more efficient technologies, and a balance between fossil and non-fossil energy sources (IPCC, 2000), all under the hypothetical assumption that no future climate change mitigation measures take place. We use the A1b projections of coal and gas use in the electric power sector and net electricity production from each fuel, together with emission factors calculated here, to project the impact of coal-to-gas substitution on global temperature in the future.

Under this scenario, we assume that CO_2 emissions per unit primary coal energy consumption in the electricity sector will remain unchanged. Global average CH_4 emission factors are expected to decrease slightly due to market-driven controls on methane from natural gas and coal mining, which can be trapped and used for its fuel value, as well as currently existing actions on climate change (e.g., Alexandrova, 2000; Coconea et al., 2000; Beck, 1993; Beck et al., 1993; EPA, 1993a,b). Under this scenario, global average CH_4 loss rates are projected to decrease linearly from 3% in 2000 to 1.5% by 2100, where 1.5% is the estimated loss rate for current additional natural gas use (GRI, 1997).

To mitigate impacts on air quality, acidification, and human health (see second footnote on p. 108) SO_2 emissions are now being controlled at some coal-fired plants in Australia, Europe, Japan, and North America (EPA, 2000a, 1997; Lefohn et al., 1999; Mylona, 1996). However, complete elimination of sulfur emissions is not project to occur in this century (IPCC, 2000). Inherent to the A1b scenario is a decrease in SO_2 emissions per unit coal use over all sectors. This relationship has been used to scale the current global SO_2 and BC emission factors from their current values of 0.24 kgS and 0.04 kgBC per gigajoule of primary coal energy consumption to 0.05 kgS and 0.009 kgBC per gigajoule by 2100.

In A1b, we assume global average coal efficiencies to begin at 32% in 2000 and grow to the current best available efficiency of 45% by 2100, while natural gas average replacement efficiencies begin at 60% in 2000 and grow to 95% by 2100. Alternate scenarios are possible, and so these results are not be taken as an indicator of the exact magnitude of the contribution of fuel switching to climate change mitigation, but are the results of one scenario set subject to factors such as those explored in Figures 1 and 2.

5.2. SENSITIVITY TO AMOUNT OF SUBSTITUTION

We examine the impact of replacing 10, 25 and 50% of global coal use in the utility sector by natural gas in terms of equivalent electricity production, relative to the baseline scenario. To put this in context, a 25% reduction in coal use in the electricity sector corresponds to approximately 13% of net world coal use being replaced by natural gas at year 2000 rates, and is in addition to any such replacement that may already be accounted for in the A1b scenario. For the substitution of 10%, 25% and 50% of global coal use in the utility sector, substitution is specified to occur gradually over 25 years at 0.4%, 1% and 2% per year, respectively. Gas-for-coal substitution, and the resulting changes in emissions, is modelled to occur across all regions, in proportion to A1b's time-dependent consumption of coal for electricity generation in that region. Global average emission factors based on regional characteristics and fuel use are used. These differ from individual region-specific emission factors; hence, results may slightly under-estimate the mitigation of projected global temperature rise of fuel switching from developed nations such as the U.S. or Europe where sulfur emissions are already controlled, and over-estimate that for developing countries with high sulfur emissions. Conversely, fuel switching mitigation of projected global temperature rise may be over-estimated in developed nations with, on average, higher efficiency coal-fired power plants, and under-estimated in developing nations with, on average, inefficient ($<25\%$) coal-fired power generation.

Figure 3a shows the estimated effect on global temperature change for 10%, 25% and 50% gradual coal-to-gas switching from 2001 to 2025. The 'break-even' point at which natural gas substitution leads to an equal global temperature change as coal use (for all percentage substitutions) occurs in 2029, 28 years after beginning and 3 years after completing the substitution. In these results, the magnitude of the projected global temperature response increases in proportion to the extent of fuel switching, with 10% to 50% resulting in global temperature change reductions from 0.14 °C to 0.68 °C for a climate sensitivity of $\Delta T_{2\times CO_2} = 2.5\,°C$. Using a similar climate model, IPCC's projected global temperature rise for the A1b scenario is approximately 2.8 °C from 2000 to 2100 (IPCC, 2001). This range of fuel substitution is therefore projected to mitigate from 5% to 25% of the temperature change projected for A1b. The range also scales with climate sensitivity, ranging from a minimum of 0.08 °C for a 10% fuel switch with $\Delta T_{2\times CO_2} = 1.5\,°C$ to a maximum of 1.2 °C for a 50% fuel switch with $\Delta T_{2\times CO_2} = 4.5\,°C$, covering the range of climate sensitivity considered by the IPCC (2001). However, the ratio of projected temperature change due to each fuel's use is unaffected by climate sensitivity. Regardless of the actual sensitivity of climate, switching from coal to gas will continue to reduce temperature change by the same percentage relative to net projected global warming.

5.3. SENSITIVITY TO TIMING OF SUBSTITUTION

The initial year and the length of time over which coal to natural gas substitution occurs also affects the magnitude of the resulting change in global temperature. For a given percentage substitution of gas for coal, the effect on projected global temperature would become evident more quickly for a substitution completed over 5 years, for example, rather than 25. Also, sulfur emission controls in the future would shorten the initial warming period following a coal-to-gas switch. In Figures 3b,c, five implementation pathways are shown for a 25% switch from coal to gas beginning with an abrupt switch in 2000 and ending with an abrupt switch in 2050. In practice, it would only be possible to replace natural gas with coal gradually, as new facilities are brought online and production is adjusted, but these pathways encompass the range of possible implementation options over the next 50 years. In Figure 3b, the 5 pathways are plotted vs. calendar year. Initially, there are large differences in the pathways, with earlier fuel substitution producing higher initial warming which is partially mitigated by spreading the substitution out over 25 years. By the end of the century, however, all pathways are following the same trajectory. Delaying coal-to-gas substitution for 25 years (switching in 2025 vs. 2000) would still lead to 90% of the absolute mitigation of temperature change in 2100 relative to switching in 2000, while delaying action for 50 years would achieve two-thirds of the effect by 2100.

In Figure 3c, temperature change due to the 5 pathways is plotted over a 50-year time scale beginning at the initial year, whether 2000, 2025 or 2050. Initially, switching from coal to natural gas has a warming effect on climate relative to the A1b baseline scenario due to the reduction in aerosol emissions. For an abrupt

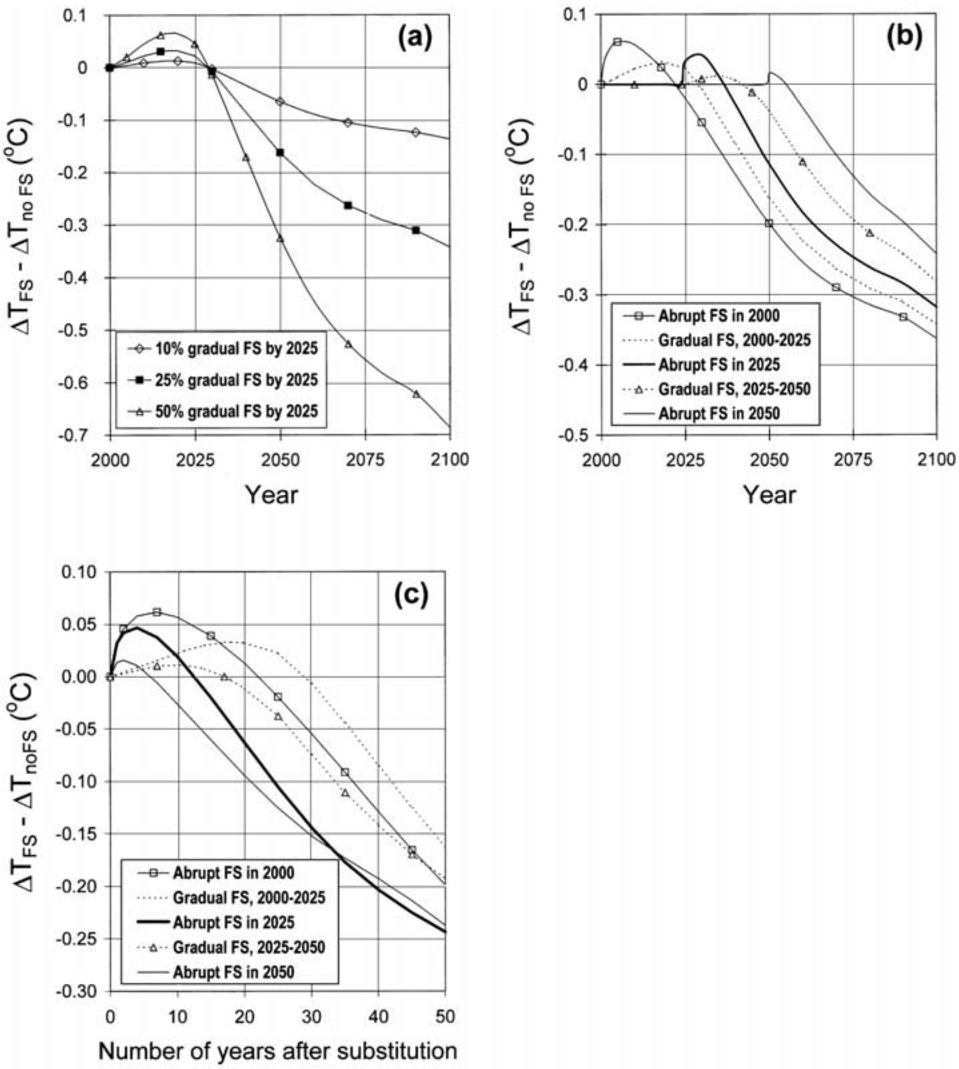

Figure 3. Difference in projected temperature change between gas-for-coal substitution in the power generation sector cases and the baseline IPCC A1b scenario for: (a) gradual substitution of 10%, 25% and 50% of coal use for electricity generation by natural gas, beginning in 2000 and ending in 2025, (b) five pathways to achieve a 25% replacement of coal by gas: abrupt switchs from coal to gas in 2000, 2025 or 2050 and a gradual substitution of gas for coal at a rate of 1% per year from 2000 to 2025 or 2025 to 2050, and (c) the same five pathways, plotted over the number of years since substitution. A positive value indicates an increase in warming due to the switch, while a negative value indicates mitigation of projected global warming.

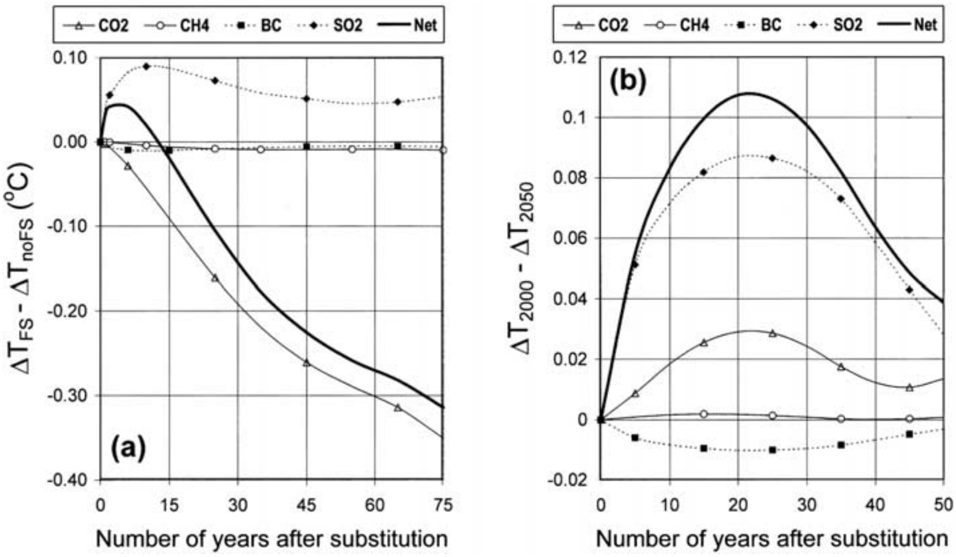

Figure 4. Contribution of CO_2, CH_4, SO_2 and BC to global mean temperature change for 25% abrupt substitution, showing: (a) the magnitude of temperature change relative to A1b baseline scenario for each component for substitution in 2025, and (b) the difference in temperature change due to each component between substitution in 2000 vs. 2050. The x-axis is given in terms of number of years following the switch (e.g., 25 years is equivalent to 2025 for a switch in 2000 and 2075 for a switch in 2050). Positive values for CO_2, CH_4 and SO_2 indicate that there will be a greater temperature effect due to these gases if coal-to-gas substitution occurs in 2000 vs. 2050. Negative values for black carbon indicate that there would be a greater temperature impact from black carbon if switching is delayed.

switch, this effect is largest for switching in 2000 (0.06 °C) and smallest in 2050 (0.03 °C), when further controls on sulfur emissions are projected to have been implemented. By 50 years after initiation, there is a projected reduction in temperature change of 0.16–0.24 °C. The magnitude is dependent on the pathway taken, with the abrupt switch in 2025 or 2050 giving the greatest mitigation of global temperature rise and gradual switch from 2000 to 2025 giving the least. Over time scales of a century or more after substitution, net temperature change mitigation due to individual pathways converges as the shorter-term effects of changes in CH_4 and aerosol forcing die out and CO_2 begins to dominate.

5.4. CONTRIBUTION OF INDIVIDUAL GASES

The contribution of each individual component to temperature change is shown in Figure 4a for an abrupt 25% gas-for-coal substitution occurring in 2025. CO_2 is the major influence on reducing temperature change relative to the baseline, with small contributions from CH_4 and BC of about 5% of the CO_2 effect. This mitigating effect is moderated by a warming effect due to decreased SO_2 emissions.

Breakdown of individual contributions can also show which components cause the differences between the different substitution pathways taken in Figure 3. Emission factors and relative efficiencies are changing over time. In the A1b scenario, SO_2 emissions decrease while the ratio of possible gas-to-coal efficiencies increases. A later switch would therefore lead to a stronger reduction in projected temperature from natural gas in comparison to coal, and allow the projected decrease in temperature to be seen sooner. In Figure 4b, the difference in temperature change due to each gas and aerosol for abrupt switching in 2000 vs. 2050 is shown. Over the first few decades, the difference between an abrupt switching in 2050 vs. 2000 is caused by the immediate removal of a larger negative forcing by sulfate aerosols in the 2000 vs. 2050 pathway. There is some difference in CH_4 and BC, as we also project their emissions to be controlled in the baseline scenario. However, its long lifetime makes CO_2 the main influence on pathways after a few decades under the base case set of factors whose sensitivity was examined in Figures 1 and 2.

6. Conclusions

The main purpose of these results is to illustrate the balances that determine the effectiveness of fuel switching as a mitigation option. These include the balance between the short-term warming effects of SO_2 reductions and the long-term cooling effects of CO_2 emission reductions, and the balance between the increase in methane emissions from natural gas versus the decrease in emissions from coal mining that would be associated with the switch. These results also highlight the contribution of black carbon and SO_2 emissions to the short-term response of climate to fuel switching, and the dependence of the outcome of fuel switching on the implementation pathway followed and the time horizon over which temperature change is evaluated.

To assess the potential effect of fuel switching on climate, the projected change in global mean-annual temperature due to CO_2, CH_4, SO_2 and black carbon emissions resulting from coal and natural gas use in electricity generation has been calculated. For constant electricity production, the replacement of coal by gas was found to reduce projected global temperature after 25 years, a delay approximately equal to the lifetime of power generation capital stock. The dependence of this delay on several key factors was examined by calculating the sensitivity of results to these factors. Four of these factors – methane emissions from natural gas loss and coal mines, and the radiative forcing associated with sulfate and black carbon aerosols – have uncertain estimates that need to be better resolved, preventing the effect of fuel switching on temperature from being precisely characterized. Three others – the relative efficiency of coal to gas-fired utilities, and controls on sulfur and black carbon emissions from coal combustion – are characteristics of an individual fuel substitution that could be adjusted to give desired system performance, including effects on climate through emissions. Analysis of the uncertainties and possible characteristics of a coal-to-gas fuel substitution produced the following main findings:

1. Uncertainty in CH_4 emissions from coal mining and natural gas loss resulted in a similar range of coal/gas temperature change ratios, suggesting that each uncertainty contributes equally to determining CH_4 emissions from a coal-to-gas switch.
2. For current emission levels, uncertainty in sulfate aerosol forcing was the dominant uncertainty, producing a range in coal/gas temperature ratio that far exceeded that of BC forcing and CH_4 emissions. Depending on the assumed direct and indirect sulfate aerosol forcing, coal-to-gas substitution would not result in mitigation of temperature increase until anywhere from 0 years (low forcing) to 80 years (high forcing) after continued use.
3. In terms of choices to be made when selecting candidate coal-fired power plants to be replaced by natural gas, the sulfur content of the fuel affected the timing of temperature change to the largest degree of any of the factors considered here, while a wide range in relative efficiencies of the utilities involved produced the highest coal-to-gas temperature change ratio ($R > 4$) over the long term.
4. Focusing on reducing BC emissions from the power sector as a primary short-term approach to climate change mitigation (e.g., Hansen et al., 2000) may not achieve the desired effect on climate. Emissions controls, or lack thereof, lead to a correlation between SO_2 and BC emissions in coal power plants. Although targeting a high-BC emitting coal power plant for natural gas substitution would result in a decrease in warming due to decreased black carbon aerosols, such a decrease would in most instances be offset by reductions in SO_2 emissions. This would lead to a decrease in the cooling effects of sulfate aerosols that could more than compensate for the reduction in BC emissions.
5. Overall, the choices that can be made in selecting the facilities to be replaced and the replacement technology to be used were found to have a greater range of effect on the mitigation potential of fuel switching than the range of uncertainties in emission factors and aerosol forcing. This implies that, regardless of the large uncertainties that still exist, selection of facilities for fuel substitution can contribute to climate change mitigation.
6. The projected global temperature effects of substituting gas-fired power generation for 10–50% of coal-fired power generation over the next century was evaluated in the context of the IPCC A1b baseline scenario. Under this scenario, fuel switching is not projected to contribute to climate change mitigation over time scales less than 5 to 30 years. This time scale depends on the year of implementation since the scenario includes varying SO_2 emissions and coal-fired electricity generation with time. Substitution of 10–50% of coal-fired power generation by gas-fired power generation results in a reduction of the

projected global temperature increase from 2000 to 2100 by 0.14 °C to 0.68 °C. This range of fuel substitution, therefore, results in the mitigation of 5–25% of projected global temperature rise from 2000 to 2100, regardless of assumed climate sensitivity.

7. Substitution of gas for coal in the baseline A1b scenario produced a cooling effect due to reduced emissions of CO_2, CH_4 and BC that is partially mitigated by warming due to decreased SO_2 emissions. The contribution of each gas depends on the time of substitution; fuel substitution in 2050 results in a much smaller decrease in SO_2 and a slightly smaller decrease in CO_2 than fuel substitution in 2000. The effect is due to the scenario for increasing SO_2 controls and decreasing coal/gas efficiency ratios. This produced a projected net temperature decrease almost 20 years sooner, and substitution in 2050 as opposed to substitution in 2000.
8. Analysis of various pathways to achieving a given percentage gas-for-coal substitution shows that the drawbacks of delaying action, in terms of mitigating net temperature change by 2100, may be compensated by accomplishing that action in a short time frame of a few years as compared to a few decades.

Reducing the long-term effect of greenhouse gas and aerosols emissions on climate is not the only issue involved in the implementation of fuel switching, or any greenhouse gas abatement strategy. For SO_2 emissions from coal-fired power plants in particular, the immediate local and regional effects of SO_2 on local and regional air pollution and acid rain need to be balanced with the regional and global effect of mitigating the risk of a highly uncertain and long-term change in climate. A complete treatment of the issues is beyond the scope of this study, as it gives rise to questions concerning capital cost, availability of resources, technology, policy implementation, regional issues, international trade, and other environmental concerns (e.g., IEA, 1999; Freedman, 1996; Johansson et al., 1996; Watson et al., 1996; Kessler et al., 1994). Despite the importance of these additional issues, however, CO_2, CH_4, sulfur and black carbon emissions appear to present additional design and deployment criteria, in terms of efficiency, fuel choice, emission controls, and selection of facilities to be replaced, that can be selected in order to capture beneficial effects of fuel switching on the radiative forcing of climate.

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