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Greenhouse Gas Emissions From High Demand, Natural Gas-Intensive Energy Scenarios

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Preface

Energy related emissions are the most prominent cause of increasing concerns over global environmental change and regional ecological impacts – concerns that, in turn, reflect a growing search for longer-term security and sustainability. At the center of these concerns is the possibility of longer-term global warming as a consequence of increased atmospheric concentration of so-called greenhouse gases. Carbon dioxide is the most important single cause of the resulting greenhouse effect. It is estimated that it contributes about half of the combined greenhouse effect of all gases in the atmosphere. Consequently, a number of international and national efforts have been instituted in order to identify appropriate policies for reducing carbon dioxide emissions. These range from efficiency improvement and conservation to fuel switching. While it is true that efficiency improvements and conservation will, in general, reduce emissions of greenhouse gases, there are important tradeoffs in the profile of combined greenhouse gas emissions implied by energy substitution.

David Victor analyses the combined effect of increasing concentrations of the two most important greenhouse gases, carbon dioxide and methane, for a number of global energy scenarios. Combustion of natural gas emits less than half the carbon dioxide per unit of primary energy compared to coal, but natural gas or methane is also a greenhouse gas. However, coal extraction and processing releases methane as well. David compares the combined effect of carbon dioxide and methane emissions for a number of natural gas intensive scenarios concluding that the total greenhouse effect would indeed be significantly lower compared to more traditional scenarios that rely more heavily on other fossil fuels. Nevertheless, the methane leaks associated with a further increase of natural gas use could be significant and may increase the total greenhouse effect by about ten percent in addition to the effect of carbon dioxide emissions. The analysis also identifies a large degree of uncertainty in estimates of methane leaks associated with fossil energy production and use. His estimates in the analysis are based on relatively high methane emission factors for natural gas leakage. Nevertheless, the presented findings confirm the relative advantage of natural gas compared to other fossil fuels also when the combined effect of methane and carbon dioxide emissions are considered.

The paper demonstrates the importance of identifying more precisely the magnitudes of all anthropogenic methane emission sources and also points to critical policy issues associated with priorities for forcing minimization of methane leaks to the atmosphere. This result confirms the importance of analyzing the strong link between the use of fossil fuels and emissions of other greenhouse gases, especially in the context of strategies to achieve lower global carbon dioxide emissions. It demonstrates that it is necessary to consider the combined effect of all greenhouse gases and their relative concentrations associated with different global energy scenarios.

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Abstract

Since coal and oil emit 70% and 30% more CO_2 per unit of energy than natural gas (methane), fuel switching to natural gas is an obvious pathway to lower CO_2 emissions and reduced theorized greenhouse warming. However, methane is, itself, a strong greenhouse gas so the CO_2 advantages of natural gas may be offset by leaks in the natural gas recovery and supply system.

Simple models of atmospheric CO_2 and methane are used to test this hypothesis for several natural gas-intensive energy scenarios, including the work of Ausubel et al (1988). It is found that the methane leaks are significant and may increase the total "greenhouse effect" from natural gas-intensive energy scenarios by 10%. Furthermore, because methane is short-lived in the atmosphere, leaking methane from natural gas-intensive, high energy growth scenarios effectively recharges the concentration of atmospheric methane continuously. For such scenarios, the problem of methane leaks is even more serious.

A second objective is to explore some high demand scenarios that describe the role of methane leaks in the greenhouse tradeoff between gas and coal as energy sources. It is found that the uncertainty in the methane leaks from the natural gas system are large enough to consume the CO_2 advantages from using natural gas instead of coal for 20% of the market share.

Text

Models used for energy-related greenhouse predictions fundamentally depend on projections for total energy growth and the mix of fuels used to supply that energy. Within this framework, the long term options for reducing greenhouse gas emissions are quite diverse: managing end energy consumption as well as the rate of efficiency improvements can help reduce growth in primary energy consumption and, therefore, in greenhouse gas emissions. For a given consumption of primary energy, switching to less CO_2 intensive fuels can also help reduce emissions since coal and oil release 70% and 30% more CO_2 per unit of energy than does natural gas (methane). Nuclear and renewable sources that don't emit any CO_2 can make an even larger difference.

Studies have examined the roles that changes in both total energy use and fuel mix can play in overall greenhouse gas emissions (e.g. Lovins et al., 1982; Rose et al., 1983; Edmonds et al., 1984; Cheng et al., 1986; Keepin et al., 1986). Some have also examined the efficacy of policy measures such as CO_2 taxes in forcing lower emissions from the energy sector (e.g. Nordhaus and Yohe, 1983).

However, most of this work has focused only on CO_2 emissions although there are strong links between fossil fuel use and the emission of other greenhouse gases such as

N_2O (Weiss, 1981 cited in Harvey, 1989) and CH_4 (Cicerone and Oremland, 1988). Of particular interest is the role of CH_4 since the large CO_2 advantages of natural gas may be offset by leaks during the recovery, transport, and final use of natural gas. Current data suggest a worldwide average leak rate of up to 3.6% (methane data in Cicerone and Oremland, 1989; conversion factors from Rotty and Masters, 1985; applied to 1985 worldwide production of natural gas from British Petroleum, 1989). However, other studies indicate the leakage rate may be higher (Wahlen et al., 1989; Lowe et al., 1988), and many believe leak rates are lower (especially in some countries). Currently it is impossible to accurately pinpoint the sources of the leaks. Nonetheless, the globally averaged current leakage rate is probably in a range from 2% to 4% although arguments can be made for even higher or lower rates. Given that atmospheric methane is 16 to 32 times more effective than CO_2 as a greenhouse gas on a molar basis, the effects could be serious. This study attempts to include the effects of leaking methane in the total greenhouse calculations under different energy scenarios. The objective is not to develop additional energy forecasts but to use existing scenarios as a vehicle for exploring the potential importance of methane leaks in greenhouse calculatations.

The work of Ausubel et al. (1988) presents an interesting opportunity to examine the role of methane leaks because, unlike other energy forecasts, their work relies heavily on natural gas. Based on data since 1860, Ausubel et al. have shown that the mix of fuels used to supply the world's energy is dynamic (figure 1). Similar to niche competition between species, new fuels enter the market with a small share and progressively invade larger portions of the market along a simple logistic curve. Since 1860, this has led to a succession of wood, coal, and now oil as fuel sources (Marchetti and Nakicenovic, 1979; Grübler and Nakicenovic, 1987). Over the next century oil will yield to gas in a "methane economy" followed by nuclear as the dominant fuel source. In the past, new fuels have emerged every 66 years so a follow-on to nuclear power such as solar or fusion (termed "solfus") is expected to appear late in the next century.

The changing fuel mix under this logistic scenario is summarized in table I. For comparison, the fuel mix derived from an economic model used by the US Department of Energy (Edmonds et al., 1984) is reported; also shown is the fuel mix in 1985. Note the much larger role for natural gas in the logistic model, especially in the first decades of the next century.

For total primary energy consumption, Ausubel et al. have bracketed potential energy futures with high and low projections (figure 2). A low projection--termed "efficiency growth--is based on high energy efficiency in the future which yields constant per capita energy consumption using World Bank population forecasts (Zachariah and Vu, 1988). A high demand projection assumes rapid growth in per capita energy consumption that occurs in 50 year pulses, or long waves, consistent with the theories of Kondratieff (1926, 1928). As with the fuel mixes, the results of economic models used by Edmonds et al. (1984) are shown for comparison.

The combination of fuel mix and energy growth yield projections for future CO_2 concentrations by applying the CO_2 emission rates for different fuels as summarized in table II. Historical emissions from cement production and natural gas flaring are included as reported in Watts (1982, table 15). CO_2 from cement is projected into the future along a least squares fit of emissions from 1950 to 1980; future emissions from gas flaring are projected in proportion to oil production based on the average rate for 1975 to 1980. These two sources comprise only a few percent of total CO_2 emissions so errors here will not significantly affect the projections. Also included in the CO_2 calculations are historical CO_2 fluxes due to deforestation as reported in Woodwell (1983); future CO_2 emissions from deforestation are not included in this model because the trends are so uncertain.

Also shown in table II are methane emission rates which are calculated from the total annual source due to a particular fossil fuel (Cicerone and Oremland, 1989) then prorated over worldwide production of that fuel (British Petroleum, 1989). Note that all fossil fuels emit some quantity of methane; but since emissions are not the same for the different fuels, the total quantity of methane vented to the atmosphere by fossil fuels will vary with the fuel mix. A median value of 2.5% leak rate for natural gas and a methane greenhouse factor of 24 is used in this study, but because there is large uncertainty surrounding the methane question I have also bracketed the curves with high methane calculations (4% natural gas leak and a methane factor of 32) and low methane calculations (0% natural gas leak and a methane factor of 16). Note that these methane error brackets will give us the opportunity of seeing the relative importance of methane leaks. Also note that the low bracket represents the effect of plugging the leaks.

In calculating the atmospheric abundance of CO_2, it is assumed that 50% of all CO_2 released to the atmosphere goes directly into the oceans where it remains; the balance stays in the atmosphere and contributes to the total greenhouse effect. This assumption will make the results comparable with other analyses since most CO_2 projections have assumed roughly a 50% airborne fraction (Bolin, 1986). A more complex model might be appropriate, but the errors that arise from assuming a constant airborne fraction are probably low for scenarios which continue growth in CO_2 emissions (Perry, 1986). However, very low CO_2 scenarios must account for a decreasing airborne fraction (Harvey, 1989). Models which yield high CO_2 emissions should probably account for an increasing airborne fraction since oceanic uptake is not unlimited (Bolin, 1986).

For methane, atmospheric concentrations decay exponentially from the year of emission since methane reacts with OH and is removed from the atmosphere:

$$CH_4 + OH\cdot \text{ -----> } CH_3\cdot + H_2O \qquad (1)$$

$CH_3\cdot$ ultimately oxidizes to CO_2 which provides a very small additional source of CO_2. The equations used in the model are discussed in more detail in the appendix. Note that the rate of (1) depends on the abundance of $OH\cdot$ which might decrease due to other fossil fuel-related activity, especially increases in CO emissions which compete with CH_4 for reaction with $OH\cdot$ (Logan et al., 1981). Such an OH-feedback might dramatically increase the effect of leaking methane by decreasing the rate of methane removal from the atmosphere, but the existence of a feedback is purely hypothetical at this point since the spatial distribution of CO emissions as well as those of nitrogen oxides and other pollutants could also yield an increase in OH concentrations (Thompson et al., 1989).

A caveat in all greenhouse research is the problem of uncertainty. In an effort to put the issue of uncertainty in perspective, I have summarized the major uncertainties that affect this study in table III. A particular concern is the amount of methane due to leaks from oil wells; for this study I have assumed that 30% of the methane leaks attributed to natural gas are actually due to oil production, but the real number is simply not known. In any case, my assumed 30% is probably high and, therefore, represents a best case for the greenhouse effects of natural gas when compared with oil. Note that for all the parameters, the uncertainties are reasonably large, especially for the methane. Furthermore, for the analyses of the methane leak fraction the uncertainties are compounded, so all these results should be treated with some caution.

Figure 3 shows the results of Ausubel et al. but corrected for methane leakage. Their findings--that a logistic scenario yields substantial savings in greenhouse gas emissions--are robust, even when methane leaks are included. In 2075, CO_2 concentrations under their long wave and efficiency scenarios (about 600 ppm and 480 ppm, respectively, including methane leaks) are still generally lower than the concentrations reported by Edmonds et al. (1984) for their scenarios (1400, 700, and 500 ppm, respectively, for the high, median, and low demand scenarios, not including methane leaks). If methane leaks are included in the results from Edmonds et al. (1984), the numbers would probably be 5% to 10% higher than reported, but it is not clear what the methane leaks from their scenarios will be because of the reliance on coal-based synthetic liquid fuels.

It is evident that the role of methane leaks is non-trivial; and as energy use increases, the problem of methane leaks increases as well. Table IV summarizes these results and reports the percentage greenhouse contribution of methane. The role of methane is systematically larger for the long-wave scenarios than for the efficiency (low demand) scenarios. As expected, high energy demand yields high methane leaks; in effect, the abundance of atmospheric methane is constantly recharged by methane leaks due to high energy production. Since the role of methane is significantly larger for high energy demand scenarios, it appears that the greenhouse forcing due to increased energy demand is not linear: higher energy demand yields the compounded greenhouse effect of higher CO_2 and CH_4.

But note that the lower CO_2 concentrations under the logistic scenarios are, in large part, due to the use of nuclear power. This is evident when the logistic scenarios are compared with a scenario that simply extends the 1985 fuel mix to 2100 using the long wave growth. Nearly 50% of the energy supplied from 1860 to 2100 is from nuclear in logistic model with long wave growth while the corresponding percentage for the 1985 mix is only 2% (table

V). As Ausubel et al. note, dramatically lower CO_2 emissions for the logistic fuel mix scenarios are the result when fossil fuels are substituted out of the market (2040 and beyond) in favor of nuclear and solfus. Indeed, the logistic and 1985 curves diverge in figure 3 after the peak of natural gas use in 2040. It appears that nuclear and solfus (i.e. not natural gas) are the real CO_2 economizers in the methane economy model of Ausubel et al. Note that because zero CO_2 technologies are extensively used, the distribution of the CO_2 emissions in the logistic scenarios is quite different from the 1985 fuel mix (Table VI). In the second half of the 21st century--when energy use is highest--most (eventually all) of the energy is supplied without emitting CO_2.

I now wish to explore the sensitivity of these greenhouse curves to changes in fuel mix. The objective is to suggest some policy trade-offs that account for the different CO_2 and CH_4 emissions of different fuels. Given that the large role for nuclear makes it somewhat difficult to analyze the effect of fuel mix on greenhouse gas emissions, I have developed some hypothetical energy scenarios based on the logistic model in which nuclear power is phased out prematurely. Such scenarios are not entirely unrealistic since there are serious social and political issues surrounding nuclear power that remain to be resolved. Indeed, no new reactors have been announced in the US since 1978 (Energy Information Administration, 1988), and in other countries national energy policies are moving away from nuclear power since the Chernobyl and Three Mile Island accidents (Bruggink, 1989; Bergman, 1981). To compensate for some of power not supplied by nuclear reactors, I have delayed the exit of oil from the logistic model. This makes sense also because versatile petroleum-based liquid fuels are critical for the transport sector. Eventually, liquid fuels will be replaced by new technologies such as hydrogen (Petkov et al., 1989), but the exit of oil-based fuels will not be as rapid as with other fuels for which substitution is easier. Since the introduction of the automobile, the market share for oil has never decreased. Nonetheless, I emphasize that this is simply an effort to explore the sensitivity of the greenhouse curves to changes in the mix of fossil fuels used to supply the world's primary energy.

The result is a "nuclear moratorium" scenario (figure 4) with an even larger role for natural gas than under the logistic scenario since all remaining energy (until "solfus" appears) is supplied by natural gas. For comparison, I examine also an "enhanced coal" scenario (figure 5) which delays at 20% the exit of coal. 20% is chosen because the CO_2 increases from supplying 20% of the market with coal instead of gas are just equal to the uncertainty in the methane game (i.e. the dotted lines).

As with the logistic model, both of these scenarios are natural gas-intensive (see tables I and IV). Because the effects of leaking methane are most serious when energy use is high I will explore these scenarios using the long wave energy growth. Thus the results presented here probably represent a worst case for methane; the problem will be less serious if energy demand is lower. The greenhouse curves for these two scenarios are reported in figure 6; note that by design, the methane uncertainty brackets are just as large as the CO_2 differences between the two scenarios.

A comparison of these scenarios is interesting for two reasons. First, it reiterates the point that methane leaks are significant and must be included in energy models. In this case--high energy growth and a phase-out of nuclear power--the uncertainty in the methane issue is large enough to consume the CO_2 advantages of substituting a 20% coal market share with natural gas. Thus a significant portion of the natural gas advantages might be consumed by the leaks so it makes sense to install incentives to reduce leaks in the natural gas system. For example, a 1% per year improvement in the leak fraction from now until 2100 would reduce the current leak rate of about 3% to about 1%.

The second (and related) conclusion from this comparison is its implications for greenhouse policy that relies on worldwide manipulation of the fuel mix, say, from coal to natural gas. Research into the economics of acid rain has demonstrated that it is frequently cost-effective for one country to pay for abatement in another country (i.e. the marginal benefits of abatement in a neighboring country are larger than the marginal benefits of abatement in one's own country). Undoubtedly this idea will become popular in research on the economics of the greenhouse: it will be argued that rebuilding the electricity grid in, for example, a developing country to use gas instead of coal will be a more cost-effective CO_2 reduction measure than other more expensive greenhouse reduction schemes at home. But this research indicates that intensive natural gas users can make a significant marginal contribution to greenhouse abatement by controlling their leaks. Given this, to some extent we should be less concerned about coal-rich developing countries such as China using their coal and more concerned with the marginal effects of leaking methane. And if the use of coal is not greater than 20% of market share under a no-nuclear, high demand energy scenario, we can probably make a larger abatement of greenhouse gas emissions by controlling natural gas leaks rather than demanding a complete switch from coal to natural gas. Another paper might explore the economics of plugging leaks in the natural gas system, but it seems that a critical research priority would be, first, to find out where all the energy-related methane leaks are.

There are two large omissions in this research. One omission is the role of natural gas in overall fuel efficiency. If the world emerges into an electricity economy this might be an important advantage for natural gas (in addition to the low CO_2 emission factor). Currently, the average efficiency for coal-, oil-, and gas-fired power plants is roughly equal (OECD, 1989). But at the margin, new gas-fired plants are more efficient (52%) than both oil-fired (43%) and coal-fired (42%) power plants (From OECD, 1989 and Manthey, 1980 in Gilli and Nakicenovic, forthcoming). A further study might include this and find more favorable greenhouse results for natural gas; however, I note that the coal emission factor is 70% higher than that for natural gas yet the results in figure 6 suggest that for high energy scenarios, the resulting differences in atmospheric greenhouse gas concentrations is not large. Another factor of 1.2 (the increase in marginal efficiency for natural gas over coal) might not make such a large difference.

A second omission is the issue of resources. This paper is intended as an illustration of the problem of methane leaks and the role of fuel mix; nonetheless, some of these scenarios may not be attainable due to limitations imposed by the availability of fossil fuels, especially oil and gas. On this point, I note that for the last twenty years the world has had about thirty years worth of oil reserves; as the price of oil rises (e.g. 1973 and 1980-81) reserves rise as well. In 1987 and 1988 reserves rose to over 40 years' worth of pumping. For natural gas, there were 56 years worth of reserves at the end of 1988; and despite wider use of natural gas, reserves have climbed steadily since 1977. This may be especially true for oil and gas. Currently, coal reserves will last 235 years at current rates of production (British Petroleum, 1989). In sum, these scenarios may not be resource limited.

To close, I note that under all scenarios, the quantities of leaked methane are large by today's standards. Leaks with the logistic fuel mix and long wave growth scenario peak at 420 Tg per year in 2050; under my "enhanced coal" scenario leaks rise throughout the period and are 1230 Tg per year in 2100. These emissions are, respectively, 5 and 15 times current methane emissions due to fossil fuel use. Leaks of this magnitude are of particular interest since concern over rising methane concentrations extends beyond just climate since methane is also linked to the chemistry of the stratosphere and, perhaps, stratospheric ozone depletion (Blake and Rowland, 1988). If biological sources of methane continue to grow as well, methane concentrations will be so high--and the potential effects so widespread--that global environmental concerns may focus on methane much more than at present.

Appendix:

Calculating the abundance of methane in the atmosphere

The rate expression for reaction (1) is:

$$k_1[CH_4][OH] = \text{rate of methane removal} \qquad \text{(A-1)}$$

where k_1 is the rate constant for the reaction and the brackets indicate concentration. Based on good knowledge of the abundance of methane (4800 Tg) and an assumed atmospheric lifetime of 9.6 years (Cicerone and Oremland, 1989), the annual steady-state source of methane is calculated to be 500 Tg per year (4800 Tg/9.6 years). Therefore, the following must be true:

$$k_1[4800][OH] = 500 \qquad \text{(A-2)}$$

Given this constraint, the atmospheric concentration of methane is calculated by applying the familiar principles of exponential decay that are also used to describe radioactivity:

$$\text{amount of } CH_4 \text{ in the atmosphere}_t = \frac{1}{2^{(t_{1/2}/t)}} \qquad \text{(A-3)}$$

For any emission of methane at time t=0, the fraction left in the atmosphere at time t is given by this expression. For this paper, t is resolved at 1 year intervals. The total amount of methane in the atmosphere at any time is simply the sum of all previous years' methane emissions multiplied by the respective fractions computed by the above equation.

The half life, $t_{1/2}$, of methane in the atmosphere (for use in equation A-3) is computed from the constraints described in equation A-2:

$$t_{1/2} = \frac{\ln 2}{k_1[OH]} \tag{A-4}$$

rearranging the equation and substituting from A-2:

$$t_{1/2} = (\ln 2)(\text{mean residence time})$$

The half life is simply proportional to the mean residence time.

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Captions

Fig. 1: Logistic model of fuel mix. Lagged lines are historical data and smooth lines represent the model calculations. Market fraction (f) is transformed to log f/(1-f) so the substitution effect is linear and easier to see. Based on the work of Marchetti and Nakicenovic (1979), Nakicenovic (1984), and Grübler and Nakicenovic (1987).

Fig. 2: Total primary energy projections in million tons coal equivalent (mtce) used by Ausubel et al. (1988) to bracket high and low energy demand. Long wave growth assumes energy growth will occur in 50 year pulses; the efficiency scenario assumes per capita energy consumption will not rise from current levels. For comparison, the projections of Edmonds et al. (1984) are also shown. Case A assumes rapid population growth and low efficiency improvements; case C assumes the reverse. Case B uses median values from the extreme cases.

Fig. 3: Greenhouse curves for the logistic fuel mix of Ausubel et al. (1988) for both efficiency and long wave growth patterns. Methane leaks from the natural gas recovery and supply system are assumed to be 2.5% and methane is assumed 24 times as effective as CO_2 in greenhouse trapping on a volume basis. Dotted lines are for calculations with 0% leak from the natural gas recovery and supply system and a methane factor of 16 (low case) and 4% leak with a methane factor of 32 (high case). The vertical axis is atmospheric concentration of CO_2 + CH_4 in parts per million (ppm) CO_2 equivalents (CH_4 concentrations converted to CO_2 using the methane conversion factors discussed above). For comparison, the curves with long wave growth but using the 1985 fuel mix extended to 2100 are also shown. Note that the logistic curve with long wave growth diverges from the 1985 curve in aroung 2040, <u>after</u> the peak of natural gas in the logistic model. From 2040 to 2100, natural gas is replaced by zero CO_2 fuels.

Captions, cont.

Fig. 4: "Nuclear moratorium" scenario based on the logistic model in figure 1 but with nuclear power phased out in an attempt to analyze the greenhouse contributions of the fossil fuels without the complication of a changing nuclear market share as well. Some of the power not supplied with nuclear reactors is supplied by delaying the exit of oil as described in the text. Natural gas is used to supply all remaining energy.

Fig. 5: "Enhanced coal" scenario based on the logistic model in figure 1 but with constraints on the penetration of nuclear power and the exit of oil as described in the text. As in figure 4, the remaining energy is supplied with natural gas. However, the exit of coal is delayed at 20%, a number chosen so that the CO_2 disadvantages of using coal are equal to the uncertainty in the leaking methane disadvantages of natural gas.

Captions, cont.

Fig. 6: Greenhouse curves for my "nuclear moratorium" and "enhanced coal" scenarios with long wave growth. By design, the difference between the two scenarios is as large as the uncertainty in the methane leaks (dotted lines). For comparison with figure 3, note that the greenhouse curve for the "coal" scenario is nearly identical to the curve for the 1985 fuel mix.

Figure 1

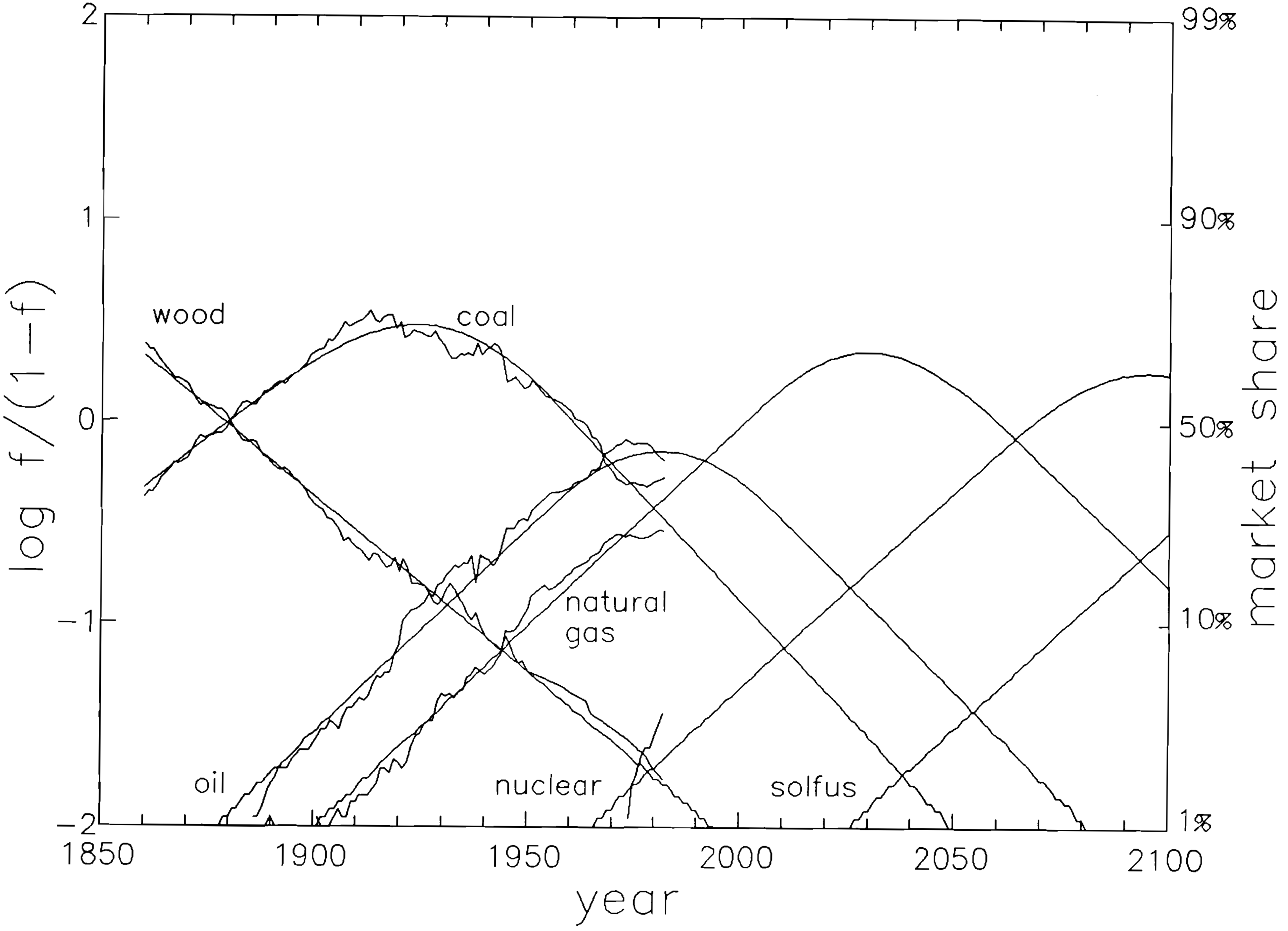

2
1
0
−1
−2
log f/(1−f)
99%
90%
50%
10%
1%
market share
1850
1900
1950
2000
2050
2100
year
wood
coal
oil
natural
gas
nuclear
solfus

Figure 2

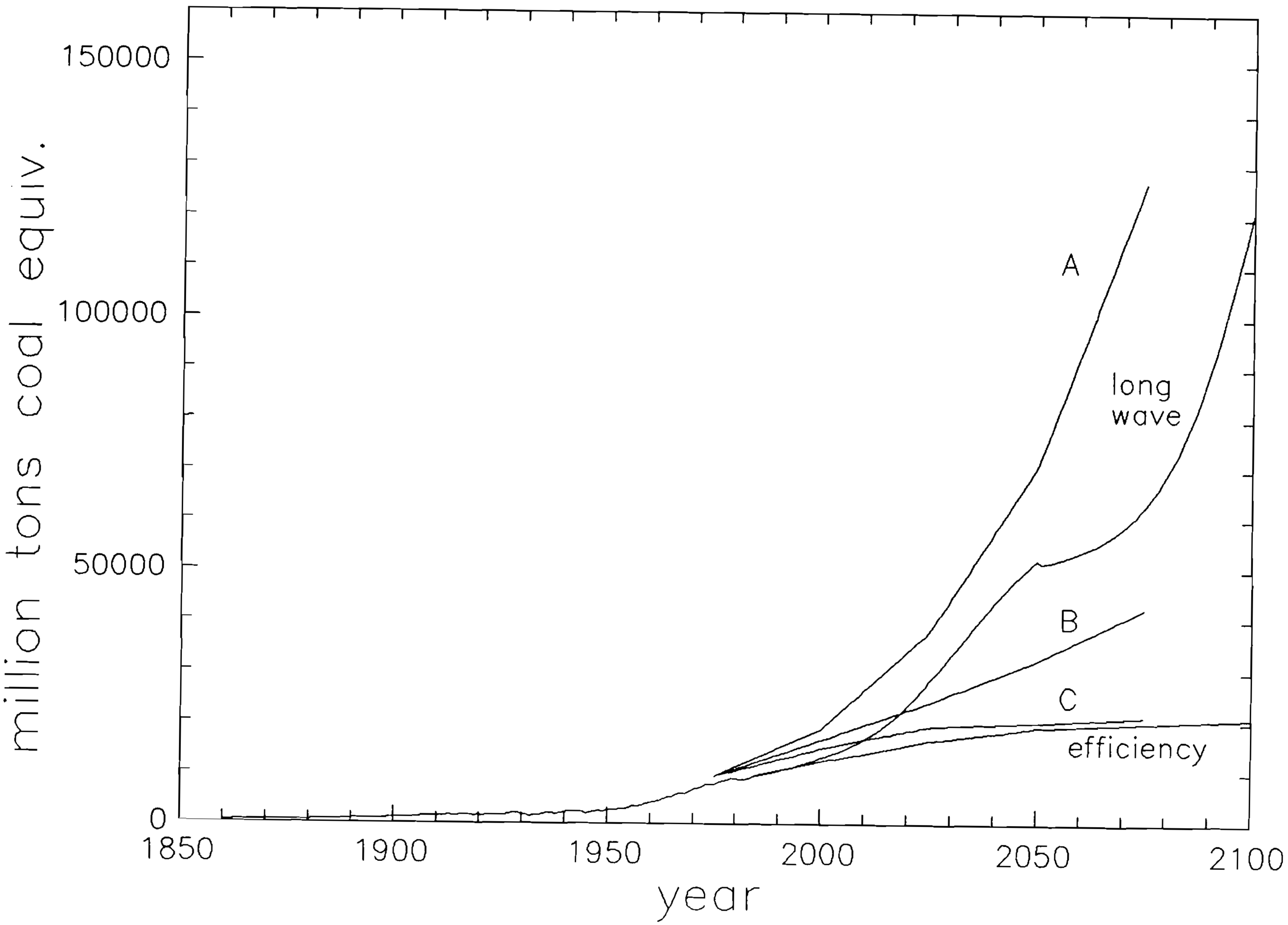

million tons coal equiv.
150000
100000
50000
0
1850
1900
1950
2000
2050
2100
year
A
long
wave
B
C
efficiency

Figure 3

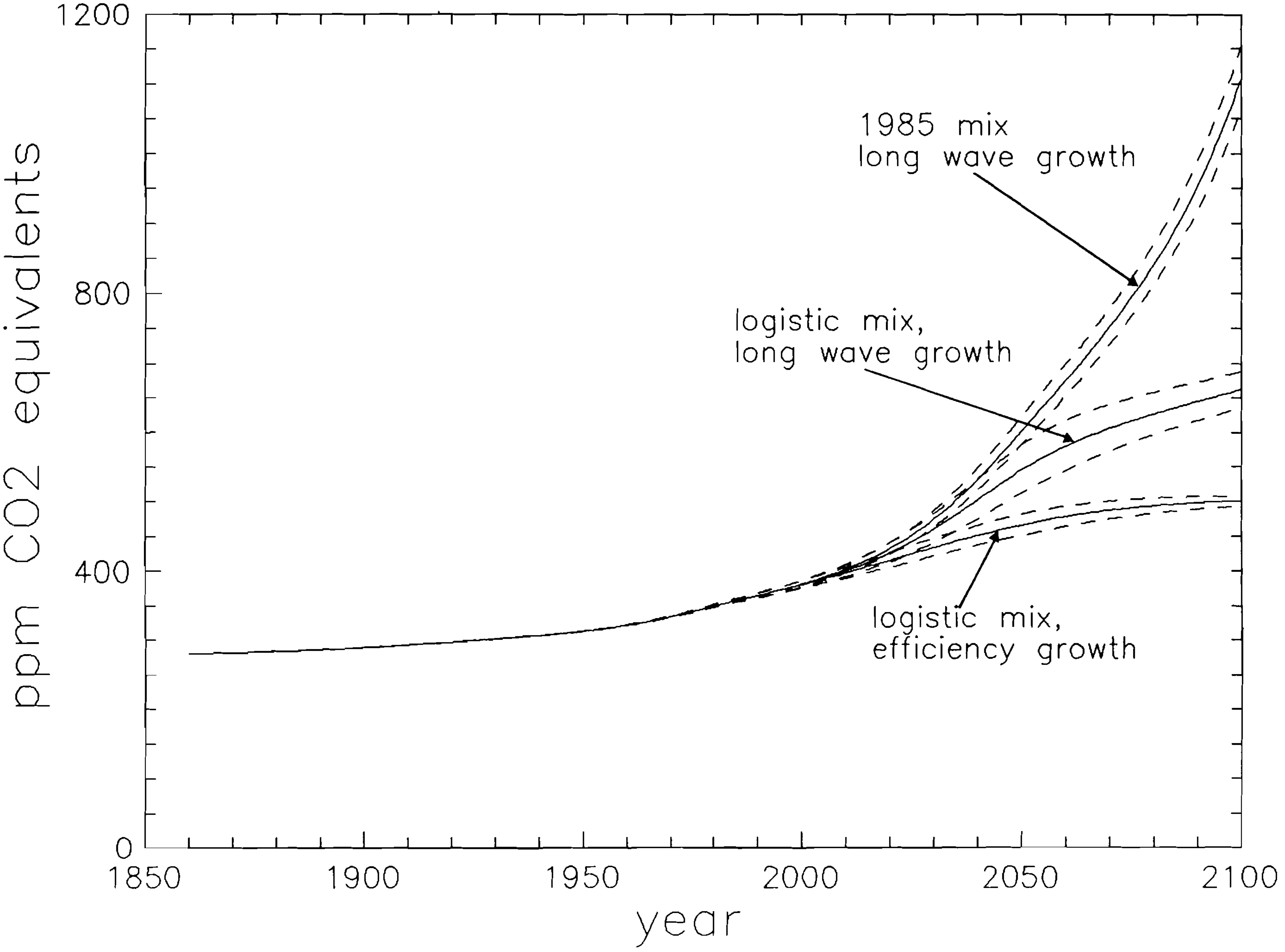
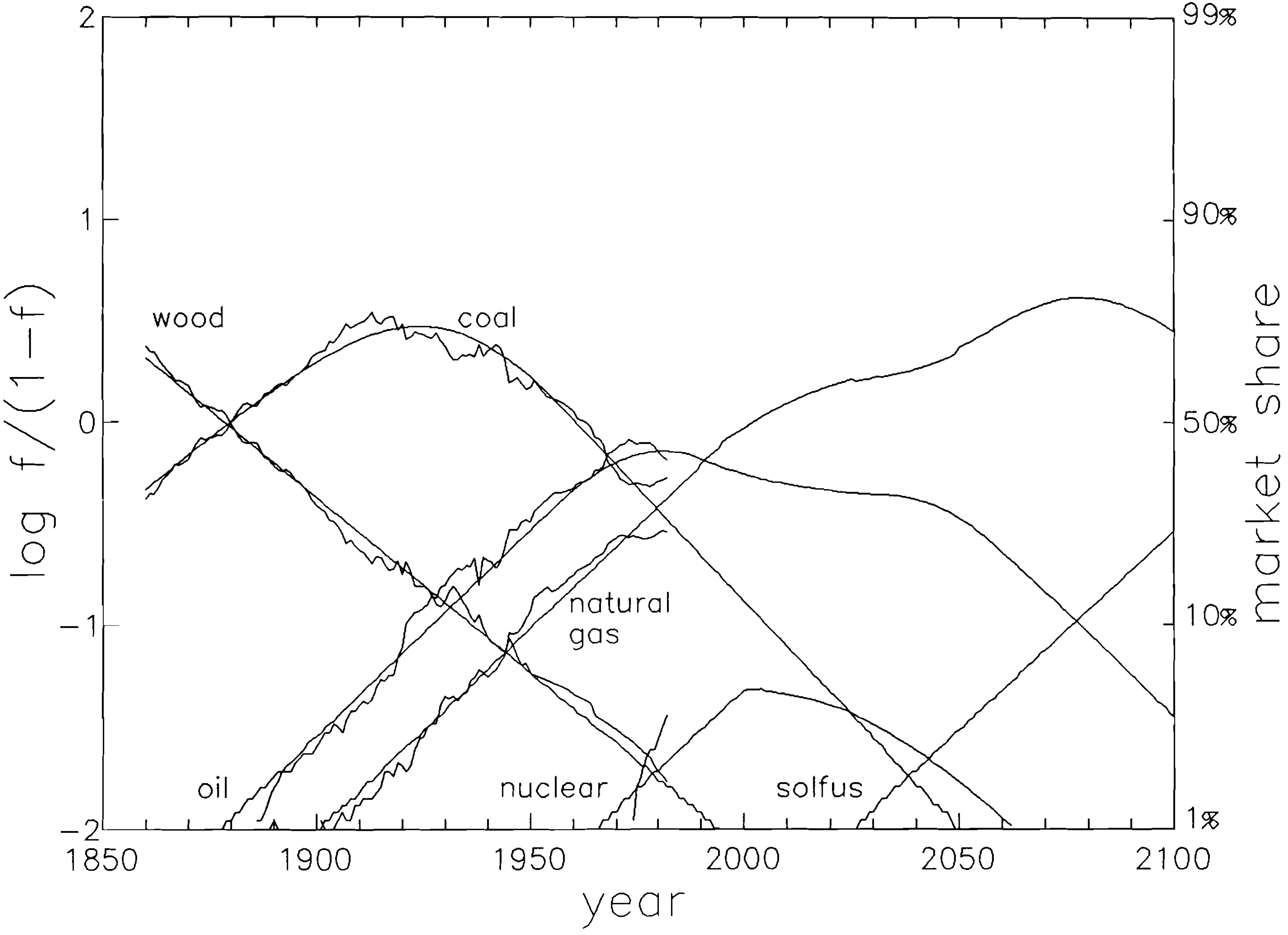

1200
800
400
0
ppm CO2 equivalents
1850
1900
1950
2000
2050
2100
year
1985 mix
long wave growth
logistic mix,
long wave growth
logistic mix,
efficiency growth

Figure 4



wood
coal
oil
natural
gas
nuclear
solfus
2
1
0
−1
−2
log f/(1−f)
99%
90%
50%
10%
1%
market share
1850
1900
1950
2000
2050
2100
year

Figure 5

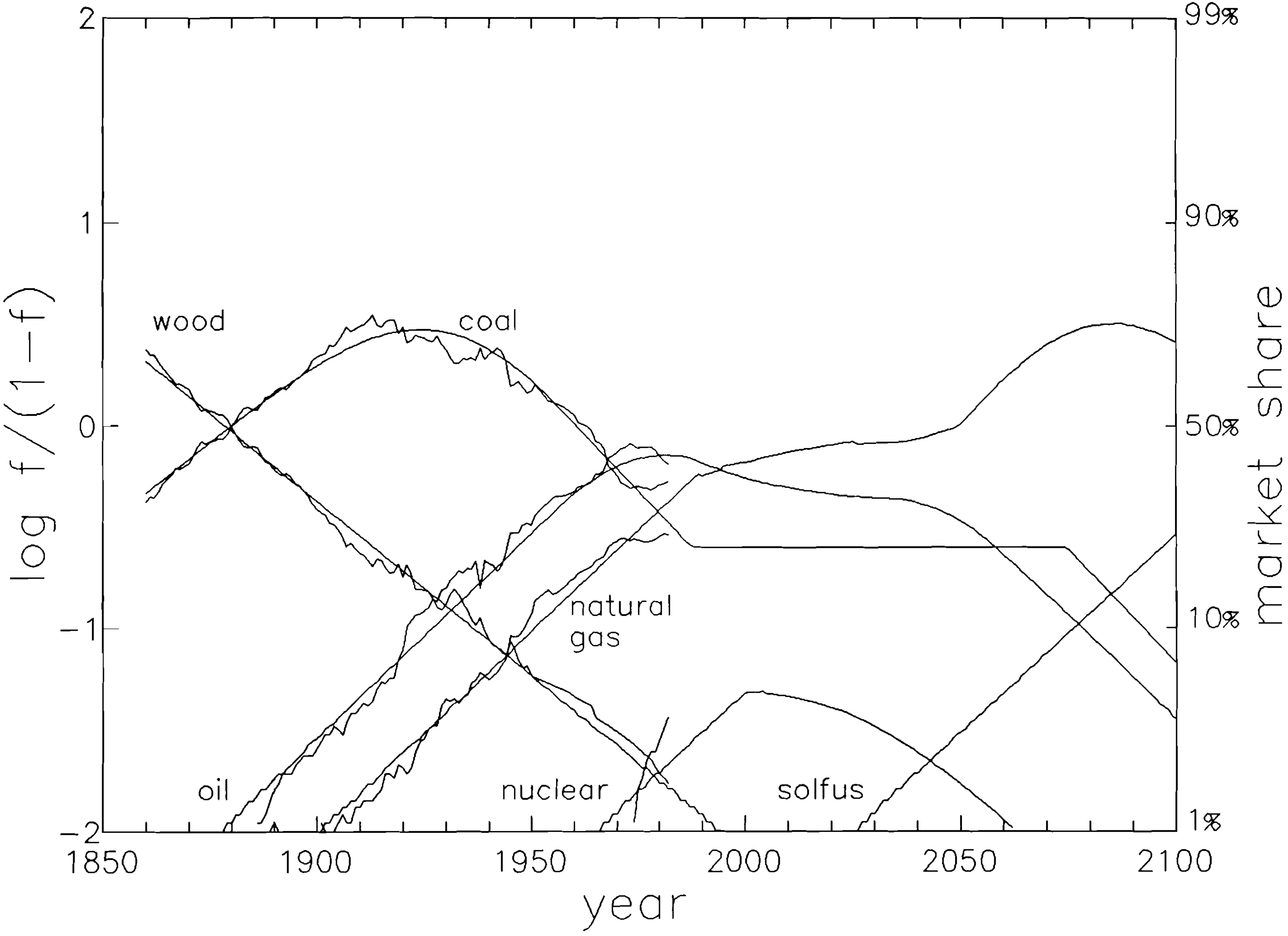

2
1
0
−1
−2
log f/(1−f)
1850
1900
1950
2000
2050
2100
year
99%
90%
50%
10%
1%
market share
wood
coal
oil
natural
gas
nuclear
solfus

Figure 6

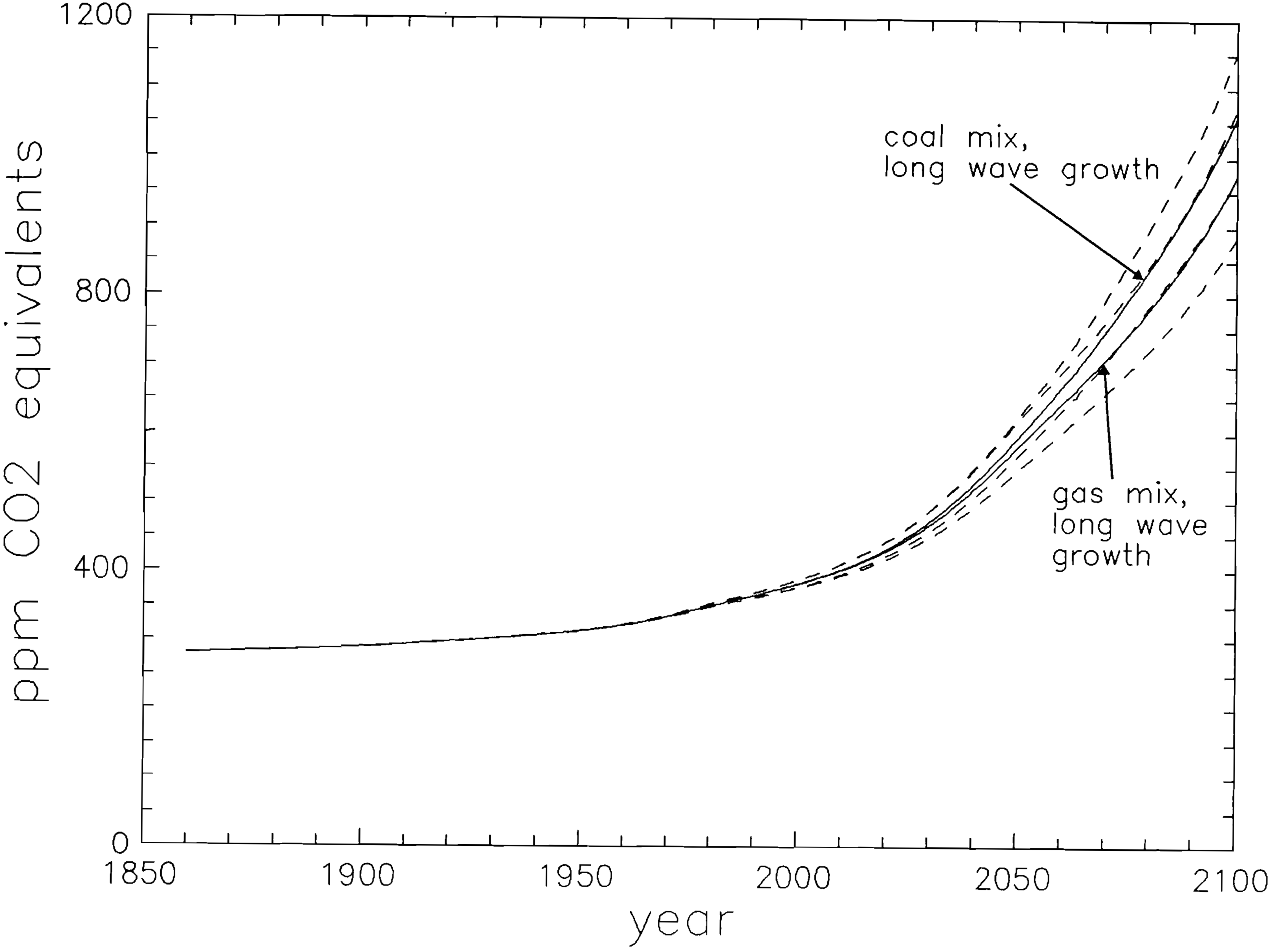

1200
800
400
0
ppm CO2 equivalents
1850
1900
1950
2000
2050
2100
year
coal mix,
long wave growth
gas mix,
long wave
growth

Table I

Summary of fuel mixes
natural gas-intensive scenarios

Scenario	wood	coal	oil	nat'l gas	nuclear	solfus[2]
"logistic"						
2000	<1%	11.6%	33.7%	48.9%	4.6%	<1%
2025	<1	3.5	13.6	68.7	12.9	<1
2050	<1	<1	4.5	60.2	31.2	3.0
2075	<1	<1	1.4	33.5	56.2	8.7
2100	<1	<1	<1	13.4	63.7	22.5
DOE; "B"[1]						
2000	n/a	33.4%	33.3%	17.8%	3.1%	<1%
2025	n/a	44.3	18.7	16.8	3.2%	3.3
2050	n/a	58.4	8.9	11.5	5.0	5.0
2075	n/a	64.0	4.1	7.0	7.5%	7.5%
1985 mix	1.4%	22.1%	41.4%	32.5%	2.4%	<1%
"nucl. mor."						
2000	<1%	11.6%	35.6%	48.2%	4.6%	<1%
2025	<1	3.5	30.9	62.0	3.6	<1
2050	<1	<1	25.2	70.2	1.7	3.0
2075	<1	<1	10.4	80.4	<1	8.7
2100	<1	<1	3.4	73.9	<1	22.5
"enh. coal"						
2000	<1%	20.0%	35.6%	39.8%	4.6%	<1%
2025	<1	20.0	30.9	45.5	3.6	<1
2050	<1	20.0	25.2	50.6	1.7	3.0
2075	<1	19.6	10.4	74.1	<1	8.7
2100	<1	6.3	3.4	72.1	<1	22.5

[1] Hydroelectric power not listed here. For DOE case "B", hydro accounts for the following percentages of total primary energy demand: 2000, 12.4%; 2025, 13.6%; 2050, 11.2%; 2075, 10.2%.

[2] DOE model does not include non-solar "new" energy types like fusion.

Table II

CO_2 and CH_4 emission factors and constants

Parameter	value	source and notes
CO_2 emission factors[1]		
wood	0.784 tC/tce	Keeling, 1973
coal	0.683 tC/tce	Rotty & Masters, 1985
oil	0.52 tC/tce	Rotty & Masters, 1985
natural gas	0.411 tC/tce	Rotty & Masters, 1985
CH_4 emission factors[2]		
coal	.011 Tg/tce	From data presented in Cicerone and Oremland, 1989 and prorated over 1985 total production (BP, 1989); see table III for more.
oil	.0032 Tg/tce	
natural gas:		
0.0% leak rate	0 Tg/tce	
2.5% leak rate	.013 Tg/tce	
4.0% leak rate	.021 Tg/tce	
Heat Contents[3]		
1 ton of wood	14.9×10^9 J	Keeling, 1973
1 ton of coal	28.1×10^9 J	BP, 1989
1 ton of oil	42.2×10^9 J	BP, 1989
1 m^3 of gas	$.038 \times 10^6$ J	BP, 1989
mass of 1 m^3 gas	540 g C	Rotty & Masters, 1985
Constants		
mass of atmosphere	5.1×10^{18}kg	Trenberth, 1981
mol. wt. of atm.	28.96 g/mole	NOAA et al., 1976
mol. wt of C	12.01 g/mole	
mol. wt of H	1.008 g/mole	
mol. wt of O	16.00 g/mole	
concentration of CO_2 in 1860	290 ppm	Neftel et al., 1985

[1] As used by Ausubel et al. (1988). These values for coal, oil, and gas are within those reported in Clark (1982) and Edmonds et al. (1989).

[2] Based on leak rates reported in Cicerone and Oremland (1989) and summarized in table III. Total leaks prorated over 1985 total production of the fuel as reported in BP (1989).

[3] All numbers in metric tons (1000 kg)

Table III

Summary of major greenhouse-related uncertainties that affect this model

Parameter	Range	Notes
Carbon dioxide:		
Atmospheric retention of CO_2	40% to 60%	May decrease in the future if ocean uptake does not grow in proport. to CO_2 emissions. 50% used in this paper.
Future source of CO_2 due to deforestation	0 to ?; 1 to 3 x 10^{15} g per year today	May decrease from current levels as forest disappear and efforts are taken to conserve forests. May increase with population. Not included in this paper
Methane:		
Mean residence time of CH_4 in the atmosphere	8 to 14 years	May increase due to OH feedback.
Methane greenhouse factor (compared with CO_2)	16 to 32	May decrease due to accumulation of CH_4 in the atm. (decreasing marg. heat trapping).
Methane sources:		
Total methane source	400 to 640 Tg annually	540 Tg per year used in this study (500 Tg per year is quasi stdy. state source; 40 Tg per year yields the 1% annual incr in atm. CH_4

Table III, cont.

Parameter	Range	Notes
Methane sources, cont.		
% from "old"[1] sources	10% to 32%	22% for this study, including 33 Tg from "old" biol. sources.
Amount of fossil fuel-derived CH_4 is from natural sources (i.e. not directly related to mining or total energy production).	?	33 Tg of "old" sources assumed from biology in this study. The rest assumed proportional to respective energy production. Biol. sources or natural fossil based seeps may be larger, so problem of CH_4 leaks from energy prod. may be overstated.
All "old" methane leaks due to energy production (coal + oil + nat. gas)	50 to 95 Tg annually	May be lower if other methane sources release substantial quan. of "old" methane.
Methane from coal mining	25 to 45 Tg annually	Currently believed to be about 35 Tg.
Methane from natural gas and oil	25 to 50 Tg annually	Currently believed to be about 45 Tg.
Leakage rate if all meth. from natural gas/oil is from nat'l gas.	2% to 4% annually	Calculated at 3.6% if annual source is 45 Tg.
Fraction of methane from natural gas/oil is from oil. (remaining is due to leaks in the nat'l gas system).	?	This study uses 30% thus postulating that leaks from the nat'l gas system are c. 2.7%

[1] "old" or "dead" methane concentration determined from isotopic analysis of atmospheric methane. Most methane is young (i.e. from recent biological activity).

Table IV

Total "greenhouse effect" under different gas-intensive scenarios

Scenario	2000		2025		2050		2075		2100	
	total	% CH_4	total	% CH_4	total	% CH_4	total	% CH_4	total	% CH_4
"logistic" mix with efficiency growth	381	1.6	425	2.6	466	2.8	491	1.9	501	0.9
"logistic" mix with long wave growth	381	1.6	441	3.6	545	5.7	617	4.3	662	3.0
1985 mix with long wave growth	382	1.5	452	2.5	602	3.9	795	3.8	1107	4.7
"nucl. morat." with long wave growth	381	1.6	446	3.3	581	5.7	744	6.6	976	8.2
"enhanced coal" with long wave growth	381	1.6	450	3.0	595	4.9	793	6.2	1060	7.7

Table V

Total Energy, 1860 to 2100
% supplied by different fuels

Scenario	wood	coal	oil	gas	nuclear	solfus	nuclear + solfus
logistic fuel mix, effic. growth	1.4%	9.4%	12.5%	42.5%	29.3%	4.9%	34.2%
logistic fuel mix, long wave growth	0.6	4.1	6.8	39.4	40.8	7.9	48.7
1985 fuel mix, long wave growth	1.9	23.6	40.7	31.5	2.3	0.0	2.3
"enhanced coal", long wave growth	0.6	17.1	16.5	57.0	1.3	7.5	8.8
"nucl. morat.", long wave growth	0.6	4.1	17.4	68.7	1.3	7.9	9.2

Table VI

Total CO_2 emissions, 1860 to 2100
% due to different fuels

Scenario	wood	coal	oil	gas	nuclear + solfus
logistic fuel mix, effic. growth	3.4%	20.4%	20.7%	55.5%	0.0%
logistic fuel mix, long wave growth	1.9	12.3	15.4	70.4	0.0%
1985 fuel mix, long wave growth	2.8	31.2	40.9	25.0	0.0%
"nucl. morat.," long wave growth	1.1	7.0	22.3	69.7	0.0%
"enhanced coal," long wave growth	0.9	26.5	19.5	53.0	0.0%