WORKING PAPER

LEAKING METHANE FROM NATURAL GAS VEHICLES:
Implications for US Greenhouse Gas Reductions from the Automobile Sector

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IIASA
International Institute
for Applied Systems Analysis

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FOREWORD

The work of the Technology, Economy and Society (TES) Program at IIASA has played an important role in examining the processes of technological evolution in societies. As the environment emerges as a limiting resource, it is natural that we explore the relationship between technologies and environmental damage. In the field of energy use, we have examined the clear link between energy consumption and the emissions of gases such as carbon dioxide and methane (known as natural gas when mined) which may warm the Earth's climate.

This paper explores the opportunities for reducing greenhouse gas emissions from automobiles in the United States through a program of switching to natural gas vehicles (NGVs). It shows that NGVs can contribute to lower emissions of carbon dioxide simply because natural gas is less CO_2-intensive than oil-based fuels like automotive gasoline. However, the benefits of using NGVs are small. Furthermore, the NGVs will likely leak some methane during operation; since methane is a very strong greenhouse gas, the CO_2 benefits of using NGVs may be outweighed by the methane.

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LEAKING METHANE FROM NATURAL GAS VEHICLES:
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D.G. Victor*

Abstract

A model of the US automobile market is used to test the role that natural gas vehicles (NGVs) might play in reducing greenhouse gas emissions. Since natural gas (methane) emits less CO_2 per unit of energy than petroleum products, NGVs are an obvious pathway to lower CO_2 emissions. High and low demand scenarios are used to forecast the emissions from unrestricted growth and a modest program of conservation, respectively. Based on these scenarios, a reference scenario is developed that projects a possible future path of automobile use and efficiency. I find that without dramatic shifts in automobile use, fuel consumption and greenhouse gas

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emissions will probably decrease in the future, provided that efficiency continues to improve at modest rates. In theory, NGVs can help shift emissions even further down.

A second objective is to quantify the role that leaking natural gas (methane) might play in offsetting some of the greenhouse advantages of NGVs. A simple atmospheric chemistry model is applied to the reference case. Based on current estimated leakage rates of about 3.6%, nearly all the greenhouse advantages of NGVs are consumed by the greenhouse contribution from leaking methane.

If oil operations (used to supply gasoline to conventional vehicles) also yield natural gas leaks then the relative case for NGVs should be more favorable. Scenarios that account for this are also explored. However, it appears that even if this source of methane is included, NGVs do not have substantial advantage over oil-based automobile fuels for two reasons: 1) the CO_2 advantage of natural gas (compared with oil) is compensated by the methane leakage, and 2) there are not large gains in efficiency from using natural gas instead of oil products in automobiles.

Introduction

Recent concern over the greenhouse effect has focused attention on opportunities to decrease emissions of greenhouse gases (GHGs) such as CO_2 and CH_4 (natural gas, methane) and reduce theorized global warming. Switching to natural gas fueled systems is one option because coal and petroleum fuels emit about 75% and 40% more CO_2, respectively, than natural gas.[1] Published reports,[2] Congressional testimony,[3] and recent bills[4] all acknowledge the role that natural gas might play in a plan to cut U.S. GHGs. Currently, large CO_2 savings are realized through natural gas use instead of oil or coal in space heating, industrial processing, and electricity production.[5] Ausubel et al. have argued that these savings will increase as natural gas becomes the dominant fuel source in a "methane economy."[6]

Natural gas-fueled vehicles (NGVs) have been explored as one such methane-based technology. Although NGVs were initially considered for local environmental reasons,[7] NGVs are now also considered under a broad program of fuel switching to reduce GHG emissions.[8] Certainly other automotive technologies--hydrogen-fueled and electric vehicles--offer greater promise as a long-term greenhouse reduction measure, but NGVs may exist as a bridge to those new technologies. Also, there are a number of environmental reasons--aside from the greenhouse effect--why NGVs might become a dominant transportation system since NGVs emit lower concentrations of some pollutants. Thus one can imagine a number of persuasive arguments on why natural gas--and NGVs in particular--will become more widely used. Given that the greenhouse effect will likely be a significant concern for energy policy in the future, this paper attempts to look closely at the role NGVs can play in reducing greenhouse gas emissions.

The paper is divided into two sections. The first section develops a model of US automobile use and applies a number of NGV switching scenarios to explore the opportunities for greenhouse gas reductions. For this section, it is assumed that the natural gas recovery and supply system does not leak. The second section addresses the effect of methane leaks. Methane is a strong greenhouse gas, so even small leaks might be serious greenhouse contributors.

Throughout the paper only effects of CO_2 and CH_4 are included; however, other greenhouse gases such as N_2O and O_3 are also byproducts of automobile use. A more detailed study might apply the methods developed here to those gases as well. However, such a study might be very difficult, especially for tropospheric O_3 which varies spatially and temporally and is also dependent upon a complex mix of other pollutants.[9]

1. The Model

The model is structured to project changes in vehicle miles travelled (VMT) and NGV penetration into the market. Efficiency projections are then included and total fuel use is calculated; greenhouse gas emissions are computed from total fuel consumption and the fuel type. In an effort to put the discussion in perspective, historical trends in all variables have been collected back to 1950.[10] The model only includes automobiles although opportunities for NGV switching also exist for trucks and buses. However, the basic conclusions for cars probably also apply to trucks. The structure is summarized in figure 1; below, the variables are systematically discussed.

Market Growth

Two scenarios are used for growth of the automobile market; one represents a high energy demand and the other low energy demand that is the result of a modest program of constraining market growth. A reference scenario--between the high and low demand scenarios--is developed as a possible future course of US automobile use and fuel demand.

The high demand scenario assumes that the VMT will grow as a linear extension of the past. Arguably, growth may be exponential in the future since increases in income will make automobiles and automobile fuel more widely available. However, congestion and availability of public transportation may offset income-based growth. From 1975 to 1985, total highway mileage in the US has remained essentially the same although the number of vehicles and total vehicle miles travelled have increased by 20% and 33% respectively.[11] Over the same period, the number of passenger transit systems (e.g. buses, rail systems, trolleys) has more than doubled, and the number of passengers has increased by 30%.[12]

The low demand scenario assumes that reductions in VMT growth will continue such that VMT growth is reduced to zero by 2010. This scenario is a possible result of efforts to decrease automobile use. Concern over energy security and the environmental side-effects of automobile use may generate pressure for such VMT reductions. Unlike other studies that predict the availability of oil energy (and therefore price) as a constraining factor, I believe that serious restrictions on VMT may result from environmental-based concern over energy use. As discussed later, these market restrictions would be coupled with strong incentives to improve efficiency.

The reference scenario incorporates constraints from both the high and low demand scenarios and assumes that the average use of passenger cars will not increase much beyond current levels of 5271 VMT per person (8434 km per person).[13] VMT growth will decrease from current levels and follow population trends in the future. The underlying assumption is that for a very affluent society the constraint on automobile <u>use</u> is not economic growth. There may be physical limits to high VMT growth: at current vehicle utilization of 1.7 persons/vehicle,[14] the passenger miles travelled (PMT) per person is about 8960 mi (14336 km). In 1985, 66% of the population held driver's licenses;[15] on average, each driver would have to operate a vehicle 7990 mi (12784 km) to achieve total VMT levels. Perhaps only as little as 60% of the population (144 million) is physically fit to drive an automobile,[16] in which case each driver would have to drive 8790 mi (14064 km). Thus if the average time budget allocated to personal travel does not change much in the future, population might be the growth limiting factor (especially if congestion favors non-highway modes of travel).

Based on this analysis, the reference scenario assumes that annual VMT growth will gradually reduce from the current average of 2.07%[17] such that by 2000, VMT growth follows population growth. Note that passenger miles travelled (PMT) per capita might continue to increase under this scenario; indeed, the pressures of congestion and a greater interest in public transportation might favor higher utilization than 1.7 persons per vehicle.

Figure 2 shows the VMT projections from the three scenarios. Figure 3 combines the data into projections for VMT per capita and VMT per potential driver, assuming that the percentage of potential drivers remains about 66% of the US population. Note the steady decline in VMT per capita for the low demand scenario: although VMT growth is zero, population continues to grow (except after 2025 when population is projected to decline .6% per year).[18]

Market Penetration

Previous research indicates that technologies compete with each other for market share in a manner similar to niche competition between species.[19] A new technology enters the market with a small share and progressively invades the market following a simple S-shaped logistic curve.[20] I am assuming that NGVs will penetrate the automobile market in a similar manner.

Since a program of NGV switching would require massive capital expenditures in refueling equipment, natural gas pipelines, and mechanic training, it is not clear what the maximum market penetration might be. Substitution between NGVs and conventional cars would likely be quite easy, so a continuous range of penetrations is possible.

In an effort to bracket all these possibilities, two market penetration scenarios are used: one with maximum penetration of 20%, the other with 60%. Market penetration is expressed as the portion of VMT driven by NGVs. The 20% scenario represents the likely penetration if just business and government fleet vehicles plus a limited number of other automobile users switch to NGVs. The most polluted cities might, for example, institute measures that make NGVs very attractive since NGVs emit lower concentrations of CO and non-methane hydrocarbons,[21] both of which are controlled under the National Ambient Air Quality Standards.[22]

The 60% scenario reflects a likely result from a broader NGV switching program. For example, national incentives might exist that favor NG use for environmental reasons (perhaps even in response to the greenhouse effect). Nonetheless, intercity and rural automobile transport will probably remain reliant upon gasoline; for this reason, a somewhat arbitrary upper limit of 60% penetration is set. However, higher penetration limits may result if natural gas refueling stations become widespread, prices for natural gas remain competitive, and consumers do not believe NGVs will become obsolete. Also, if natural gas is widely used in other areas (e.g. electricity generation and heating) then the large supply network may assist high market penetration of NGVs by providing some of the infrastructure required for refueling stations.

Figure 4 summarizes the changing market shares for the 20% and 60% scenarios. The most rapid period of diffusion (from 10% of the market to 90%) is expected to take 20 years ($\Delta t=20$ years); complete diffusion (from 1% to 99%) takes twice that time, or 40 years. This is less rapid than for other technological shifts: catalytic converters diffused into the US market with $\Delta t=13$ years,[23] and data on the survival rate of passenger vehicles supports a diffusion rate of about $\Delta t=10$ years.[24] However, changes in the refueling infrastructure as well as necessary shifts in consumer behavior make a somewhat slower diffusion more likely.

Efficiency

Predicting future efficiencies is quite difficult since the future will, most likely, not follow past trends. Since 1973, improvements in automobile efficiency have been dramatic, and if the addition of energy-intensive pollution control equipment is accounted for, the results have been even more impressive. These improvements are the result of consumer demands for more efficient cars after the 1973 oil shock, but US policy of setting minimum efficiencies for new cars has also contributed. It is not clear how any of these variables will fluctuate in the future. Furthermore, other factors such as consumer tastes and levels of vehicle ownership are also important for long-term projections since they affect the character of the fleet which, in turn, affects overall efficiency.

For the high demand scenario, average fleet efficiency is assumed to grow at current levels through 1995 as the least efficient, older cars are retired from the fleet. Thereafter, efficiency growth decreases to zero and after 2000 there are no improvements in efficiency (i.e. efficiency remains at the 2000 level of 27 mi gal^{-1}, MPG, or 11.4 l km^{-1}). This scenario posits that energy will remain relatively cheap and incentives to improve efficiency will be nonexistent. This is consistent with the other high demand assumptions of unbounded automobile and fuel use.

The low demand scenario assumes that restrictions on market growth will be accompanied by strong incentives to improve efficiency. By 2050 the average fleet efficiency is assumed to increase to 60 MPG (25 l km^{-1}). This growth is less rapid than for the period 1975-1985, but it is assumed that the most dramatic efficiency improvements such as the reduction in the sales of very large cars have already happened.[25] Nonetheless, the low demand efficiency assumptions require substantial improvements in all automobile systems and probably also require shifts in consumer tastes to favor smaller, lighter cars. However, the scenario is not unrealistic since vehicles that perform at 50 MPG (21 l km^{-1}) are available today; presumably higher efficiencies will result from 60 years of future innovation, provided that proper incentives exist.

The reference scenario assumes that pressure improve efficiency will continue through 2050 but the improvements will be less dramatic than for the low demand scenario. By 2050 efficiency is 45 MPG (19 l km^{-1}). As with the other scenarios, I am assuming that the overall fleet efficiency will continue to increase along the average trends for the period 1975-1985 as the major post-shock efficiency improvements filter through the fleet. After 1995, efficiency is assumed to increase by 1% per year, or about half the efficiency growth rate for 1975 to 1985. By 2050 the efficiency is 45 MPG which is technically feasible today.

A major challenge to the reference scenario's efficiency assumption is the recent trend that the efficiency of new cars sold is decreasing after two years of stagnation.[26] However, over the long run, cyclic decreases are expected.

An earlier version of this model attempted to study fuel consumption in more detail by focusing on the efficiency and sales of new cars; based on survival and utilization rates, total VMT and fuel use were, theoretically, calculated.[27] However, the attempt failed to make realistic long term projections because the dynamics of survival and scrappage rates are not well understood; the number of free parameters is unmanageable.[28] For this reason, the current model explicitly avoids the question of how many cars will be on the road and focuses just on VMT. However, the per capita ownership of cars will probably increase from 1985 levels of 561 cars per 1000 to about 700 cars per 1000.[29] In 1985, Connecticut had ownership levels of 745 automobiles per 1000 population, so even higher levels of vehicle ownership are not impossible. Survival rates are expected to decrease; if so, the fleet will be newer and (perhaps) more efficient than my projections. This should be kept in mind when analyzing my results.

Efficiency of natural gas vehicles is highly dependent upon their basic design. For a dual use vehicle (i.e. runs on both gasoline and natural gas) there may be no gain in fuel efficiency (e.g. km per joule of energy) over a purely conventional fuel vehicle.[30] However, a vehicle optimally designed for compressed natural gas (CNG) may ultimately be 15% more efficient than a conventional-fueled vehicle for two reasons: 1) Natural gas has a higher octane number so it can burn more efficiently; and 2) NGVs may ultimately require less pollution control equipment, at least for CO emissions since natural gas has a lower carbon content than conventional fuels. This assumes that NO_x emissions and NO_x control equipment will be about the same as for conventional-fueled vehicles, but even this is not clear since the NO_x/CO tradeoff may favor less NO_x control equipment for NGVs.[31] It is possible to imagine an ideal NGV which might have higher efficiency than the case used here, but with current NGVs this is probably the most reasonable case. However, the NGV fleet may initially be much more fuel efficient than the conventional gasoline-powered fleet because the NGVs will be new (assuming they are dedicated NGVs and not converted gasoline automobiles). If this is the case, the model will overestimate fuel consumption by a progressively decreasing percentage over the early (ten to fifteen years) period of NGV use.

If liquified natural gas vehicles (LNGVs) become popular instead of compressed natural gas, the overall efficiency will likely be 5% to 10% lower due to the energy required for fuel liquefaction. The actual amount depends on the design tradeoff between fuel pressure and temperature in the NGV storage tanks.

The efficiency of conventional gasoline-powered vehicles and NGVs is summarized in figure 5. Note that in the past, efficiency has not always increased, so even the high demand assumption that efficiency will remain level is suspect, especially if real energy prices decline as they did up to the oil shock of 1973. Also note the vigorous improvements in efficiency since the oil shock.

As mentioned before, most of the advantages of NGVs come from the lower CO_2 emissions per unit of energy. This advantage for natural gas is in addition to the greater energy efficiency just discussed.

Pipeline operations and refining

The combination of market growth, NGV penetration, and efficiency lead to total fuel consumption by fuel type. Before calculating greenhouse gas emissions I also included energy requirements for refining and "own use" of fuel for pipeline operations and fossil fuel recovery. For gasoline production, it is assumed that 8% of each ton of oil is burned in refining and in oil recovery operations, releasing CO_2.[32] For natural gas, about 5.5% of total gas consumption is for "own-use."[33] As discussed in the next section, some percentage beyond the 5.5% required for pipeline operations is assumed leaked by the natural gas recovery and supply system.

CO_2 emissions from industrial activity required to build the automobiles themselves are not included. This omission probably exists systematically for NGVs and gasoline passenger cars so it will not affect my comparisons. Also, CO_2 emissions from non-pipeline transport of oil and oil products are not included, so greenhouse gas emissions from oil-based fuel consumption may be underestimated by a few percent.

Results

Figure 6 summarizes the total energy use for the permutations of three growth scenarios (high and low demand and the reference case) and three penetration scenarios (0%, 20%, and 60% VMT by NGVs). Note that in the recent past, energy consumption has been decreasing although VMT has, on average, been increasing (figure 2). Since 1975, efficiency has grown much faster than VMT; both the reference and low demand scenarios assume that this trend will continue in the future. For the high demand scenario, VMT will grow much faster than efficiency, but due to the major efficiency improvements since 1975, total fuel use in 2050 is only 50% higher than 1975 levels whereas VMT has increased 60% over the same period. Thus even if efficiency does not improve over the next century, the oil shock will continue to influence fuel consumption patterns by raising the average economy of the fleet to a new plateau (assuming it does not decline again).

CO_2 emissions are calculated from total energy use; 50% of all CO_2 is assumed retained in the atmosphere for the period of my projections (until at least 2050).[34] CO_2 is expressed as the increase in parts per million (ppm) airborne CO_2 concentration since 1950. Concern over the greenhouse effect is directly tied to the magnitude of steady-state concentrations of greenhouse gases such as CO_2 so this convention of expressing results as a cumulative "greenhouse effect" is adopted.

Figure 7 summarizes the increase in greenhouse trapping (measured in ppm of CO_2) since 1950.[35] The atmospheric content of CO_2--because it is a cumulation of many years' emissions--responds sluggishly to changes in the pattern of CO_2 emissions. The curve rises exponentially from 1950 to 1975 as VMT grew rapidly while efficiency gradually decreased. Since 1975, CO_2 concentrations from the US automobile sector have grown linearly. Note that by 1988, atmospheric CO_2 concentrations had increased about 1.5 ppm due to automobile use in the US alone; the total increase (due to all CO_2 emissions worldwide, including deforestation) over that period was about 35 ppm.

According to these calculations, NGVs can make only a small difference in CO_2 concentrations. Projected atmospheric CO_2 is 5% lower for the 60% penetration scenarios in 2050 than for zero NGV penetration (but over time the savings are increasing). NGVs are slightly more efficient than conventional gasoline-powered vehicles so they require less energy (figure 6), but the lower CO_2 emission factor for natural gas yields the largest savings. Nonetheless, the combination of the two can yield only modest changes in atmospheric CO_2.

The most dramatic differences in atmospheric CO_2 come from different fuel consumption patterns, not NGV switching. Atmospheric CO_2 from the high demand scenario is nearly 70% higher than the low demand scenario and 60% higher than the reference scenario. This paper does not address the economics of fuel switching under these three scenarios, but it is clear that market constraints coupled with efficiency improvements offer larger opportunities for greenhouse gas reductions than do NGVs. Nonetheless, a program of NGV switching may help reduce greenhouse gas emissions, and other benefits in lower urban pollution may favor NGVs as well.

2. The Problem of Methane Leakage

The results are less favorable for NGVs if the effects of leaking methane are included since only small emissions of methane can have a large effect on total greenhouse heat trapping. At steady state concentrations, methane is 16 to 32 times more effective than CO_2 as a greenhouse gas.[36] Given the uncertainty in this number, all greenhouse projections in this section will be presented for both estimates. As discussed throughout this section, a number of variables are highly uncertain; where possible I have tested the sensitivity of the model to these uncertainties. Table I summarizes the major greenhouse-related uncertainties that affect the parameters used in this model.

Currently, methane concentrations are increasing by about 1% per year. Of the estimated annual source of 540 Tg (540 x 10^{12} grams), I am assuming that about 15% (80 Tg) is from fossil fuel recovery and supply;[37] however, some isotopic measurements of atmospheric methane suggest the sources of such "old" or "dead" methane may be up to twice as large.[38] Of this 80 Tg, 35 Tg are assumed from coal mining activity and the rest (45 Tg) from natural gas leaks.[39] Based on 1985 worldwide natural gas use of 1.71 x 10^{12} m^3 (1230 Tg),[40] average leakage rates are about 3.6%. However, the level of fossil fuel-related emissions is quite uncertain since there may be natural sources of methane which have the same isotopic signature as methane leaked from energy-related activities. Thus the 45 Tg attributed to natural gas leaks may not be entirely proportional to natural gas production. Also, the 35 Tg assigned to coal mining may be actually be different. All of these uncertainties affect the calculations, especially the average leak rate assigned to worldwide natural gas activities.

The US leak rate may be lower than the world average; US natural gas industry statistics support a leakage rate of 2.3% or lower.[41] However, it is not clear what is actually lost and what is due to accounting errors since both figures must be reported as one. Also, these statistics only include losses in the supply system; most likely, wellhead losses and losses by end users are significant as well.

Over the period of this analysis, better pipelines and supply systems may help reduce leak rates. Conversely, leak rates may increase with NGVs since refueling operations and poor maintenance may become large sources of previously nonexistent leaks. To include this range of possibilities, I have computed two leak scenarios: one at 2% and the other at 4%. Note that this also corresponds with the range of reported numbers (table I) for methane attributed natural gas leaks (25 to 50 Tg which translates to 2% or 4% leakage).

Computing the steady-state concentration of methane is more complicated than for CO_2 because the kinetics of atmospheric removal must also be included. Like CO_2, methane emitted in one year contributes to the greenhouse effect in subsequent years, but the methane contribution changes over time whereas the airborne fraction of CO_2 probably remains about the same.

A first-order attempt at including the chemistry of atmospheric methane is made by assuming a well-mixed atmosphere and simplifying methane emissions from NGV and pipeline leaks to a single emission each year. Most methane (85%) reacts out of the atmosphere through reaction with OH radicals in the troposphere:

$$CH_4 + OH \text{ ------> } CH_3 + H_2O$$

The rate of the reaction depends on the concentration of OH and CH_4 and a constant k:

$$\text{rate} = k_1[OH][CH_4]$$

The brackets indicate concentration. The balance (15%) of methane removal takes place in the stratosphere where the most abundant reaction is also reaction with OH as above.[42]

Note that the process proceeds at a rate which is linearly dependent upon the concentration of CH_4, assuming the concentration of OH remains about the same and the atmosphere is homogenous (i.e. k, which is also dependent upon temperature, does not fluctuate). Mathematically, a description of the amount of methane left in the atmosphere at any time, t, is similar radioactive decay where the probability of a decay in a unit time depends linearly on the concentration of remaining sample; the amount of sample left (in the atmosphere) at any point in time depends on the half life and is expressed in the following standard formula of exponential decay:

$$\text{fraction of } CH_4 \text{ remaining in atmosphere}_t = \frac{1}{2^{(t/t_{1/2})}}$$

Clearly this equation does not account for the spatial variations--especially between the hemispheres and with altitude--that are important.[43] But my assumptions probably allow an adequate first-order approximation of the methane fraction that remains airborne.

Figure 8 shows this equation applied to a steady state representation of methane sources and sinks in today's atmosphere. Assuming a constant 500 Tg annual emission starting at t=0, a half life of 6.6 years is chosen so the model fits current atmospheric methane concentrations of 4800 ± 3% Tg.[44] The model predicts a slightly higher value (5000 Tg) due to annual instead of continuous iterations. A half life of 6.6 years corresponds with a mean residence time of about 9.6 years (a range of 8 to 14 years is reported in the literature).[45]

Figure 9 shows the greenhouse contribution in parts per billion (ppb) of CO_2 due to leaking methane for a simplified natural gas consumption scenario. At t=0, 10^{18} joules of natural gas (81 x 10^9 m^3)[46] is burned, releasing CO_2. An additional 2% (1.6 x 10^9 m^3, or 0.4 Tg)[47] of the methane is assumed leaked to the atmosphere before combustion. The greenhouse potential of methane relative to CO_2 is assumed to be 16 (the methane curves are 100% higher if a greenhouse potential of 32 is used). Since CO_2 that remains in the atmosphere (50%) has essentially an infinite lifetime, the CO_2 greenhouse contribution remains roughly the same over time (there is a small increase since CH_4 decays to CO_2). Methane decays over time so its greenhouse contribution changes. For emissions that span many years, the total greenhouse contribution at a given year, t, is simply the sum of "total" curves calculated at year t for each previous year's emissions.

The major process for methane removal is dependent upon OH concentrations. Perturbations elsewhere in the chemistry of the lower atmosphere will affect methane concentrations. For example, CO competes with methane for OH so increasing CO concentrations (i.e. from increased fossil fuel use) may create an "OH feedback" that depletes OH and extends the mean residence time of methane in the atmosphere. It is unclear what the future path of such an OH-feedback will be, or even if it will exist,[48] but if it does, the effects of leaking methane will be worse than depicted here.

Results

Figure 10 shows the effects of leaking methane applied to my reference scenario with 60% NGV penetration. For better resolution, the period 2030 to 2050 is shown in figure 11. As before--when considering only CO_2--the curves diverge over time; the effect of NGV substitution becomes larger the longer NGVs are used. The contribution of leaking methane to total greenhouse trapping is summarized in table II.

For a methane factor (m.f.) of 16, there are greenhouse advantages from using NGVs even above a leak rate of 4%. At 2050, the break-even point is about 6%, but if the methane factor is 32 the break-even point is 3%. Note that the shape of the "no NGVs" curve is different from the others after 2030 since the effect of logistic NGV diffusion is absent from the "no NGVs" curve. Over time, the benefits of NGV use increase. Beyond 2050 there are greenhouse advantages to using NGVs even if the methane factor is 32 and the leak rate is 4%.

Generally, however, leaking methane seems to consume most of the greenhouse benefits that NGVs might have because of their higher efficiency and the lower CO_2 emission factor of natural gas. Perhaps NGVs can make a very small difference over the long run, but by 2050 it seems likely that NGVs will, in turn, be replaced another fuel technology. As a greenhouse gas reduction measure, NGVs probably have little or no effect, and if leaks are high the effects may be negative.

Natural gas leaks may also be due to oil exploration and recovery operations. If this is the case then NGVs should be more attractive than suggested here: leaks from the natural gas system would be lower than I calculated and greenhouse gas emissions from oil-based fuels would be higher. In essence, the conventional gasoline-powered fleet yields methane leaks as well.

An upper bound on oil-based natural gas leaks may be 30% of the total leakage of 45 Tg (i.e. 13.5 Tg); the remaining 31.5 Tg corresponds with a 1985 natural gas leak rate of 2.7% which is closer to industry statistics. 1985 worldwide oil production was 118 x 10^{18} joules;[49] based on this 30% scenario, natural gas leaked from oil operations at an average rate of 0.11 Tg per 10^{18} joules of oil energy consumed. Figure 12 presents the results for the reference scenario with 60% NGV penetration when this additional source of methane is included. The percent contribution from methane is summarized in table III.

Including methane leaks from oil will shift all the greenhouse curves slightly upward (less than 0.05 ppm CO_2

equivalents), but the relative position of curves does not change much. The findings still support the claim that leaking methane will offset many of the advantages of NGVs. Note that the 0% leak curves (i.e. if the natural gas supply system does not leak) are nearly identical for methane factors of 16 and 32; this demonstrates that if the natural gas supply system does not leak then the total methane greenhouse contribution is quite small, even if oil recovery operations are a significant source of methane. With 60% penetration, relatively low market growth, and modest efficiency improvements under the reference scenario, the total consumption of oil (and associated methane leaks) is decreasing dramatically up to 2050. Over the same period the use of natural gas for NGVs is increasing. In sum, methane emissions from oil are not very large and do not affect the conclusions. At a 2% leak rate, the natural gas system is leaking about 0.37 Tg per 10^{18} joules which is nearly 4 times the rate for oil. The effects of leaks from oil are significant, but leaks from the natural gas system are much larger.

As discussed before, the uncertainties here are quite large, and the largest is the source and magnitude of leaking methane. Even if substantial methane leaks are due to the natural gas recovery and supply system, it is possible that such leaks will decrease in the future as the system is improved. Here I note that if the leakage is about 3% today but improves at 1% per year--similar to the improvements in efficiency I have postulated--by 2050 leakage will have dropped to about 1.5%. If leakage improves by 2% per year then the leakage rate would fall to below 1% by 2050. Leakage rates below 1% are technically feasible today, so it is likely that an even more dramatic improvement is possible. Thus we can probably reduce the problem of leaks dramatically, but doing so will probably require a system of incentives.

Conclusions

In terms of VMT and fuel consumption, the US automobile market grew dramatically from 1950 to 1975. Since then, VMT has continued to grow while total fuel consumption (and greenhouse gas emissions) have declined. If efficiency continues to improve into the future, these declines will persist. If efficiency stagnates and VMT continues to growth as it has in the past (high demand scenario), primary fuel consumption will climb to nearly 4 times 1950 levels (1.5 times 1975 levels). My research suggests that programs which constrain VMT growth and improve efficiency can have a much larger effect than fuel switching to natural gas in the automobile sector.

Furthermore, at today's estimated leak rates, the problem of leaking methane is significant, and if leakage increases with the introduction of NGVs the problem will likely be more serious. Natural gas may not be as good a greenhouse reduction fuel as previously thought. However, the two most important parameters in the methane analysis are the leak rate and the greenhouse efficiency of methane, both of which are not well understood. Better characterization of these would be an appropriate prerequisite to an NGV switching program. However, given that NGVs can make only a small difference even if the system doesn't leak at all, a better option would be waiting until robust, "zero-CO_2" technologies such as hydrogen and electric powered vehicles are suitable for market diffusion. If NGVs are pursued, we should set out to make the natural gas recovery and supply system as tight as possible which may be a Herculean task since even small leaks make a large difference.

The same is generally true of all natural gas technologies: in a world of increasing concern over the greenhouse effect it makes sense to plug methane leaks, provided it is known where they are and how large they are. In closing, I note that the advantages of natural gas are probably robust for many other switching schemes, especially when natural gas is used to replace coal. Also, for applications such as electricity generation where natural gas offers substantial efficiency improvements over oil and/or coal, the advantages of natural gas are greater.[50]

Notes

1. In terms of grams of carbon per BTU: oil=0.020256, gas=0.0144535, and coal=0.025109; from J.A. Edmonds, W.B. Ashton, H.C. Cheng, and M. Steinberg, 1989. "A preliminary analysis of U.S. CO_2 Emissions Reduction potential from Energy Conservation and the Substitution of Natural Gas for Coal in the Period to 2010." U.S. Department of Energy, DOE/NBB-0085. I have assumed in this analysis that oil products--gasoline in particular--have about the same emissions per BTU as oil. These numbers vary from source to source. For example they differ by +1.5% for gas, +5% for oil products (gasoline), and +<1% for bituminous coal from the carbon emission factors given in G. Marland, 1982 "The impact of synthetic fuels on global carbon dioxide emissions," in W.C. Clark, ed. Carbon Dioxide Review: 1982 (New York: Oxford). Roughly the same deviation exists (+1% for gas, +4.7% for oil, and +2.1% for coal) when compared with data from R.M. Rotty and C.D. Masters, 1985. "Carbon dioxide from fossil fuel combustion: Trends, resources and technological implications," in J.R. Trabalka, ed., Atmospheric Carbon Dioxide and the Global Carbon Cycle, ER-0239 (Washington: Department of Energy). Losses due to refining are included separately in the model.

2. e.g. W.M. Burnett and S.D. Ban, 1989. "Changing prospects for natural gas in the United States," Science 244:305-310.

3. e.g. Testimony of M. Oppenheimer, 1989. Hearings before the Committee on Energy and Natural Resources, United States Senate, S. Hrg. 100-461, Pr. 2, p. 89.

4. e.g. 101st Congress, S.324, Sec. 1001-1008.

5. About 26% of U.S. energy production is from natural gas, and the gas-fired electricity is, for example, increasing. See Table 1.3 in Monthly Energy Review Energy Information Agency, July 1988. (Although 26% of the energy is from gas, only 18% of U.S. CO_2 production is due to gas.)

6. J.H. Ausubel, A. Grübler, and N. Nakicenovic, 1988. "Carbon Dioxide Emissions in a Methane Economy," Climatic Change 12: 245-263.

7. NGVs have lower emissions of some pollutants than do gasoline automobiles, and other countries such as Italy and New Zealand have taken advantage of this as part of pollution-reduction programs. For recent work on NO_x, CO and HC emissions from NGVs as they pertain to local environmental concerns see, for example, Enoch J. Durbin, 1989. "Understanding Emissions levels from Vehicle engines fueled with gaseous fuels," Department of Mechanical and Aerospace Engineering, Princeton University.

8. See "National Energy Policy Act of 1989," S.324 101st Congress., Sec. 2 (a) (5) for the role of fuel switching in GHG reductions and Sec. 1001 to 1006 on NGV research priorities.

9. J.A. Logan, M.J. Prather, S.C. Wofsy, and M.B. McElroy, 1981. "Tropospheric Chemistry: A Global Perspective," <u>Journal of Geophysical Research</u> <u>86</u>, 7210-7254.

10. The general data source for 1950 to 1970 is U.S. Department of Commerce, 1975. <u>Historical Statistics of the United States: Colonial times to 1970</u> part 2 (Washington: Govt. printing office). Data updated to 1985 from U.S. Department of Commerce, 1987. <u>Statistical Abstract of the United States: 1988</u> (Washington: Govt. printing office), and earlier editions of the same document. Throughout the paper I will refer to specific data sources used for the above two books.

11. 3.838 million total highway mileage in 1975 and 3.862 total in 1985; from US Federal Highway Administration, <u>Highway Statistics</u>. Total number of cars based on Motor Vehicle Manufacturer's Association estimates of cars in use. Data compiled in US Dept. of Commerce, <u>Statistical Abstract of the United States</u>.

12. American Public Transit Association, <u>Transit Fact Book</u>, annual publication summarized in <u>Statistical Abstract of the United States: 1988</u>, series no. 1011.

13. 1950 to 1970 VMT from US Federal Highway Administration compiled in <u>Historical Statistics of the United States</u>, part 2, series Q 199-207; 1970 to 1985 VMT from US Federal Highway Administration, <u>Highway Statistics Summary to 1985</u> compiled in <u>Statistical Abstract of the United States: 1988</u>; historical population data from US Bureau of the Census, <u>Current Population Reports</u>. VMT for cars in 1970 to 1985 and passenger vehicles (cars plus buses)

for 1950 to 1970. Buses never comprise more than 0.5% of passenger vehicles for the period 1950 to 1970 so errors from these accounting differences are probably very small.

14. From 1984 data compiled in M.C. Holcomb, S.D. Floyd, and S.L. Cagle, 1987. Transportation Energy Data Book: Edition 9 ORNL-6325 (Oak Ridge: Oak Ridge National Laboratory).

15. Estimated 1986 drivers licenses were 158.594 million in a total population of 241.596 million. Source: US Bureau of the Census and US Federal Highway Administration, various publications, compiled in Statistical Abstract of the United States series no. 2 and no. 991.

16. OECD, "Long term Perspectives of the World Automobile Industry," (note by the secretariat), November 1982, Annex I, pp.5-7. Cited in A. Altshuler, M. Anderson, D. Jones, D. Roos, and J. Womack, 1984. The Future of the Automobile (Cambridge: MIT press), p.110.

17. The average growth rate for 1975 to 1985 (i.e. average growth in the post-oil shock period).

18. Population forecasts from the World Bank. K.C. Zachariah and My. T. Vu, 1988. World Population Projections, 1987-88 Edition: Short- and Long-Term Estimates (Baltimore: Johns Hopkins Press).

19. e.g. J.C. Fisher and R.H. Pry, 1971. "A Simple Substitution Model of Technological Change," Technological Forecasting and Social Change 3: 75-88.

20. The S-shaped curve is from an equation of the form:

$$\text{market fraction} = \frac{K}{1 + \exp(-b(t-t_o))}$$

where K is the maximum market fraction. Δt, the time it takes from penetration of 10% of the market (when K=1) to 90% of the market is 20 years. b is a constant set in proportion to Δt (b=0.2197 for this model).

21. Hydrocarbons are controlled through the O_3 standards; also, CH_4 leaked from the NGVs can also form O_3 so the case in favor of NGVs is not so simple with respect to

hydrocarbon emissions.

22. For more on the standards and compliance see Council on Environmental Quality, Environmental Quality published annually (Washington: Government Printing Office).

23. see N. Nakicenovic, 1986. "The Automobile Road to Technological Change," Technological Forecasting and Social Change 29:309-340. This article addresses a series of technical innovations in the automobile industry.

24. The age difference between 90% survival and 10% survival is about 10 years; thus a technology that affects new cars will diffuse into the market with that time constant. Survival data reported in M.C. Holcomb, S.D. Floyd, and S.L. Cagle, 1987. Transportation Energy Data Book: Edition 9 (Oak Ridge: Oak Ridge National Laboratory) ORNL-6325.

25. e.g. in 1978, 51% of US new car registrations were cars with engine size of 5.0 liters or greater ("very large"); that number dropped to 16% in 1982. International Energy Agency, 1984. Fuel Efficiency of Passenger Cars (Paris: OECD), p.117.

26. Data reported in G. Rosegger, 1989. "Diffusion through Interfirm Cooperation: A Case Study," International Conference on Diffusion of Technologies and Social Behaviour, Laxenburg, Austria 14 to 16 June, p.11.

27. From data compiled in M.C. Holcomb, S.D. Floyd, and S.L. Cagle, 1987. Transportation Energy Data Book: Edition 9 ORNL-6325 (Oak Ridge: Oak Ridge National Laboratory).

28. Using current data the model could not even reliably predict current fuel consumption. For this reason, projections were likely to be quite unrealistic.

29. A. Altshuler et al., 1984. The Future of the Automobile (Cambridge: MIT Press), ch.5. Data on vehicle ownership updated with US Highway Administration statistics.

30. EPA tests of existing automobiles converted to dual fuel use found that burning natural gas gave about the same efficiency (BTU/mile) as an unconverted vehicle.

Gasoline efficiency for the converted vehicle was about 10% lower. See R.I. Bruetsch, 1988. "Emissions, Fuel Economy, and Performance of Light-Duty CNG and Dual-Fuel Vehicles," EPA/AA/CTAB-88-05.

31. For recent work on NO_x, CO, and HC emissions from NGVs see Enoch J. Durbin, 1989. "Understanding emissions levels from vehicle engines fueled with gaseous fuels," Princeton University, Department of Mechanical and Aerospace Engineering. My study does not address the effect on NGV efficiency of pollution control equipment such as catalytic converters.

32. 7.5% for refining which includes net transfers to petroleum refineries (i.e. consumption during refining) of 0.13 mtoe coal, 13.85 mtoe gas, 2.92 mtoe electricity, and 38.47 mtoe oil; coal, gas, and electricity corrected for different carbon contents (elect. based on 1986 fuel mix and generation efficiency). 0.5% for "own use" which includes oil pipeline consumption and energy required for oil extraction (0.5% for indigenous US production for oil). Computed from 1986 OECD statistics for the United States. OECD, 1988. Energy Balances of OECD Countries (Paris: OECD), pg. 120.

33. Includes consumption for pipeline operations and gas extraction. Computed from 1986 OECD statistics for the United States, Energy Balances of OECD Countries (Paris: OECD), p.120.

34. A range from 40% to 60% has been reported for the airborne fraction. See B. Bolin, 1986. "How much CO_2 will remain in the atmosphere," in Bolin et al., eds., The Greenhouse Effect, Climatic Change, and Ecosystems. SCOPE 29 (New York: Wiley).

35. Greenhouse trapping calculated by computing the molar quantity of CO_2 that remains airborne and then assuming an atmosphere that weighs 5.137×10^{18} kg and has molecular weight of 28.96 g/mole (1.77×10^{20} moles total). All concentrations done by volume, not mass.

36. Sources for the greenhouse potential of CH_4 include R.E. Dickinson and R.J. Cicerone, 1986. "Future Global Warming from Atmospheric Trace Gases," Nature 319:109-115. Also, V. Ramanthan, R.J. Cicerone, H.B. Singh, and J.T. Kiehl, 1985. "Trace Gas Trends and their Potential Role in Climate Change," Journal of Geophysical Research 90:5547-66. The greenhouse potential of methane is one of the many unanswered

questions in the methane debate.

37. R.J. Cicerone and R.S. Oremland, 1988. "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles 2:299-327. This 15% excludes 33 Tg of "dead" CH_4 attributed to natural wetlands.

38. 32% reported in D.C. Lowe, C.A.M. Brenninkmeijer, M.R. Manning, R. Sparks, and G. Wallace, 1988. "Radiocarbon determination of atmospheric methane at Baring Head, New Zealand," Nature 332: 522-525. A minimum of 15% reported in M. Wahlen, N. Tanaka, R. Henry, B. Deck, J. Zeglen, J.S. Vogel, J. Southon, A. Shemesh, R. Fairbanks, and W. Broecker, 1989. "Carbon-14 in Methane Sources and in Atmospheric Methane: The Contribution from Fossil Carbon," Science 245: 286-290.

39. R.J. Cicerone and R.S. Oremland, 1988. "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles 2: 299-327.

40. British Petroleum, 1989. BP Statistical Review of World Energy, 1989. Carbon content of natural gas (used to convert to Tg of CH_4) from R.M. Rotty and C.D. Masters, 1985. "Carbon Dioxide from fossil fuel combustion: Trends, resources, and technological implications," in J.R. Trabalka, ed. Atmospheric Carbon Dioxide and the Global Carbon Cycle DOE/ER-0239 (Washington: Department of Energy).

41. This number varies greatly from year to year. See American Gas Association, 1986. "Lost and Unaccounted for Gas," p.4. In 1985, 2.3% of marketed gas was unaccounted for; in addition, 2.5% of total gas production was vented and flared. OECD statistics for 1986 support a leak rate of 2.9%, from OECD, 1988, Energy Balances of OECD Countries (Paris: OECD), p.120.

42. R.J. Cicerone and R.S. Oremland, 1988. "Biogeochemical Aspects of Atmospheric Methane," Global Biogeochemical Cycles 2:299-327.

43. i.e. k, [OH], and [CH_4] all vary spatially and seasonally.

44. For a well mixed, uniform atmosphere the halflife is:

$$t_{1/2} = \frac{\ln 2}{k_1[OH]}$$

The value $k_1[OH]$ is constrained by the rate expression for the removal of methane:

$$k_1[OH][4800 \text{ Tg}] = 500 \text{ Tg}$$

this yields a half life of about 6.6 years.

45. Mean residence time (or lifetime) is the ratio of the steady state sink (500 Tg) to the total burden (4800 Tg). Additional sources of 40 Tg (total of 540 Tg) account for the 1% annual increase. See R.J. Cicerone and R.S. Oremland, 1988. "Biogeochemical aspects of atmospheric methane," Global Biogeochemical Cycles 2:299-327.

46. Converted using BP standard conversions. See BP Statistical Review of World Energy, 1989.

47. Converted to mass using 540 g C/m^3 natural gas from R.M. Rotty and C.D. Masters, 1985. "Carbon Dioxide from fossil fuel combustion: Trends, Resources, and Technological Implications," in J.R. Trabalka ed., Atmospheric Carbon Dioxide and the Global Carbon Cycle, ER-0239 (Washington: Department of Energy).

48. Rising tropospheric ozone concentrations from urban pollution may increase OH concentrations. In general, the spatial distribution of CO emissions will be an important factor in determining whether OH concentrations will rise or fall in the future. See A.M. Thompson, R.W. Stewart, M.A. Owens, and J.A. Herwehe, 1989. "Sensitivity of Tropospheric Oxidants to Global Chemical and Climate Change," Atmospheric Environment 23: 519-532.

49. British Petroleum, 1989. BP Statistical Review of World Energy.

50. I would like to thank J.H. Ausubel, Arnulf Grübler, N. Nakicenovic, and J. Van de Vate for helpful comments on several drafts of this paper. Research for this paper began under the guidance of M.A. Weiss and the MIT program on global change and was supported by a grant from Sandia National Laboratory to the program on Global Change at the Energy Laboratory of the Massachusetts Institute of Technology. This work was

completed at the International Institute for Applied Systems Analysis with a grant from the Center for International Studies at MIT.

Captions

Fig. 1: Structure of the model.

Fig. 2: Projections for total vehicle miles travelled (VMT) in the United States for the high and low demand and reference scenarios (see text).

Fig. 3: US VMT per capita for entire population (lower curves) and VMT per capita for estimated potential driving population (upper curves) assuming 65% of the population can drive a car.

Fig. 4: Hypothetical curves for diffusion of NGVs into the US automobile market. Vertical axis is the fraction of US VMT driven by NGVs. Two scenarios--20% and 60% diffusion--are used; a curve for 100% diffusion (i.e. diffusion into that portion of VMT that is susceptible to NGV diffusion) is also shown.

Fig. 5: Projected efficiency of conventional gasoline-powered fleet and NGVs in the US for the high demand, low demand, and reference scenarios. For reference, historical data on the efficiency of the total automobile fleet is also shown. NGV efficiencies were converted to MPG equivalents using the heat content of natural gas and

gasoline along with the assumption that NGVs will consistently be 15% more efficient than conventional gasoline-powered vehicles.

Fig. 6: Annaul US total energy consumption for permutations of three growth/efficiency scenarios (high and low demand and reference) and three NGV diffusion scenarios (0%, 20% and 60%).

Fig. 7: Increase in atmospheric CO_2 concentration (in parts per million) since 1950 due to automobile use in the United States.

Fig. 8: Atmospheric methane model applied to a steady-state representation of methane in today's atmosphere. An annual 500 Tg source is started at t=0 with 0 atmospheric methane concentration; methane concentrations stabilize at 5000 Tg by t=50

Fig. 9: Greenhouse contribution (in ppb CO_2 equivalents) from burning 10^{18} Joules of natural gas at t=0 with 2% leakage and methane factor of 16. Note that the effect of methane leaked at t=0 decays over time but the CO_2 concentration (by assumption) stays the same (there is a slight increase in CO_2 due to the decay of CH_4 to CO_2).

Fig. 10: Increase in atmospheric concentration of greenhouse gases (CO_2 and CH_4) since 1950 due to automobile use in the United States using the reference scenario with 60% NGV penetration. Concentrations expressed in CO_2 equivalents which is the sum of the increase in CO_2 concentration since 1950 and the atmospheric methane concentration due to fossil fuel use. Atmospheric methane concentrations are computed by the methane model described in the text and multiplied by the methane factor (m.f.) that converts ppm CH_4 into ppm CO_2 based on their relative greenhouse capacities. Two leakage scenarios (2% and 4%) are shown with methane factors of 16 and 32. Also shown is a curve for 0% leak rate and a curve for no penetration of NGVs.

Fig. 11: Same as figure 10 but with better resolution for the period 2030 to 2050.

Fig. 12: Same as figure 11 but 30% of the methane source is assumed from oil recovery operations.

Figure 1: Model Structure

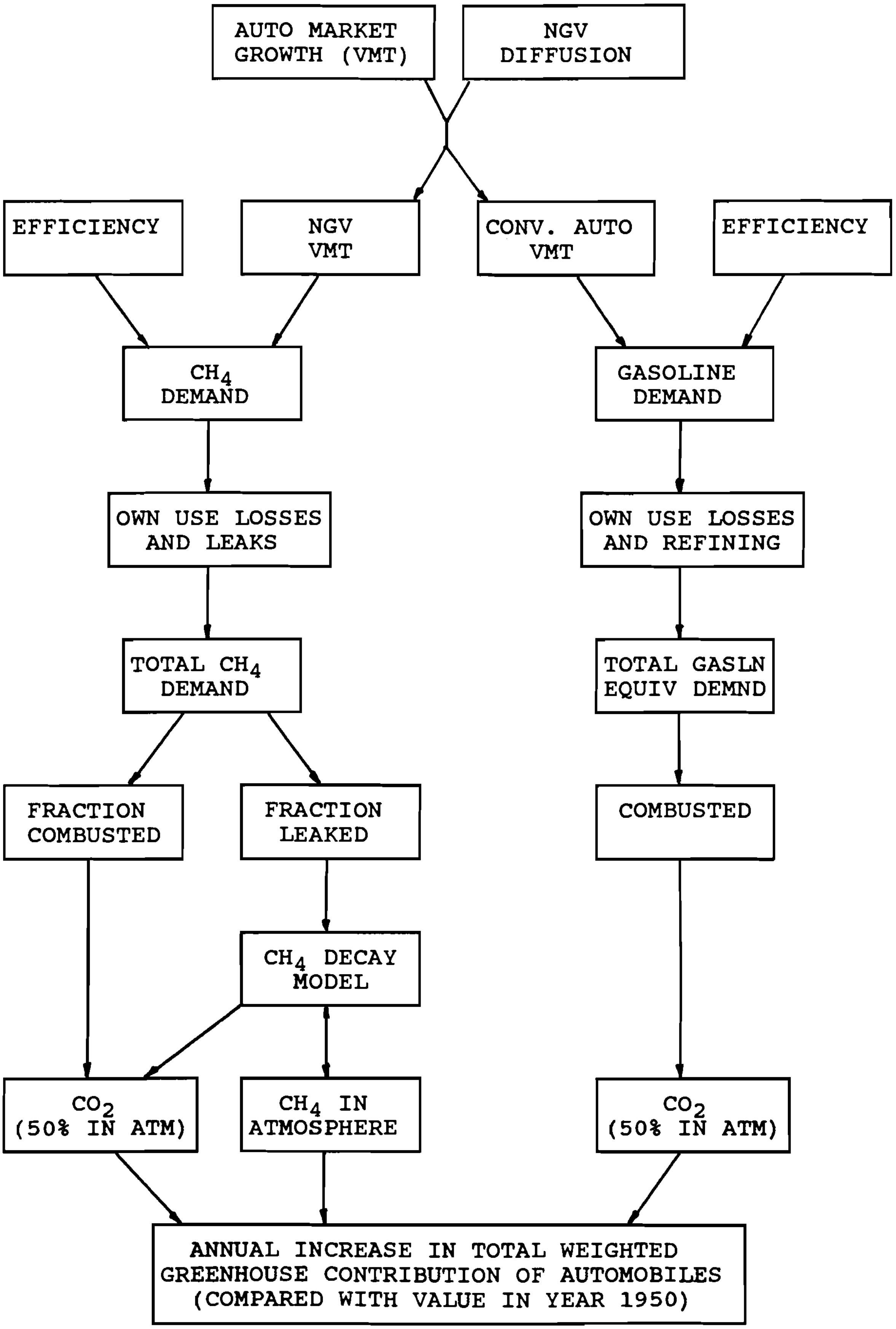

Figure 2

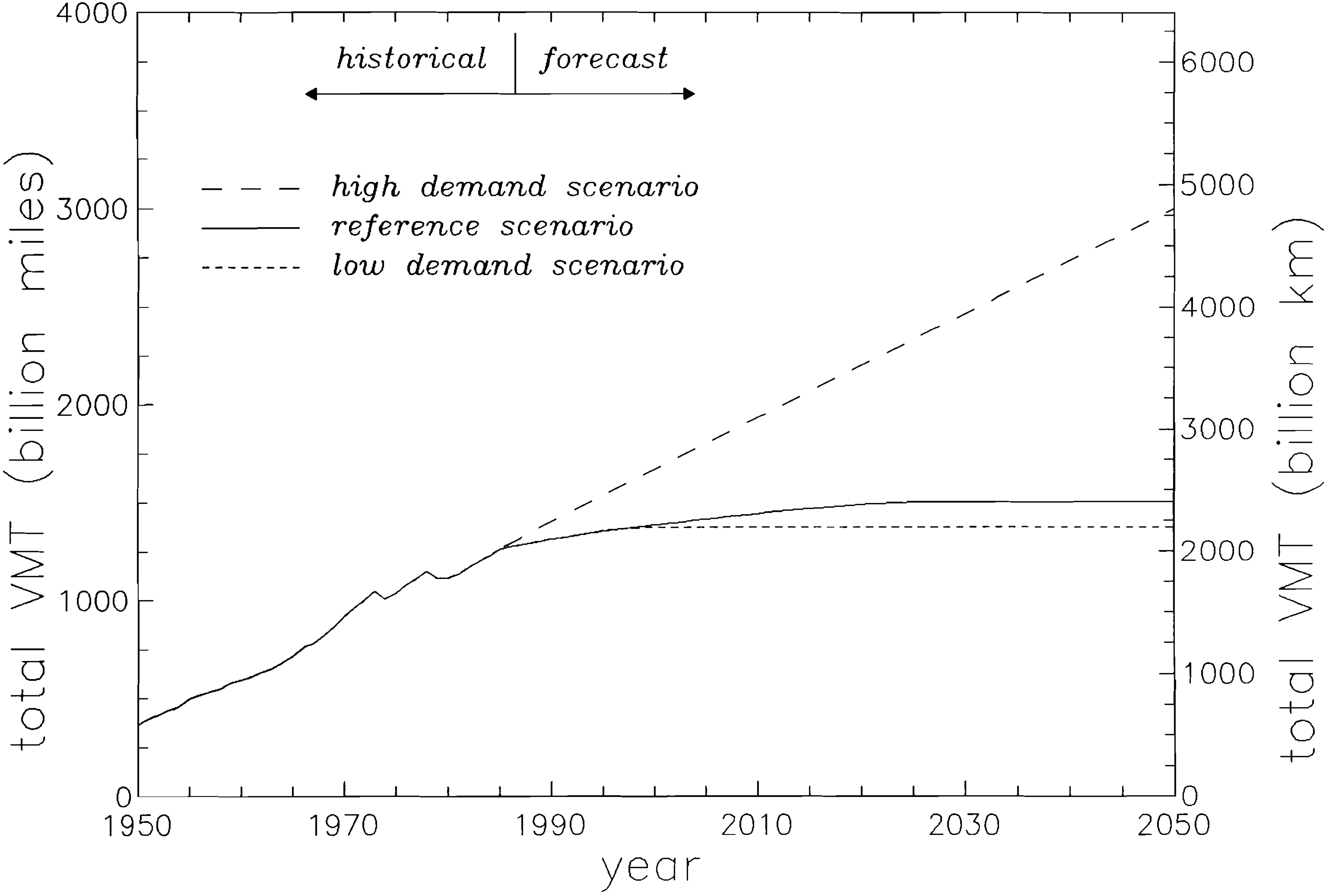
historical
forecast
high demand scenario
reference scenario
low demand scenario
total VMT (billion miles)
0
1000
2000
3000
4000
total VMT (billion km)
0
1000
2000
3000
4000
5000
6000
year
1950
1970
1990
2010
2030
2050

Figure 3

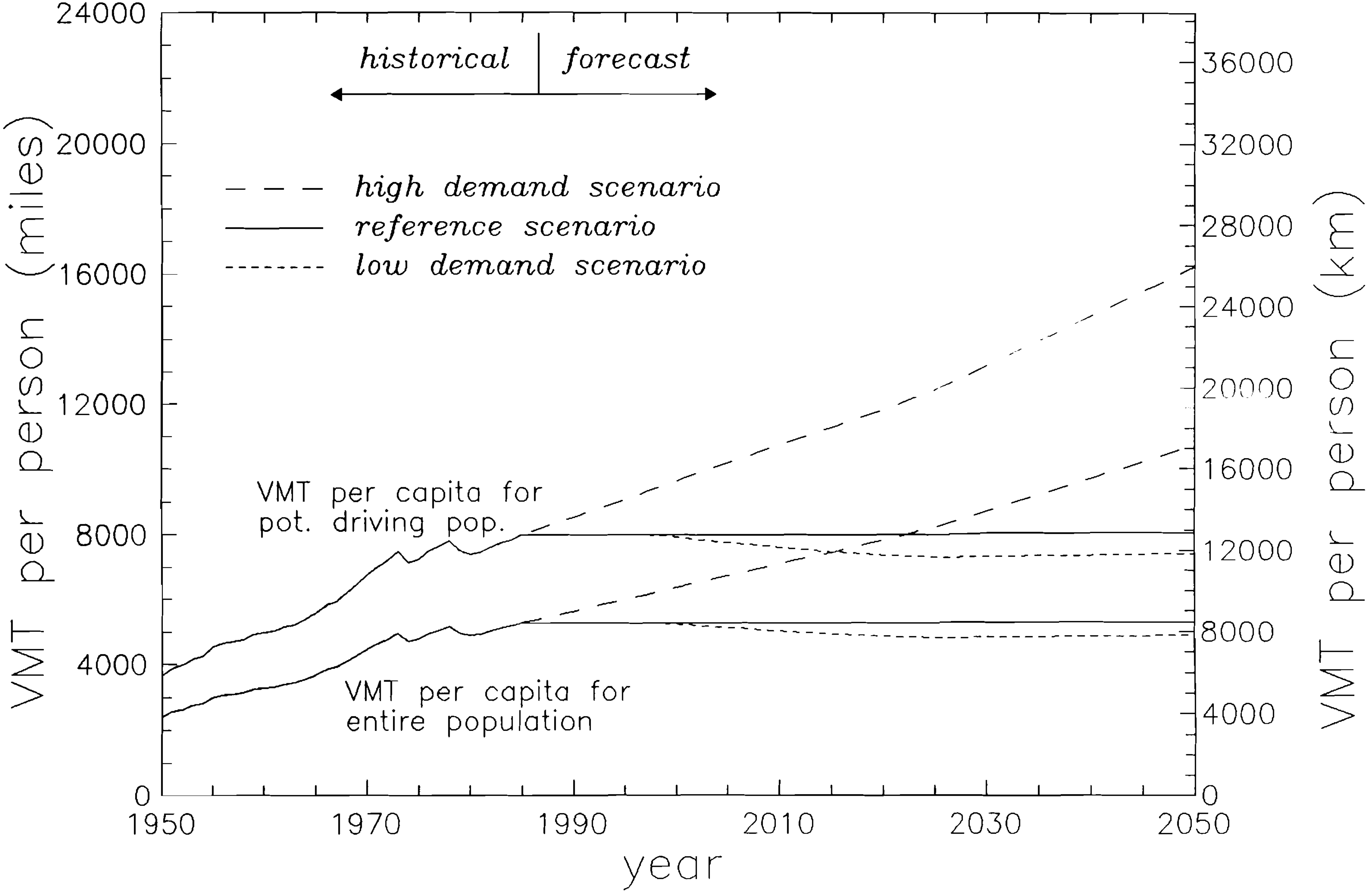
historical
forecast
high demand scenario
reference scenario
low demand scenario
VMT per capita for
pot. driving pop.
VMT per capita for
entire population
VMT per person (miles)
0
4000
8000
12000
16000
20000
24000
VMT per person (km)
0
4000
8000
12000
16000
20000
24000
28000
32000
36000
year
1950
1970
1990
2010
2030
2050

Figure 4

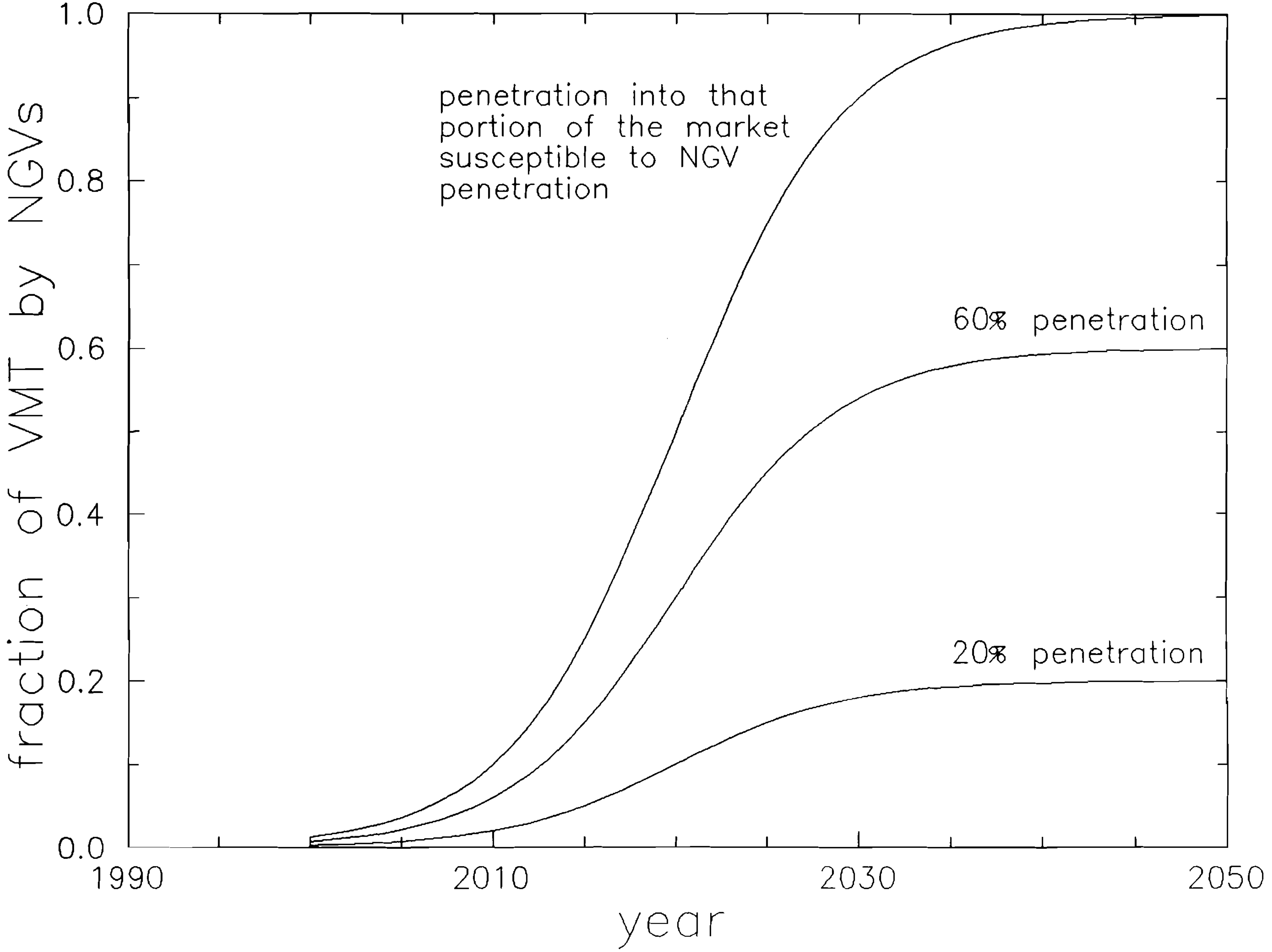
1.0
0.8
0.6
0.4
0.2
0.0
fraction of VMT by NGVs
1990
2010
2030
2050
year
penetration into that portion of the market susceptible to NGV penetration
60% penetration
20% penetration

Figure 5

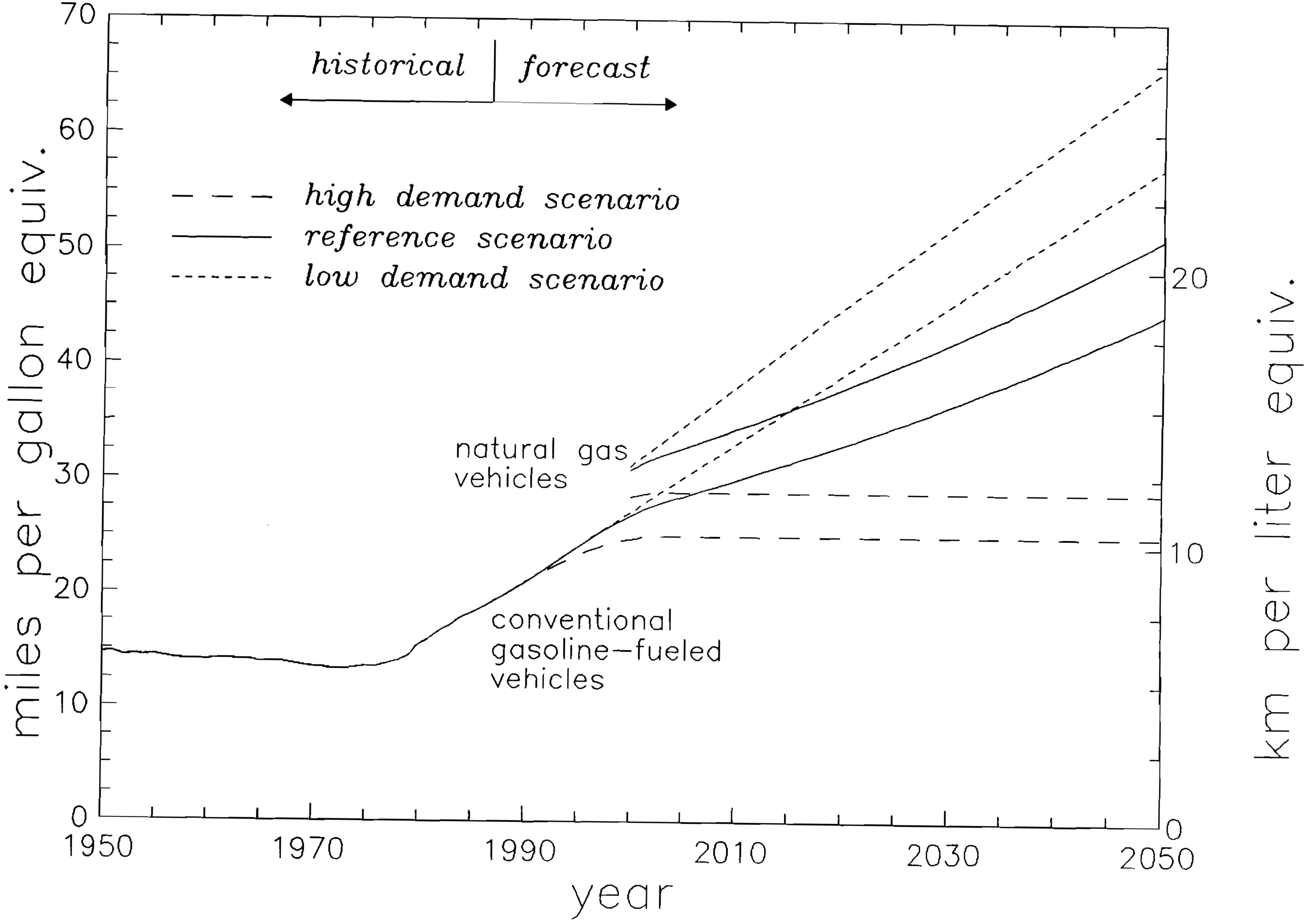
historical
forecast
high demand scenario
reference scenario
low demand scenario
natural gas vehicles
conventional gasoline-fueled vehicles
miles per gallon equiv.
km per liter equiv.
year
70
60
50
40
30
20
10
0
1950
1970
1990
2010
2030
2050
20
10
0

Figure 6

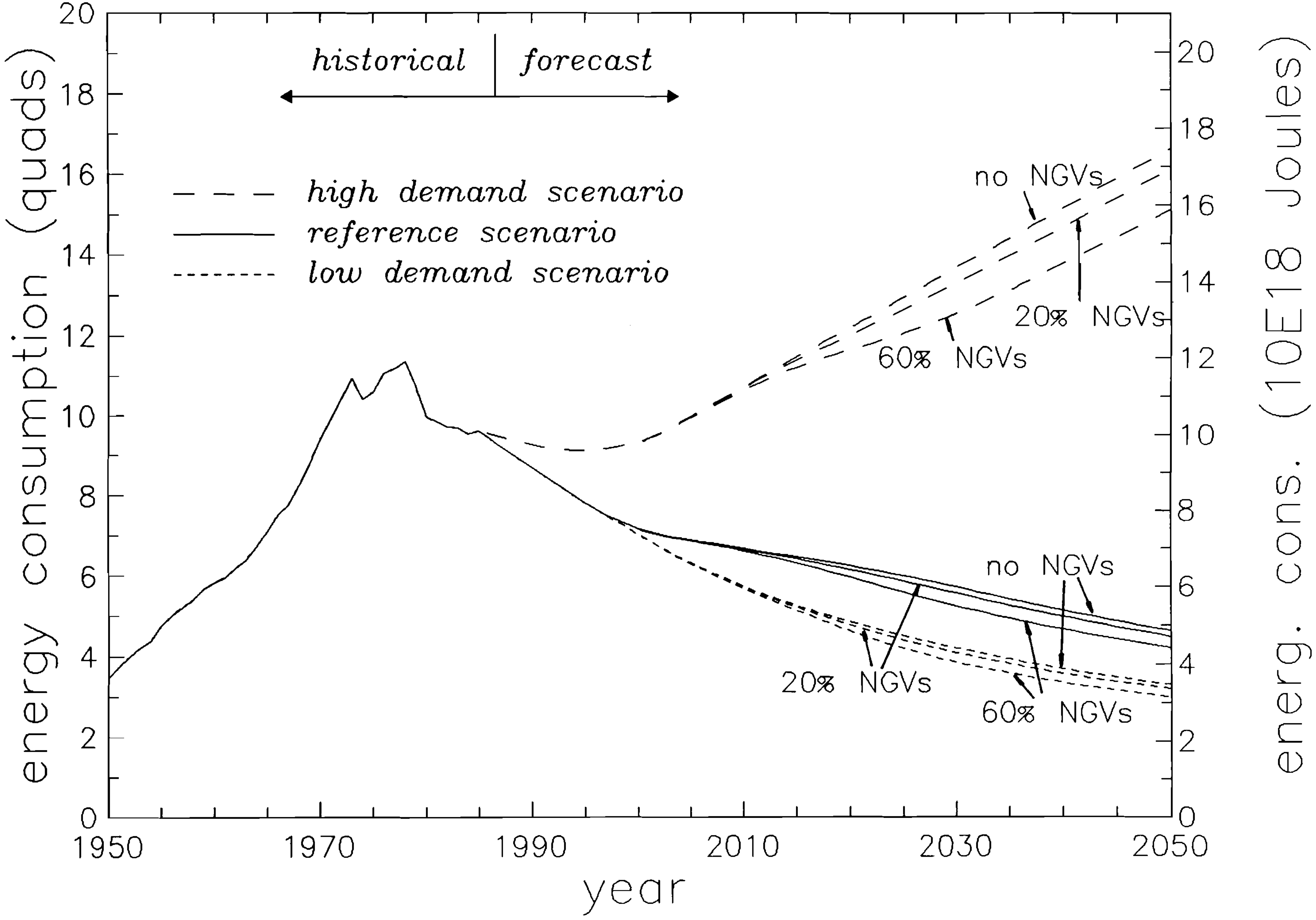
historical
forecast
high demand scenario
reference scenario
low demand scenario
no NGVs
20% NGVs
60% NGVs
no NGVs
20% NGVs
60% NGVs
energy consumption (quads)
energ. cons. (10E18 Joules)
year
0
2
4
6
8
10
12
14
16
18
20
1950
1970
1990
2010
2030
2050

Figure 7

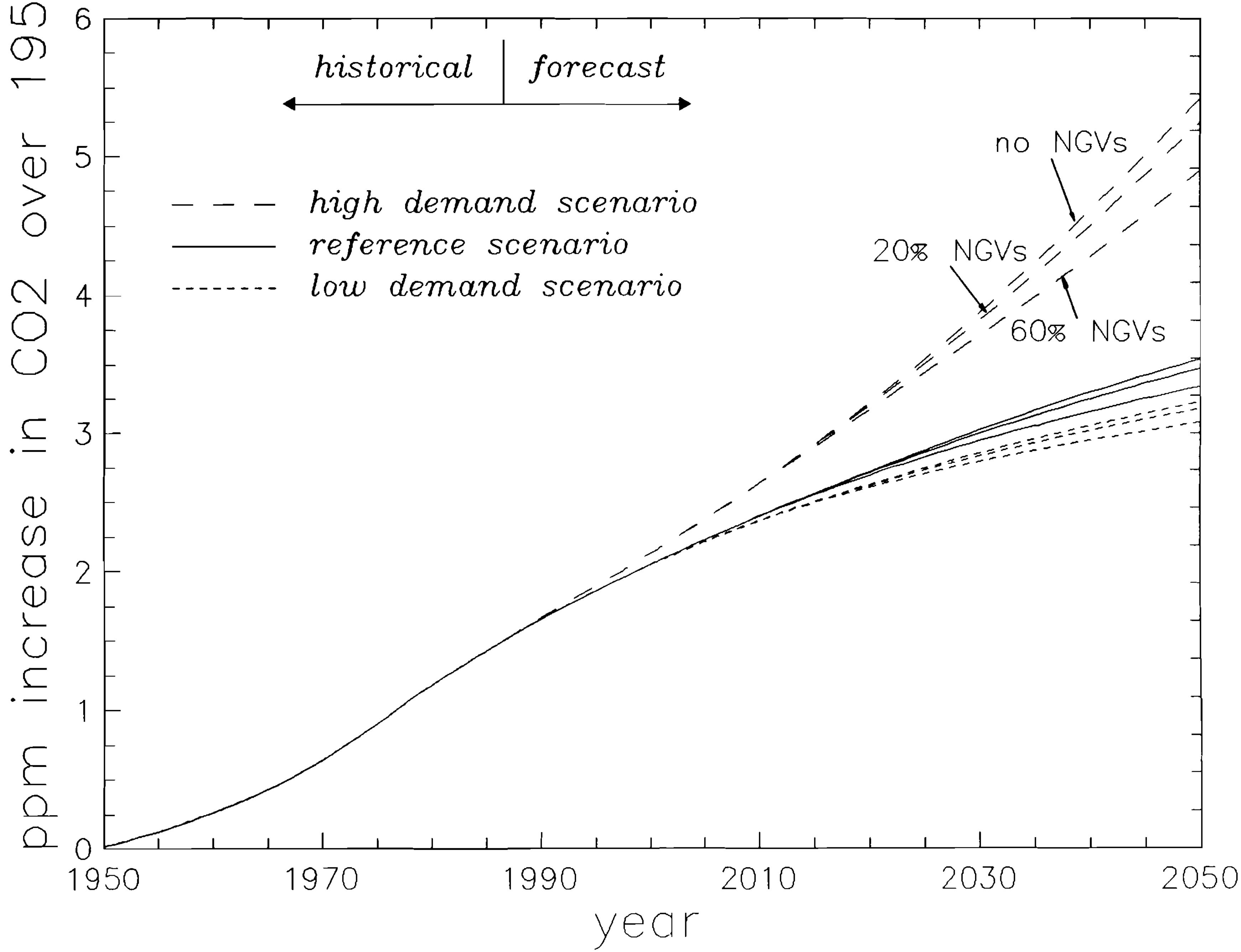
historical
forecast
high demand scenario
reference scenario
low demand scenario
no NGVs
20% NGVs
60% NGVs
ppm increase in CO2 over 1950
0
1
2
3
4
5
6
1950
1970
1990
2010
2030
2050
year

Figure 8

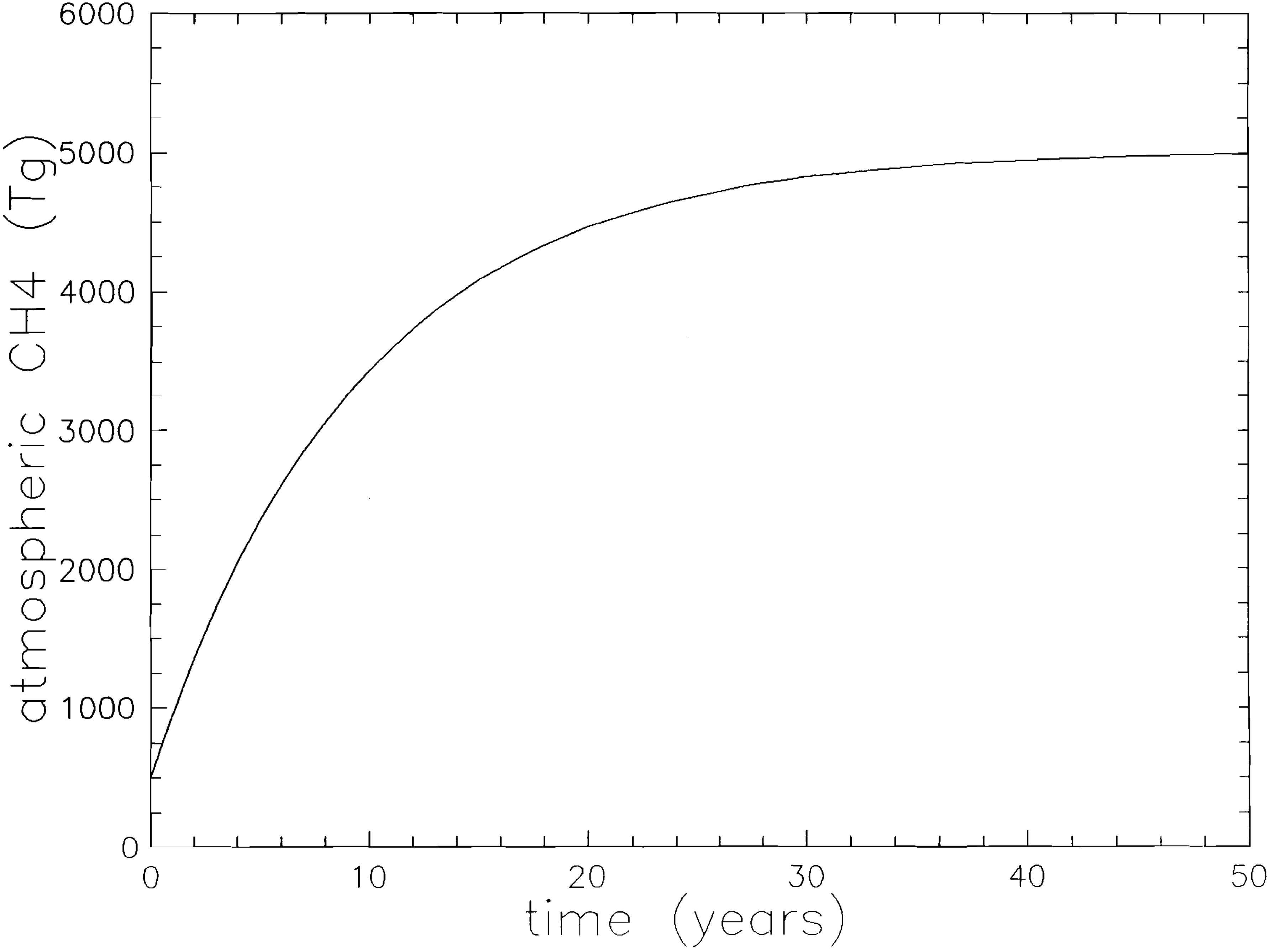
6000
5000
4000
3000
2000
1000
0
atmospheric CH4 (Tg)
0
10
20
30
40
50
time (years)

Figure 9

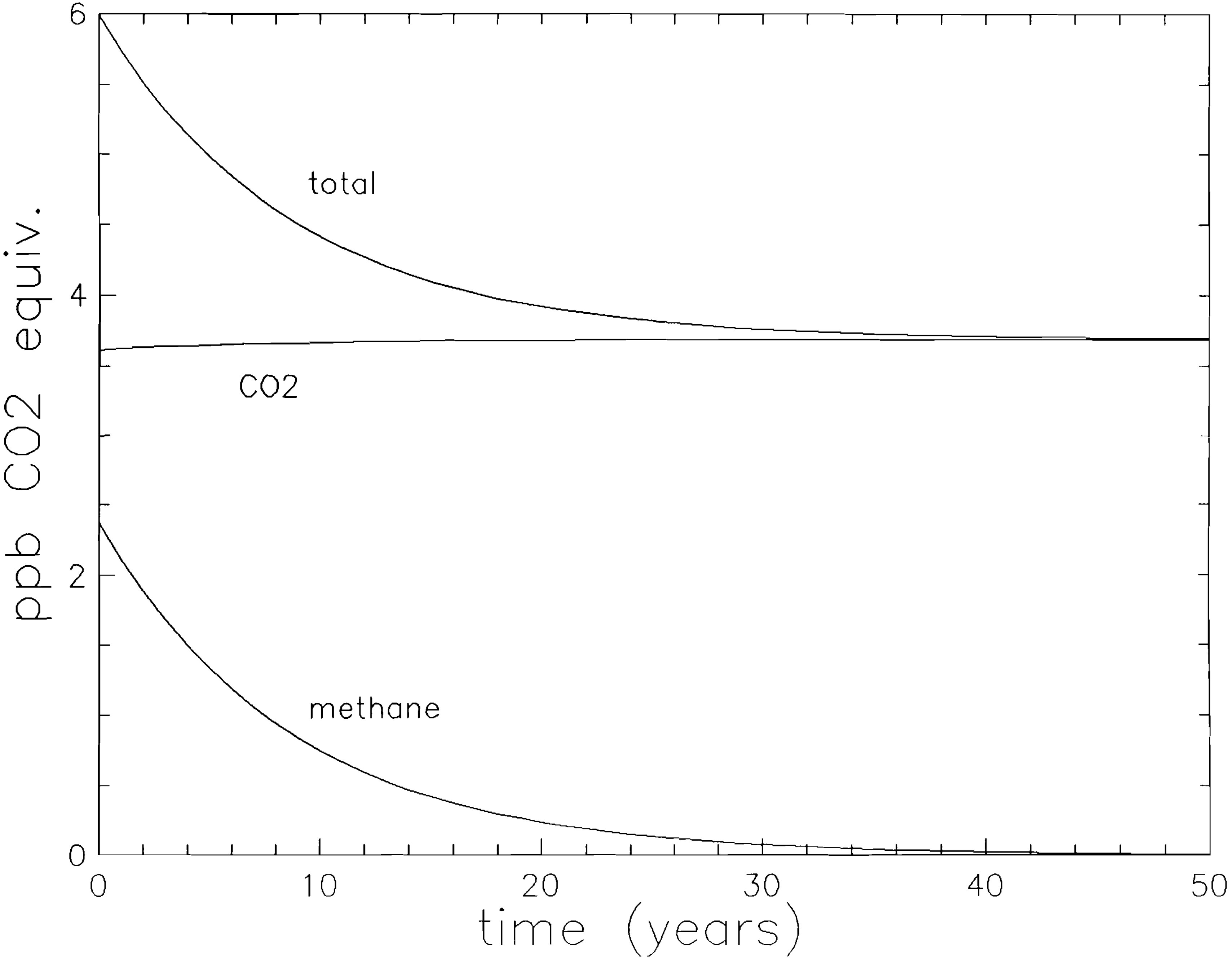
total
CO2
methane
6
4
2
0
ppb CO2 equiv.
0
10
20
30
40
50
time (years)

Figure 10

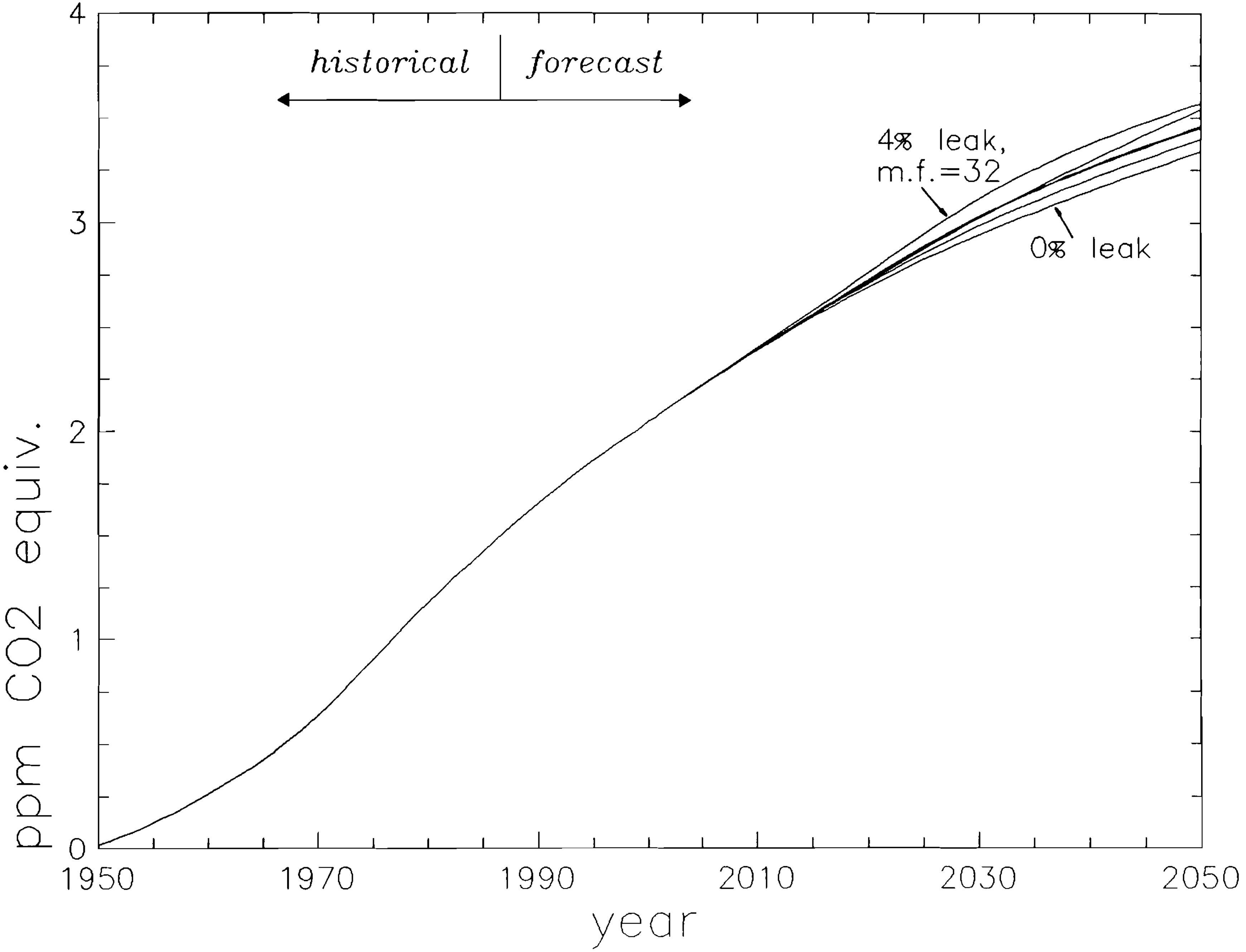
historical
forecast
4% leak,
m.f.=32
0% leak
ppm CO2 equiv.
0
1
2
3
4
year
1950
1970
1990
2010
2030
2050

Figure 11

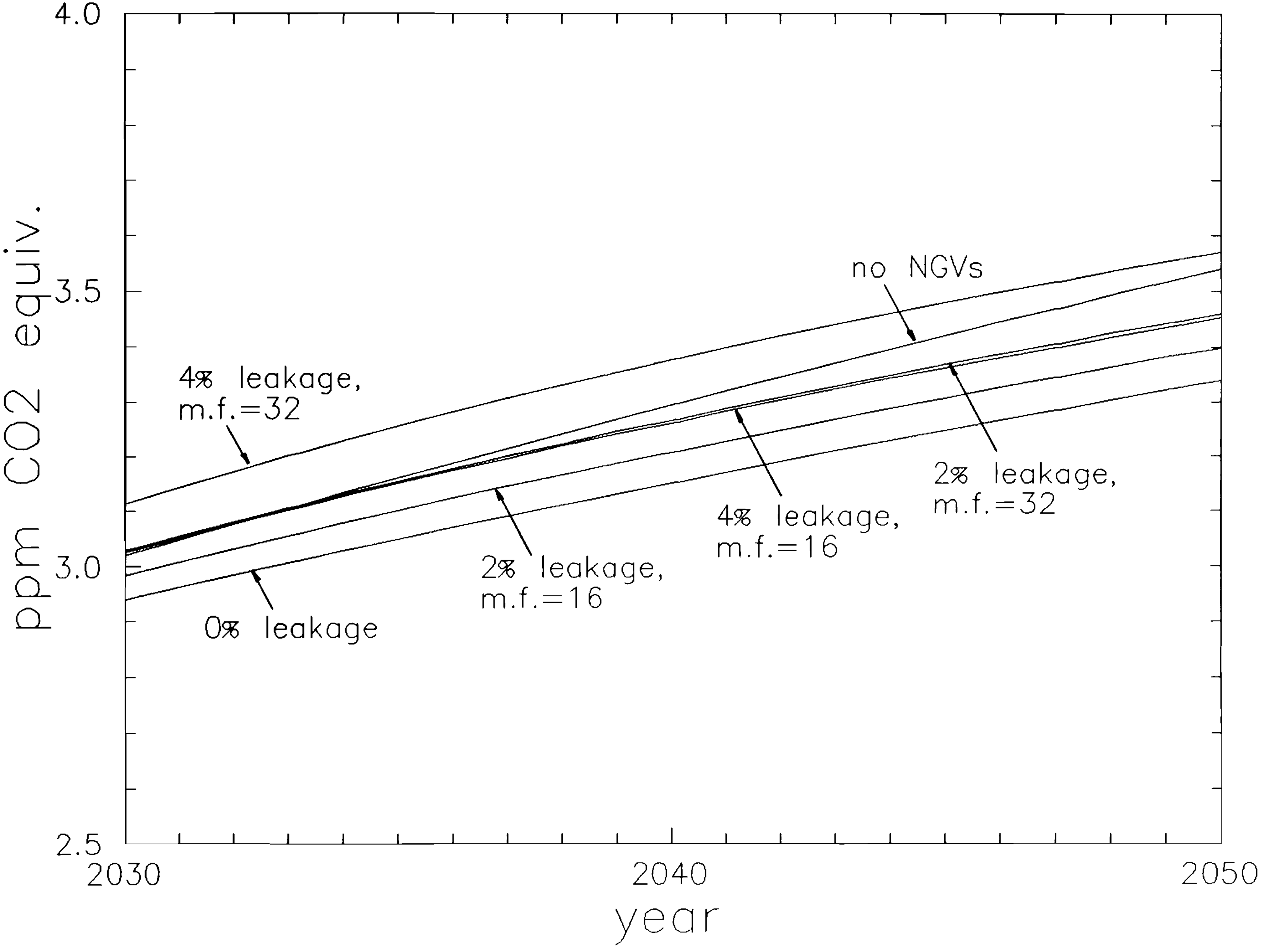
4.0
3.5
3.0
2.5
ppm CO2 equiv.
2030
2040
2050
year
no NGVs
4% leakage,
m.f.=32
2% leakage,
m.f.=32
4% leakage,
m.f.=16
2% leakage,
m.f.=16
0% leakage

Figure 12

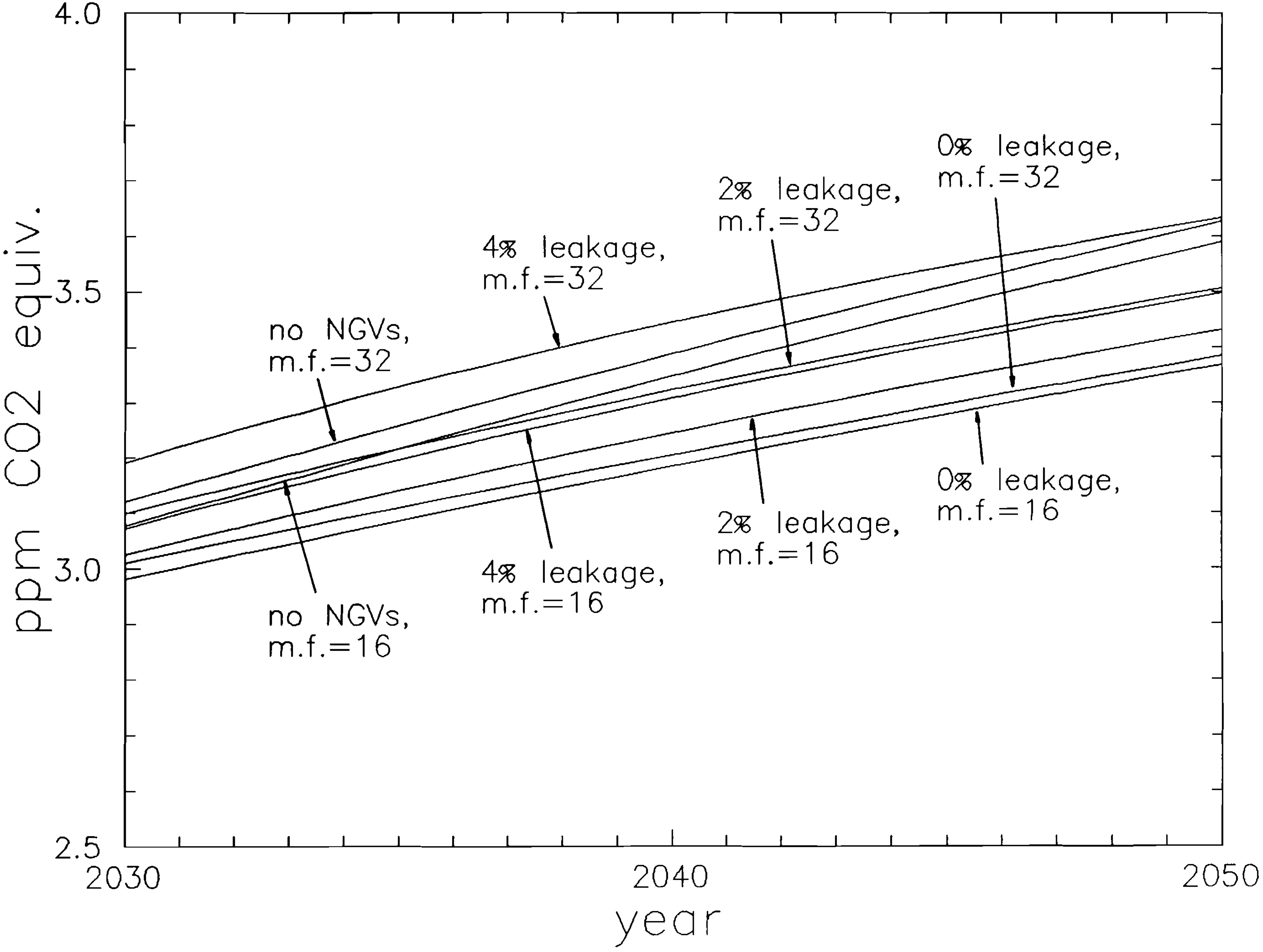
4.0
3.5
3.0
2.5
ppm CO2 equiv.
2030
2040
2050
year
no NGVs, m.f.=32
4% leakage, m.f.=32
2% leakage, m.f.=32
0% leakage, m.f.=32
no NGVs, m.f.=16
4% leakage, m.f.=16
2% leakage, m.f.=16
0% leakage, m.f.=16

Table I

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.
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
% from "old"[1] sources	10% to 32%	22% for this study, including 33 Tg from "old" biol. sources.

Table I, cont.

Parameter	Range	Notes
Methane sources, cont.		
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.	?	This study uses 0% but the model is tested at 30% and the results remain about the same.

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

Table II

Total greenhouse effect (in ppm CO_2 equiv.)
and percentage contribution of methane

Scenario	2000		2025		2050	
	total	% CH_4	total	% CH_4	total	% CH_4
no NGVs	2.04	0.0%	2.87	0.0%	3.54	0.0%
0% leak	2.04	0.0%	2.82	0.0%	3.34	0.0%
2% leak m.f.=16	2.04	0.0%	2.85	1.1%	3.40	1.7%
2% leak m.f.=32	2.05	0.0%	2.89	2.2%	3.46	3.4%
4% leak m.f.=16	2.05	0.0%	2.89	2.2%	3.47	3.5%
4% leak m.f.=32	2.05	0.0%	2.95	4.3%	3.59	6.7%

Table III

Total greenhouse effect (in ppm CO_2 equiv.)
and percentage contribution of methane

30% of natural gas leaks from oil

	2000		2025		2050	
Scenario[1]	total	% CH_4	total	% CH_4	total	% CH_4
no NGVs m.f.=16	2.11	2.8%	2.93	1.6%	3.59	1.0%
no NGVs m.f.=32	2.17	5.4%	2.98	3.1%	3.63	2.0%
0% leak m.f.=16	2.11	2.8%	2.87	1.2%	3.37	0.5%
0% leak m.f.=32	2.17	5.4%	2.90	2.4%	3.38	0.9%
2% leak m.f.=16	2.11	2.8%	2.90	2.3%	3.43	2.2%
2% leak m.f.=32	2.17	5.4%	2.97	4.5%	3.51	4.3%
4% leak m.f.=16	2.11	2.8%	3.03	3.4%	3.50	3.9%
4% leak m.f.=32	2.17	5.4%	2.93	6.5%	3.63	7.5%

[1] Leakage percentages are for leakage of the natural gas recovery and supply system. Oil-based leakage assumed fixed at 0.12 Tg per quad of production.