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Many Gases and Many Measures

Choice of Targets and Selection of Measures in Climate Policy

by

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PREFACE

This report discusses economic principles and impacts of taking many greenhouse gases into account in the design of a climate policy. The project has been funded by the Norwegian Ministry of Finance. I am indebted to Jan S. Fuglestvedt in modelling the impacts of emissions on greenhouse gas concentrations and radiative forcing. Responsibilities for remaining errors are of course my own.

CONTENTS

SUMMARY

This report discusses the economic impacts of taking a comprehensive approach to climate policy. A comprehensive climate policy implies that all relevant sources, sinks and reservoirs of climate gases are covered. From the outset, this widens the policy options, and leads to a higher degree of flexibility when it comes to the implementation of measures. This study provides a model-based analysis of how the costs of climate policy may be affected.

Inclusion of many greenhouse gases requires that one have to pay attention to two problems which need not be considered when analysing emission control of carbon dioxide (CO_2) alone. The first is how to include all relevant measures appropriately, and the second is how to aggregate different greenhouse gases. The problem of including relevant measures does not become critical when focusing on CO_2-emissions, because nearly all of these emissions are attached the use of fossil fuels. Being a commodity subject to market transactions, the use of fossil fuels, and thereby CO_2-emissions, can be regulated by means of charges. For other gases, this is not equally evident. Emission of e.g. methane (CH_4) may be subject to 'non-economic' factors, and it might therefore be possible to find less costly measures to reduce these emissions than those being implemented as a response to charges.

Emissions of three greenhouse gases, CO_2, CH_4 and N_2O (nitrous oxide), are considered. The measures include enhancement of carbon sinks by forest management, reduction of emissions of CH_4 from landfills, reduction of N_2O-emissions from production of fertilisers and from fertilisation in agriculture, henceforth called direct measures, and charges on fossil fuels. Cost functions for each of these measures are estimated on the basic of other studies, and explicitly included in the model.

The problem of aggregation is usually solved by the use of global warming potentials (GWP). By this measure, one attempts to express the change in radiative forcing due to the emission of a unit of a greenhouse gas relative to that of CO_2-emissions. That is, the GWPs aim at expressing the emissions in terms of 'CO_2-equivalents'. GWPs are, however, highly inaccurate. This is due to the fact that the life-time of different greenhouse gases in the atmosphere varies considerably. The life-time of methane (CH_4) is approximately 12 years,

between 100 and 150 years for CO_2 and approximately 50 000 years for chlorfluor carbons. Hence, the GWP for a gas is strongly conditioned upon the time-horizon over which the integrals are taken.

One way to solve this problem is to calculate radiative forcing directly by means of a dynamic model. Radiative forcing is an expression for the warming effect of a change in atmospheric concentrations. According to the IPCC (1994), a doubling of the atmospheric concentrations of greenhouse gases in the atmosphere results in a radiative forcing of 4. Model studies indicate that the global average surface air temperature thereby increases between 1.5 and 4.5 °C, with 2.5 °C as a "best estimate" (IPCC, 1996b). Application of radiative forcing requires that also the economic model is dynamic, and that the target for climate policy sets limits for radiative forcing, or concentrations of greenhouse gases, at a given future point in time rather than emissions. This has large impacts on the choice of optimal policy. This report addresses this issue by comparing the optimal policy under emission control with that of a control of concentrations.

Some main results are presented in table 1. The calculations should be considered as illustrations, only. Indications of how e.g. GDP is affected by climate policy should not be taken as a quantitative estimate since, in particular, the long-term properties of the model are not realistic. Due to the properties of the solution, we also had to limit the time horizon to 50 years. However, the results may give indications on the relative importance of gases and measures for a climate policy, and how to change the relative emphasise of different gases over time. The reference case, to which all the alternative runs of the model are compared, assumes that no initiatives to reduce emissions of greenhouse gases are taken. According to the calculations, the cost of a 10 percent target for emission reductions is minimised if CO_2 accounts for nearly 85 percent of the total emission reductions. CH_4 accounts for 7 percent and N_2O for 9 percent. The contribution from other measures than a carbon charge on the use of energy is substantial under emission control. The least costly way to reduce greenhouse gas emissions by 10 percent is to apply approximately equal emphasis on carbon charges and other, direct measures where forest management is of major importance. The level of the charge at this target for emission reductions were approximately 6 percent of the basic energy price. This corresponds to an admissible abatement cost for direct measures at 1 øre/kg CO_2

Table 1 Summary of the main numeric results

	Emission reductions		Targets on radiative forcing of 5	
	10 percent	30 percent	Static allocation of initial abatement	Dynamic allocation of initial abatement
t = 0				
Average charge (pct)	6	27	1.9	0.7
Abatement cost				
CO_2 (NOK/kg)	0.01	0.04	0.003	0.001
CH_4 (NOK/kg)	0.17	0.93	0.063	0.091
N_2O (NOK/kg)	2.25	13.78	0.939	0.023
T = 50				
Average charge (pct)	-	-	638	768
Abatement cost	-	-		
CO_2 (NOK/kg)	-	-	0.05	0.01
CH_4 (NOK/kg)	-	-	110.28	157.05
N_2O (NOK/kg)	-	-	18.24	4.52

for forest management, 17 øre/kg CH_4 for reducing methane emissions from landfills, and 225 øre/kg N_2O for reducing emissions from production and use of fertilisers.

With more ambitious targets, the contribution from charges increases. If the emissions are to be reduced by 30 percent relative to the reference alternative, charges contribute more than 70 percent of the reductions. With this target, the charge amounts to 27 percent of the basic energy price, and the admissible direct abatement costs for CO_2, CH_4 and N_2O measures are 4, 93 and 1378 øre/kg, respectively. According to the calculations, CO_2 is becoming slightly more important when the target for reductions in greenhouse gas emissions is increased. In other words, to the extent that these calculations are representative, one is slightly better off in terms of abatement costs by concentrating on CO_2-emissions alone.

A shift of policy from emission targets towards targets on radiative forcing causes a substantial shift in cost minimising behaviour. Firstly, the general timing of policy becomes crucial. For example, a 50 percent reduction of greenhouse gas emissions relative to the reference path results in a forcing of 8.5 relative to the present forcing over the next 50 years[1]. This requires an emission charge equal to 64 percent of the basic energy price. When timing the policy according to optimality criteria, a forcing of 5 might be achieved in 50 years by starting with a charge at 1.9 percent of the basic energy price ‘today’. A charge rate of 64 percent is not reached before 30 years, but after that, one has to tighten up the policy considerably. After 50 years, the charge is about 640 percent of the basic energy price.

Secondly, the relative emphasise of the different gases under a concentration target is changed compared with the optimal composition under emission control. This is due to the different life-times of greenhouse gases. Short-lived gases, such as methane, give a quicker response in the atmosphere than long-lived gases, such as carbon dioxide. Thus, one may reach a target on radiative forcing earlier, or alternatively postpone the efforts to reduce emissions, if putting more weight on the abatement of methane. Compared with a policy which allocates measures according to the marginal cost of emissions in terms of GWP, an optimal long-term allocation of measures would put more weight on reducing the emissions of methane, because there is an economic yield in delaying abatement costs. By following this advice, the initial carbon charge would decrease from 1.9 percent to 0.7 percent of the basic energy price for a target on radiative forcing at 5 in year 50. In the terminal year, the charge has increased to 768 percent. Admissible abatement cost for reducing the emissions of methane from landfills increases initially from 6.3 øre/kg, when measures are allocated according to marginal costs measured in GWP, to 9.1 øre/kg under optimal allocation. At $t = 50$ they reach 157.05 NOK/kg. Abatement costs related to forest management and emissions of N_2O are comparably small when allocating the abatement of different gases optimally.

The aim of the discussion in this report is to point out some properties embedded in the comprehensive approach, which may change the conception of optimal climate policy. There is no doubt that CO_2-emissions will remain the most important issue in climate policy. Nevertheless, inclusion of other gases may provide an opportunity to expand the options and thereby reduce costs. If the targets are set on concentrations rather than emissions, availability of measures to reduce the emissions of methane may cause a substantial reduction in the abatement costs. Moreover, the calculations indicate quite clearly that it may be worthwhile to search for measures as supplements to CO_2-charges in the design of climate policy.

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[1] Note, however, that the growth in energy demand is unrealistically high in the reference path - about 9 percent per year.

1 INTRODUCTION

The importance of achieving cost effective measures in climate policy has been subject to considerable attention over the past six to seven years. With a few exceptions, studies of economic implications of climate policy focus on CO_2-emissions only.[2] There are many reasons for this. Emissions of CO_2 are expected to constitute the major contribution to climate change in the future. Being attached to the use of fossil fuels, a reduction in the emissions of CO_2 requires that the increase in world energy use comes to an end. This is perhaps the greatest challenge for the international society in meeting the problem of global warming.

Article 3.3 of the Framework Convention on Climate Change states, however, that policies and measures to curb climate change should be comprehensive, and cover all relevant sources, sinks and reservoirs of climate gases. Although reasonable, this statement raises several questions when it comes to the implementation of an agreement. Fuglestvedt and Skodvin (1996) discuss the problems of comparing and assessing the contribution from different greenhouse gases. Some of these are of a scientific nature. The scientific problems spread to the political process where other problems occur, for instance for those greenhouse gases that are covered by other international agreements. Nevertheless, they conclude that a comprehensive approach implies advantages compared with bare focus on CO_2-emissions. One major advantage which they point at is that the availability of measures to curb climate change widens significantly.

It is indeed of interest to see how inclusion of other greenhouse gases in climate policy might affect climate costs. This report is a first step in this direction. Compared with most of the models that has been applied to assess the cost of implementing a climate policy, a model to study a comprehensive approach needs to be extended in two ways. First, measures to reduce emissions of other gases are usually not well covered by the production technology described in the models. Such measures must therefore be represented directly by separate cost functions. Second, different gases cannot be aggregated adequately by means of emissions only, since the contribution to global warming from a given amount of emissions changes considerably over time with different rates for different gases. Thus, when taking a comprehensive approach one should set targets on concentrations instead of emissions (Smith and Wigley, 1996).

This report studies a mix of measures to reduce emissions of CO_2, CH_4 and N_2O. We start with a discussion of so-called direct measures, and relate them to charges on emissions of fossil fuels in order to assess conditions for an optimal combination of the two. Then, cost functions for direct measures are established, based on Norwegian data. The model is briefly presented in section 3, and section 4 discusses the atemporal conditions, which are relevant for a policy with emission targets. Implications for the choice of direct and indirect measures as well as the emphasis on different gases are studied. In the final section, the intertemporal approach is taken, where the targets are related to concentrations of greenhouse gases by their radiative forcing. This includes a comparison between optimal policy under an emission target and under a target on radiative forcing.

The calculations presented in this report must not be taken as expressions for beliefs about trends, or as realistic estimates of expected cost. The figures aims at illustrating some issues,

[2] Håkonsen and Mathiesen (1993) present a model which includes measures to reduce emissions of CH_4.

poorly analysed in most of the economic literature on climate change, which ought to be analysed more carefully. A realistic analysis of the effects of following the optimal policy in the long run clearly needs a more sophisticated model than the one applied here. On the other hand, the figures probably give an indication of how alternative measures should be *distributed* among instruments and gases, both from a static point of view, and in a dynamic context.

2 THE CHOICE OF MEASURES

Hardly anyone would object to the necessity of selecting cost-effective measures to curb climate change. There are, however, different opinions as to what the cost-effective measures are, and how governments should enforce implementation of them. Most economists argue that cost effectiveness can be attained only if private agents are free to choose among measures. Central authorities ought to create incentives for private agents in order to achieve the climate policy targets. Charges on fossil fuels is an example of the use of such incentives.

This view is opposed by many who are sceptic to the use of economic instruments in climate policy in general, or believe that innovation of technologies are deferred by private agents for some reason. They prefer the use of policy instruments that allow for a direct control by central authorities, and claim that subsidising certain technologies, imposing quantity or quality standards for certain industries, or even public investments in energy saving may be cost-effective.

It may be argued that both incentives and direct control measures should be considered in climate policy, at least within an analytical context. The traditional economist's view referred to above assumes in general that emissions of greenhouse gases may be controlled directly by some economic activity. This means that there has to be a functional relationship between an economic activity and the policy target attached to climate change. If not, that is if factors exogenous to the economy have any impact on the climate policy target, one may find less costly means to curb climate change than those implemented as a response to charges. Hence, the requirement for indirect measures to be cost effective is quite strong. Nevertheless, it is fulfilled to a certain extent in the case of climate policy. Emissions of carbon dioxide (CO_2) are expected to constitute the major part of future anthropogenic emissions of greenhouse gases. Nearly all of these emissions are due to the use of fossil fuels. By charging different fossil fuels for their specific CO_2-emissions, a nearly perfect control is attained for policies aiming at reducing the emissions of CO_2.

There are in general two reasons why direct measures need to be specified. The first relates to the real domain of economic instruments. If the target for climate policy from emissions of CO_2 is extended to a common target for emissions of several gases or to concentrations, the picture becomes more complex. Landfills are a significant source of methane emissions (CH_4). The extent to which emissions of methane from landfills can be reduced depends on a system of waste disposal, location of the landfill, placement of the waste at the landfill etc. However, landfill management aims at more than reducing the emissions. An economic management of landfill and waste would require, if possible, establishment of a number of 'new' markets, such as compensation for people living nearby the landfill, deposit- and refund-systems for waste and incentive systems for waste disposal. Most of these markets are poorly developed. Under these circumstances, a part of the emissions of methane cannot be managed effectively by economic instruments. Therefore, direct measures seem more appropriate at present.

Moreover, methane is a very reactive gas. The contribution to the greenhouse effect from emissions of methane depends largely on the concentrations of other gases in the atmosphere. By controlling other gases, one therefore indirectly controls the effect from methane. Many of these other gases, such as halocarbons and nitrogen oxides, are very difficult to control effectively by means of economic instruments alone. Indirectly, therefore, the potential for controlling methane by means of economic instruments also decreases.

A second reason why direct measures should be specified in a macroeconomic analysis of climate policy is that these measures are usually not adequately represented in the macroeconomic models that are being used. Charges on emissions implies that non-charged goods are substituted for charged fossil fuels, and the emissions are thereby reduced. How strong this effect is depends on the macro production functions and the utility functions. These are usually too general to allow for an inclusion of all cost effective measures to reduce the emissions. A charge on energy, for instance, will have exactly the same effect whether it is implemented in order to reduce emissions or to reduce the dependency of energy imports. Actually, a cost-effective climate policy should encourage private agents to initiate investments in technologies with the only purpose to reduce greenhouse gas emissions or enhance sinks. Such investments may be out of the question if the aim was to decrease the dependency of energy imports.

In this study three ‘direct’ climate measures are added to those expected to be embedded in the macro production and utility functions. These are investments in sinks of CO_2, utilisation of CH_4 to energy production in landfills and reduction of nitrous oxide (N_2O) in agriculture and production of fertilisers. In order to fit into the model, cost functions for these measures, based on micro studies, are established. These cost functions express the amount of annual emission reductions (or annual sinks) obtainable at a given annual cost. It is assumed that the cost functions are continuous, and that all costs can be regarded as operating costs. Thus, direct abatement does not imply irreversible decisions. Both are clearly strong assumptions, but digestible in the context set in this report, where the aim is to illustrate certain effects of extending the traditional approach, and uncertainty is not taken into account.

To implement micro-studies in macro analysis always leads to problems. In this study, we have calculated cost curves on the basic of current prices. Thus, if the prices solved in the model changes, the cost curves will in fact be affected. For instance, if the cost of a measure includes energy costs and costs of other goods, a future change in the relative price between these two goods would also affect the cost function of this particular measure. This is not taken into account in the model, where the cost function ideally is expressed in ‘physical’ terms. All the abatement cost curves are assumed to be log-linear.

2.1 Investments in carbon sinks

Enhancement of the sinks of carbon dioxide, e.g. by afforestation, is considered by many to be an attractive measure to curb climate change. Lunnan *et al.* (1991) have estimated the costs of different means to enhance sinks in Norway. Common to bio-sinks is that their binding capacity changes over time, and the rate of change differs among different alternatives. 14 alternatives are considered by Lunnan *et al.* (1991), with a total capacity of binding between 4 and 9 mill. tons of CO_2 per year after 10 years. After 40 years between 10 and 28 mill. tons are bound. Few measures will contribute significantly before 20 years.

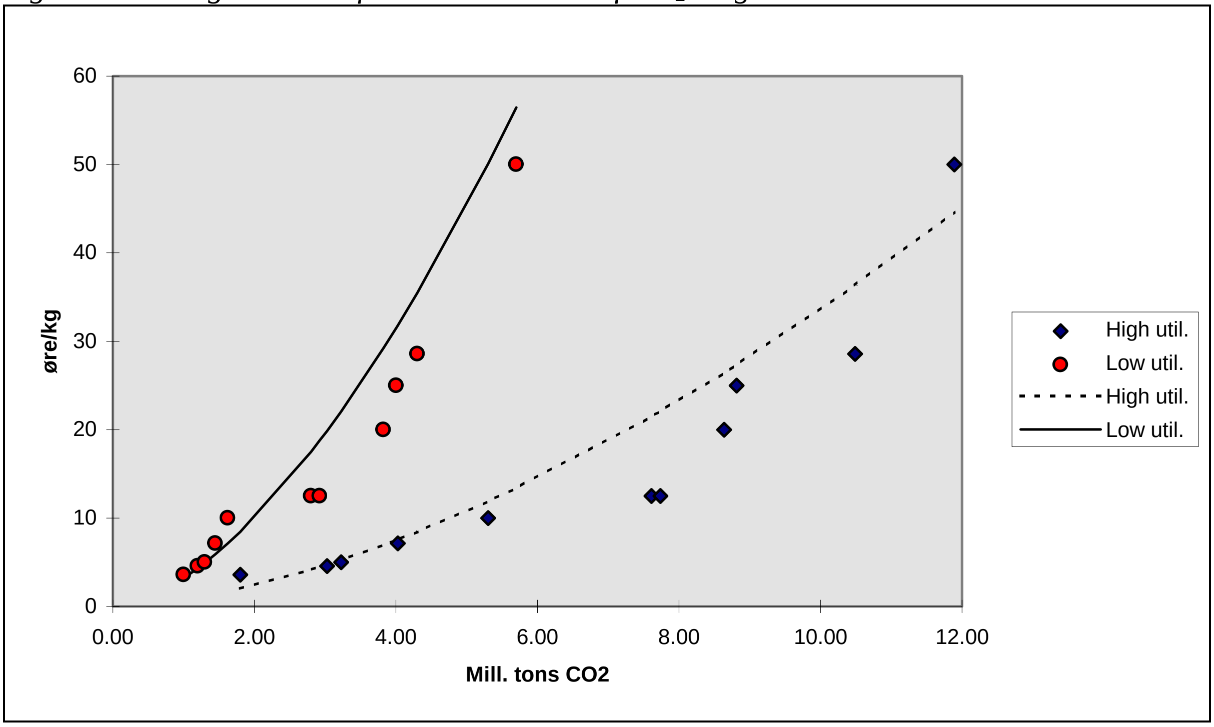
Box 2.1 Measures to enhance sinks of CO_2 included in the abatement cost curve. Average sink capacity per year in mill. t CO_2.

Measure	*Low - High*
i) Forest planting in Western Norway	0.18 - 1.28
ii) Forest planting in Northern Norway	0.30 - 1.68
iii) Forest planting on marginal agricultural areas	1.18 - 2.31
iv) Tree planting in power-line traces	0.18 - 0.18
v) Fertilisation of mineral ground, spruce	0.20 - 1.23
vi) Fertilisation of mineral ground, pine	0.15 - 0.80
vii) Enhance tree density	0.13 - 0.13
viii) Drainage of forest land	1.00 - 1.80
ix) Bio energy in households	0.90 - 0.90
x) Utilise waste to energy	1.03 - 1.03
xi) Utilise energy forests	1-40 - 1.40
xii) Utilise marginal areas to energy	0.10 - 0.20

In order to incorporate these measures in the model applied in this study, we have to simplify considerably. We assume that all measures have an immediate binding effect, that this effect is constant over time, and that the costs accrue annually. Moreover, we have not included all the measures considered by Lunnan *et al.* (1991). Drainage and fertilisation of wetlands affects emissions of CH_4 and N_2O, and enhances the sink of CO_2. During the first 5-10 years the main effect is a reduction in the emissions of methane. This combined effect is very difficult to deal with in a macroeconomic model, and this alternative is therefore discarded. Another alternative analysed by *Lunnan et al.* (1991) is to substitute bio-mass for fossil fuels. This reduces the emissions from fossil fuels and affects the decay process. The cost figures of this alternative is highly dependent on the price of fossil fuels, and is excluded from the cost curve in this study.

The estimated cost curve is based on the remaining 12 measures. The alternatives are listed in Box 2.1. All the alternatives are reported with a high and a low rate of utilisation. A low rate of utilisation means that the measure could be carried out without significant conflicts with other interests, according to Lunnan *et al.* (1991). Such conflicts are considered to be substantial if the measures are carried out with a high rate of utilisation. For instance, the drainage of forest lands will affect the bio-diversity, and may therefore have considerable secondary effects which are not taken into account when estimating costs. A number of the measures have other effects than just to enhance the sinks of CO_2, such as to change the energy consumption pattern, although their main effect is to enhance sinks. No attempts has been made to model these secondary effects of the measures in the analysis. All the measures are taken to be “purely” sink-enhancements.

Figure 2.1 Marginal cost of direct abatement of CO_2. High and low utilisation.



The estimated abatement curves for the high and the low alternatives are shown in Figure 2.1. The ‘observations’ are indicated as well. The curve for high utilisation of the measures may be interpreted as excluding social costs not subject to market prices. The model therefore applies parameters very close to the low utilisation alternative.

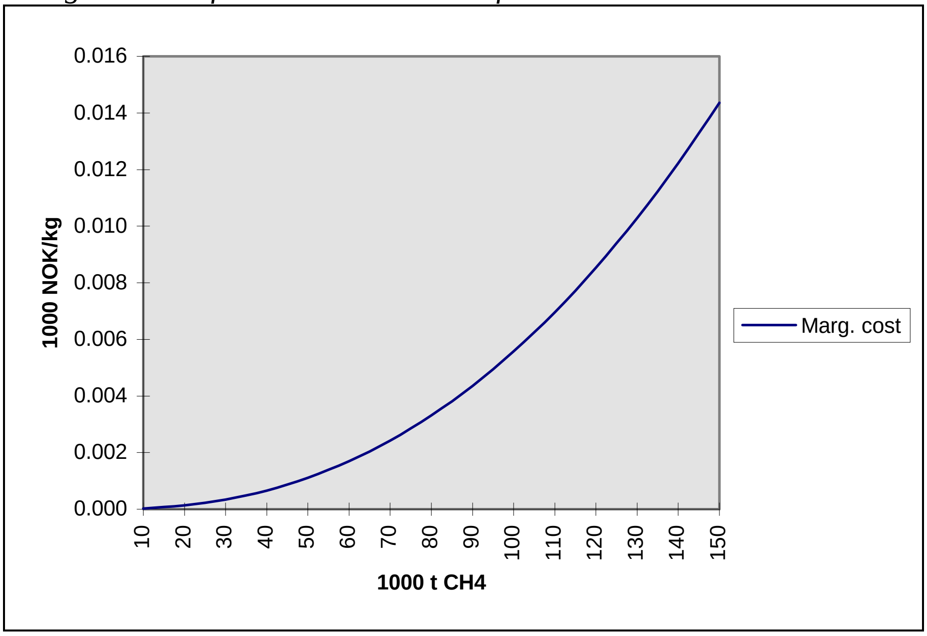
2.2 Measures to reduce emissions of methane

Total emissions of methane from waste deposits amount to about 160 000 tons of CH_4 per year. This is nearly 60 percent of total Norwegian emissions of methane. The measure to reduce the emissions of methane aims at utilising gas from waste deposits for energy generation, and has been described by the State Pollution Authority (1990). The reduction in emissions of methane results in more emissions of CO_2 and additional supply of energy. To account for the higher emissions of CO_2, the emission reductions of methane is net of this increase. We have calculated the net reductions as if we could aggregate CO_2 and CH_4 in terms of the GWP.[3] As emphasised earlier, this leads to a bias in intertemporal analyses. However, this bias can be considered negligible in a macro context.

The effect of this measure on the supply of energy is also neglected. Economically speaking, this might not be too serious, since the profitability of the project is considered to be marginal by the State Pollution Authority. However, in a long term perspective it should be noted that two effects of importance may occur. First, the costs are sensitive to the price of energy, which is solved endogenously in the model. A lower energy price means that income from the measure decreases, and thereby the net cost increases, and vice versa. The energy output of

[3] The GWP is based on a 100 years time horizon.

Figure 2.2 Marginal costs for direct abatement of methane emissions



this measure may therefore be considered spoiled. Second, the reduction in the emissions of methane leads to an increase in the emissions of CO_2, thereby affecting the emission coefficient for CO_2.

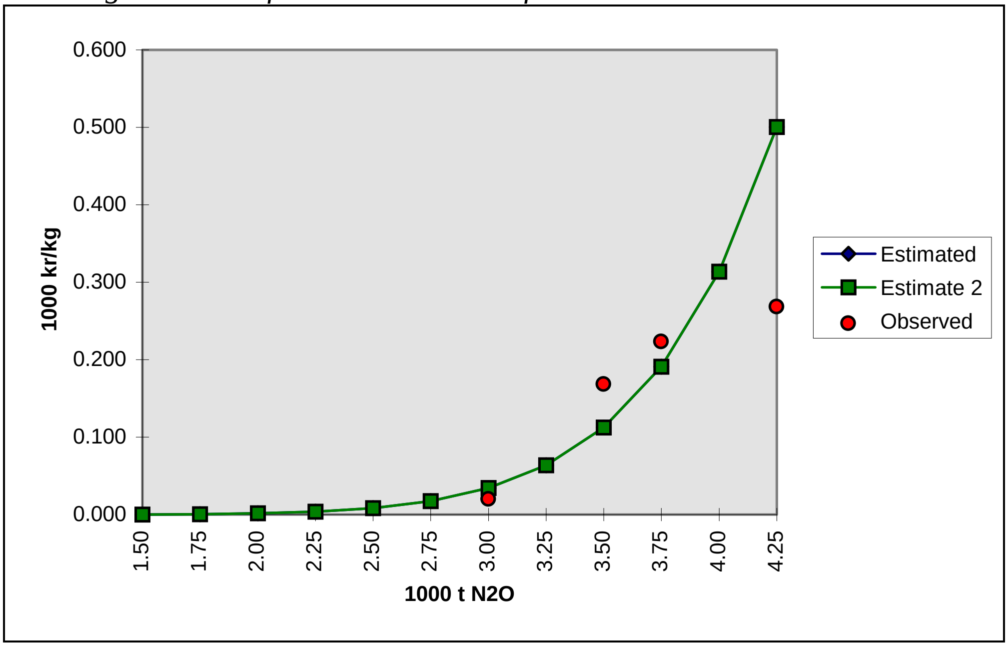
The costs were reported at two points, for which the reductions of emissions of methane amounted to 43 000 tons and 82 000 tons of CH_4. This leads to comparably low marginal costs for very high abatement. To avoid unrealistically high abatement of methane, the curve applied in the model, which is shown in figure 2.2, exhibits somewhat lower cost at low levels of abatement, and higher costs at high abatement.

2.3 Measures to reduce emissions of nitrous oxide

About 30 percent of the Norwegian emissions of nitrous oxide originate from the use of fertilisers in agriculture and 50 percent from production of nitric acid. In order to reduce the runoff of nitrogen to waterways, lakes and to the sea, a number of measures to increase the effectiveness of fertilisation in agriculture has been carried out in later years. The Norwegian State Pollution Authority (1990) suggests that a maximum of about 40 percent of the emissions of nitrous oxide from the agriculture can be reduced.

The costs of a lower intensity of fertilisation is given in terms of productivity loss in agriculture. It is assumed that about 10 percent of the emission reductions can be attained at nearly no loss of productivity, but that the last 30 percent will lead to a productivity loss of up to 20 percent. Because of the public regulations of the agricultural sector, it difficult to assess the national cost of this loss of productivity. The subsidies per NOK contribution to the GDP from agriculture exceed 1 NOK. Hence, to the extent that subsidies are linked to production, the productivity loss will actually lead to a national economic gain. On the other hand, it is

Figure 2.3 Marginal costs of direct abatement of nitrous oxide emissions.



unlikely that a 20 percent reduction in productivity will lead to a 20 percent reduction of the transfers to the sector. In the lack of better advice, we have calculated the present value of a continuation of the present policy. This indicates a slight reduction in the subsidies to the sector over time. The estimated cost is about ½ of the full cost of a subsidised loss of productivity, where the “harvest” is considered to constitute 25 percent the total output from the sector.

With appliance of new technology, the State Pollution Authority also assumes that it is possible to reduce the emissions of nitrous oxide by 50 percent in the production of nitric acid by investments of 1 000 mill. NOK. This is considered as a net cost. Calculated in terms of unit costs for emission reductions, we may approximate a curve for emission reductions for increasing costs as depicted in figure 2.3. The first 3 500 tons of annual emission reductions are based on higher fertilisation effectiveness in agriculture and new technology in the production of nitric acid. More reductions demands a significant productivity loss in agriculture.

3 THE MODEL

A formal description of the model is provided in the annex. We consider one country over a given period of time. There are no trade with foreign countries. The economy is divided into two productions sectors and households. One sector produces fossil fuel energy, and the other, which we call the commodity and service sector, produces all other goods. The output from the commodity and service sector can be used for consumption, investments or to abate greenhouse gas emissions. The input to both production sectors consist of real capital and fossil energy (henceforth called energy), while households derive utility from goods from the commodity and service sector and from energy consumption.

The solution is found by maximising total utility over a given time horizon. This gives conditions for how to allocate the total national output to consumption, investments and direct abatement costs at each point in time under constraints given by the initial capital stock, targets for the capital stock by the end of the period, and targets for the concentrations of greenhouse gases by the end of the period.

Greenhouse gas emissions are represented by carbon dioxide, methane and nitrous oxide. These are partly related to energy consumption. In the cases of methane and nitrous oxide, only a given share of the emissions is related to the use of energy. The rest is added as an exogenous amount. The emissions may be controlled either by charges on energy, or by "direct abatement". The costs of abatement are described by the cost functions discussed in section 2.

Policy both under an emission target and under targets on the concentrations of greenhouse gases will be discussed. There is a major political difference between these targets. While targets on emissions may be set by national authorities in isolation, the concentrations are subject to policies world wide. An assessment of possible outcomes of climate negotiations between nations is far beyond the scope of this analysis. Nevertheless, a link between national and total world emissions is required if the policy aims at controlling the concentrations. Therefore, it is assumed that the emissions of *all* countries are adjusted by the same rate. This corresponds to a climate agreement with 'flat' reductions for all countries, an alternative which is controversial, even if limiting the partners of an agreement to the Annex 1-countries of the Framework Convention.

In an atemporal context, the authorities will have to limit themselves to emission targets in climate policy. To compare the contribution to global warming from emissions of different greenhouse gases, one usually applies global warming potentials (GWP). The GWP of a greenhouse gas is meant to express the contribution to global warming in terms of radiative forcing, of emitting one unit of the gas relative to the contribution of emitting one unit of CO_2. This allows emissions of all gases to be expressed in terms of CO_2-equivalents. Radiative forcing is calculated as the change in forcing due to a change in the concentrations of gases. Since the lifetime of one emitted unit differs between gases, the GWP depends on the time horizon over which it is calculated. Hence, GWP is an incomplete measure of the warming potential. This is due to the fact that we study a problem which is basically dynamic in a static context.

When we study the results of the intertemporal model, we avoid the use GWPs, and instead calculate radiative forcing directly at each point in time. Radiative forcing is expressed as an index for the change in concentrations of greenhouse gases. According to the IPCC (1994), a doubling of the atmospheric concentrations results in a radiative forcing of 4. Model studies indicate that the global average surface air temperature thereby increases between 1.5 and 4.5 °C, with 2.5 °C as a "best estimate" (IPCC, 1996b).

It is assumed that the production sectors exhibit constant elasticity of substitution. That is, the model applies CES-functions in the production sectors. It was assumed that real capital may substitute energy rather easy in the commodity and service sector, by setting the elasticity of substitution close to 0.93. The technology is assumed to be less flexible in the energy sector, where the elasticity of substitution were set to 0.58. In the household sector, a linear expenditure system is applied.

In order to set the parameters, the model were calibrated by Norwegian national accounts data for 1994. Emission data were taken for Statistics Norway (1996). The Norwegian economy is, however, quite different from the closed economy described by the model. Being a small open economy, a foreign sector would be necessary in order to describe Norway in a realistic way. In particular, the production of fossil energy, which is dominant in the Norwegian economy at large, exports most of its products. The energy sector is therefore limited to necessary production for domestic purposes, by reducing the activity to the level where it meets domestic demand. This assumption also applies for the rest of the economy. Implicitly, this means that trade has to be balanced at all points in time, and that there are no effects on the terms of trade in the future.

Data for the capital stock were unavailable for years after 1990, and was estimated on the background of investment data and the capital stock reported in 1990. For the energy sector, all data were estimated by taking the share of domestic fossil energy to total energy production (excluding hydro power). Due to these shortcomings, we focus on the use of measures and the emphasis on different greenhouse gases in climate policy in this presentation.

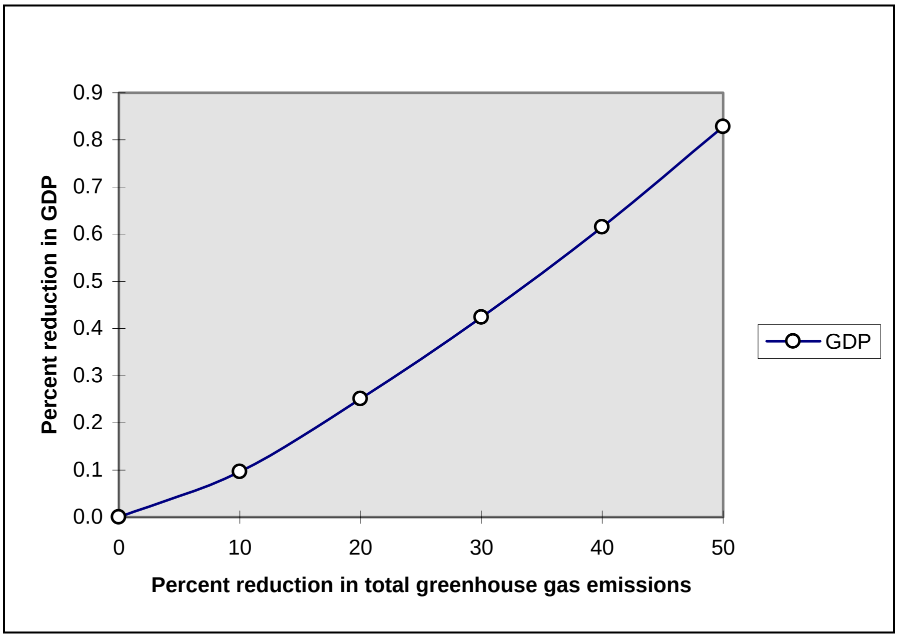
The optimum conditions provide one set of instantaneous, or atemporal, equilibrium conditions, which determine the equilibrium prices, including optimal charges and optimal expenditure on direct abatement, at each point in time. Moreover, a set of intertemporal conditions is provided. These govern the growth paths of the control variables, which are the consumption level and the costs of direct abatement. For the sake of convenience, we discuss the properties of the atemporal conditions first, and then describe the intertemporal conditions in section 3.2.

3.1 Atemporal equilibrium

The model allocates capital and output from the two productions sectors to the commodity and service sector, the energy sector and the households. The total initial capital stock is given. However, the division of this stock between the two production sectors is determined by the equilibrium conditions. A more aggressive climate policy will lead to less production of energy, and thereby an immediate reallocation of capital from the energy sector to the commodity and service sector. Such changes would take a long time in practice. Moreover, there are no financial sector in the model. Charges are used only as a mean to change relative prices and cannot be considered as revenues for the public sector. In other words, the model generates first-best solutions, only.

A more realistic description of the macro economy would give second-best solutions. For example, the effects on the macro economy by alternative reallocation of the revenues from environmental charges have been analysed extensively in recent studies (see e.g. Jorgenson . and Wilcoxen, 1994, Bouvenberg and van der Ploeg, 1994 and Holtsmark, 1997). Many of them indicate that environmental charges may replace direct taxes and thereby enhance the effectiveness of the economy. Substantial gains may be obtained in this way. In some cases, emissions of CO_2 may be reduced by up to 40 percent without reducing GDP (Holtsmark,

Figure 3.1 Reduction in GDP for 'immediate' reductions in greenhouse gas emissions. Percent



1997). Other macroeconomic studies indicate much higher losses of GDP from different emission targets. IPCC (1996) reports national studies of OECD countries which give annual losses in GDP at approximately 0.3 percent per 10 percent reduction in CO_2-emissions within a 25 to 30 years time perspective.

The loss in GDP of different emission targets in the present model is lower than the results from most other studies. Figure 3.1 gives the instantaneous loss in GDP for reductions of total greenhouse gas emissions of up to 50 percent. Since the model assumes first-best solutions, any reduction will lead to a loss. However, the loss is much less than most of the studies reported by the IPCC (1996a). The flexibility of the allocation of real capital assumed here explains some of this. As we shall see later, the inclusion of direct measures is a second explanation. A third reason may be that all alternatives assume that the consumption of commodities and services in the household sector is constant, and independent on the emission target. This assumption is introduced in order to make the 'atemporal' solutions of the model indicated in figure 3.1 comparable with the 'intertemporal' solutions discussed later. No attempt is therefore made to consider the effects on investments from alternative emission targets in these figures. As shown by Weitzman (1976), this makes GDP inappropriate as a measure for the national costs of these targets. In the analysis, we will therefore report the costs in terms of charges and costs of abatement.

The value of emission reductions follows from the shadow prices of the different compounds which are solved in the model. The level of abatement efforts is thereby determined such as to equal these shadow prices with the marginal costs of abatement. The optimal energy charge equals the value of the emissions, or more technically, the shadow price times the emission coefficient. Thus, we may interpret the charge as the social cost of emissions from energy use in optimum. This condition establishes the relation between optimal charges and optimal direct abatement costs, as it follows that the marginal abatement cost of reducing the emissions of one unit of CO_2-equivalent equals the charge avoided by reducing one such unit.

In the static analysis, this also suggests how abatement should be allocated among different gases. By means of the GWP and the shadow prices of emissions reductions, we may require that the marginal cost of reducing one GWP is the same across gases. Although this condition may seem obvious and intuitive, it is not valid in general in a dynamic context, because then, the question of *when* measures should be initiated comes up.

3.2 Intertemporal optimum

When considering a given period of time, we may allow policy makers to set targets on the concentrations of greenhouse gases, thereby getting closer to the aim of climate policy; to curb climate change. The model provides conditions for how to control the economy and the emissions over time. The relation between the growth rate for consumption and the rate of return in the economy is

$$\frac{\dot{c}}{c} = \frac{1}{\mu_c}(\rho - \delta)$$

where μ_c is the elasticity of consumption between two points in time. It expresses to what extent the welfare function emphasises intergenerational equity. The higher μ_c is, the more important is intergenerational equity considered to be. ρ is the rate of return on capital, or the discount rate, and δ is the rate of impatience in consumption. The relation is familiar from theoretical models of economic growth, and is often referred to as 'the Ramsey rule', after Ramsey (1928).

Of more interest for the problems discussed in this report is how abatement costs develop over time. The growth rate for abatement costs for gas *i* can be written as

$$\frac{\dot{a}_i}{a_i} = \frac{1}{\mu_i}(\rho + \frac{1}{\tau_i} + \lambda\varphi_i)$$

where μ_i expresses the curvature of the abatement cost function for gas *i*. τ_i is the lifetime of gas *i*, that is the time it takes before the concentrations of one unit emitted is reduced to *1/e* (approximately 0.37). λ is the constant shadow price of the target for the concentrations of greenhouse gases, and φ_i is the marginal effect on radiative forcing from 1 NOK abatement of gas *i*. Thus, φ_i includes marginal abatement costs, and the shadow price of the emissions of gas *i*.

This relation is important for the understanding of the control of climate change. It says that abatement efforts over time is to be related to the discount rate. An increased discount rate has a proportional effect on the growth rate of abatement. This is the 'mirror' effect of discounting. A higher discount rate means that abatement is to be lowered, and that investments in real capital should be advanced in time compared with abatement efforts. However, this does not affect the concentration target. Thus, delayed abatement efforts have to be compensated at a later stage. As a result, the growth rate of abatement efforts is to be increased.

The second term in the expression for abatement growth relates to how the gases behave in the atmosphere. Gases with short lifetimes, i.e. low τ_i, exhibit higher growth rates than gases with long life-times. Taken in isolation, the growth rate for abatement of methane, where ($\tau \approx 10$) is therefore likely to be higher than for carbon dioxide and nitrous oxide, for which $\tau > 100$. How to distribute measures among gases depends also on the marginal effect on radiative forcing of each gas. It is therefore difficult to say from the above expression which gases should be reduced first at the expense of other gases compared with the intuitive atemporal condition. Recall, also, that chemical reactions between gases are left out this analysis. Methane is a very reactive gas in the atmosphere, and the timing of different gases might therefore change if chemical reactions are taken into account.

The cost of alternative targets on radiative forcing depends on how the policy emphasises different gases, and on how fast it is optimal to speed up abatements. To find the optimal level of abatement efforts for the different gases at each point in time, and the shadow price of the target, λ, we have to put additional conditions to the end points of the state variables. The numeric solutions presented below are based on the observed initial stock of total capital, and an arbitrarily chosen terminal stock of total capital. To compare the paths for different targets, it is required that the terminal stock of total capital is the same for all alternatives.

4 ATEMPORAL ANALYSIS OF CLIMATE POLICY

In this section, we present some numerical examples of the results discussed in section 3.1. Figure 4.1 shows how emission reductions should be distributed among the gases with alternative emissions targets. More than 90 percent of the reductions are due to measures directed against reductions in the emissions of CO_2. This is more than the CO_2 share from

Figure 4.1 Reduction of different gases when alternative targets for reduction of greenhouse gas emissions are set. Mill. t. CO_2 equivalents.

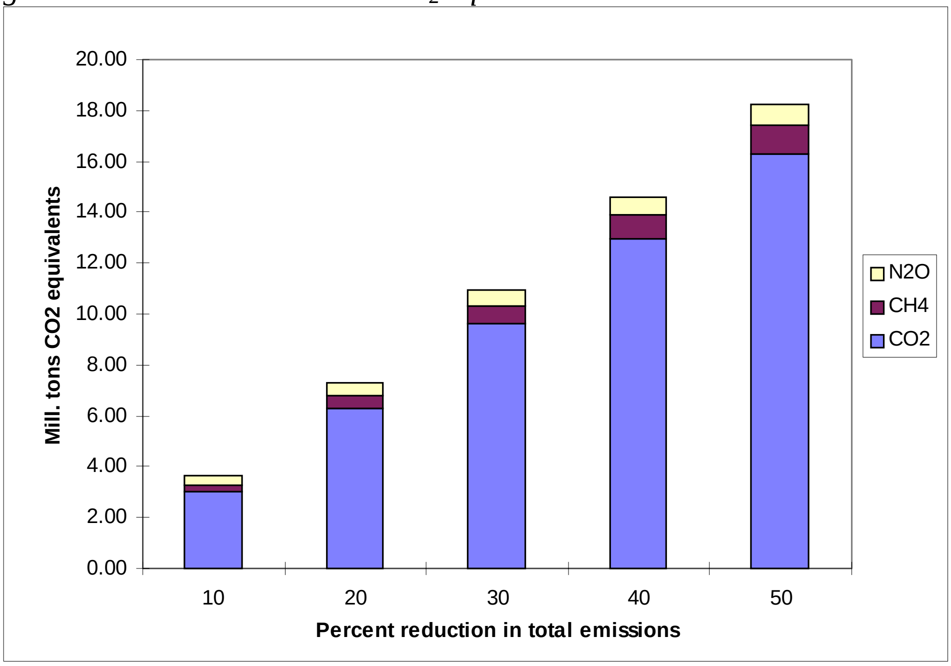
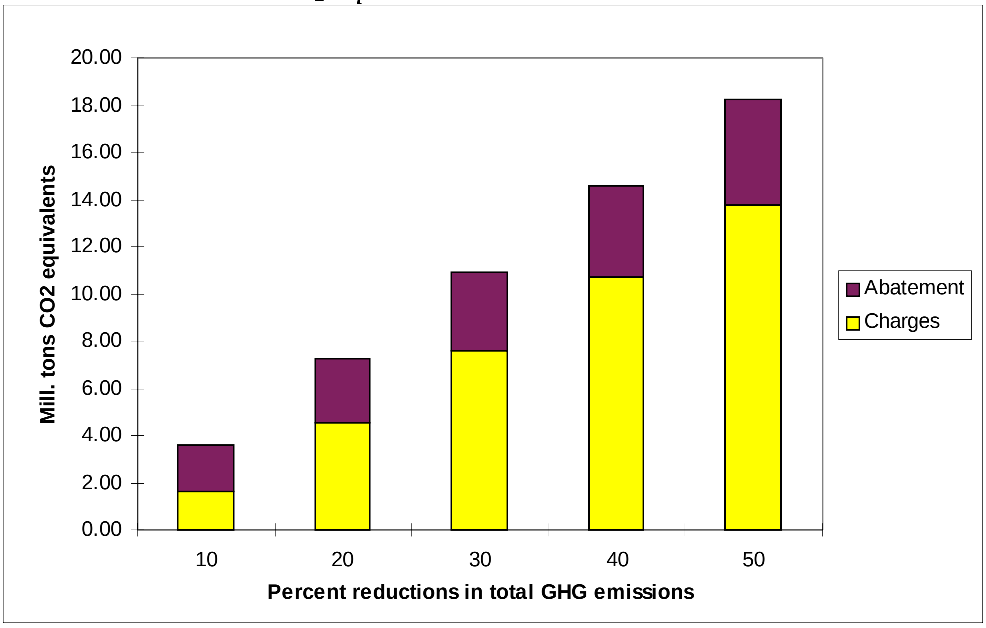


Figure 4.2 Reductions of greenhouse gas emissions originating from charges and direct measures. Mill. t. CO_2 equivalents.

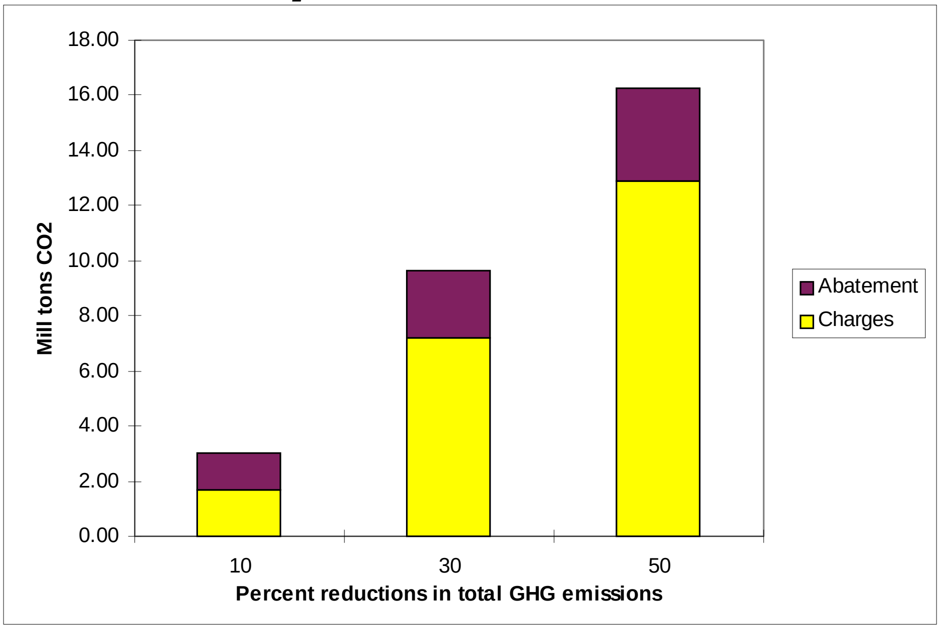


today's emissions of greenhouse gases, which amounts to less that 80 percent. The emphasis on CO_2 is slightly increasing for increasing targets for emission reductions. The share of CH_4 abatement is about the same as for N_2O at low reduction targets, but more emphasis is put on CH_4 emissions at higher reduction targets. This reflects the fact that abatement of nitrous oxide has high marginal costs at high abatement.

Figure 4.2 shows how the emission reductions originate from charges and from direct abatement. The share of direct abatement is more than 50 percent at 10 percent reductions, and about 40 percent at 20 percent reductions. For a more aggressive climate policy, one have to rely on charges, as the additional contributions from direct measures are relatively small. In other words, there may be other possibilities than charges worthwhile to search for in greenhouse gas emissions control. Especially in an early phase of climate policy, when the emission targets probably are moderate, these results indicate that more emphasis might be put on direct abatement than on charges.

The emphasis on gases and measures also indicate what kind of direct measures is the most attractive. Figure 4.3, 4.4 and 4.5 show the shares of charges and direct abatement of CO_2, CH_4 and N_2O, respectively. Figure 4.3 indicates that forest management and enhancement of carbon sinks is very attractive, and may contribute to a substantial share of the emission 'reductions' in climate policy. Recall also that the cost function applied for the carbon sequestration policy is based on a very moderate utilisation of the opportunities. According to Lunnan *et al.* (1991), these were measures that might be carried out without significant controversies with other interests.

Figure 4.3 Reductions of emissions of carbon dioxide originating from charges and direct measures. Mill. t. CO_2.



As expected, the reductions of the emissions of methane and nitrous oxide is primarily based on direct measures, especially for moderate emission targets. This is to a large extent due to the fact that nearly 60 percent of the emissions of methane and approximately 80 percent of the emissions of nitrous oxide are regarded as exogenous. Hence, only at a 50 percent reduction of total emissions will there be any significant effect on the emissions from the charges to reduce nitrous oxide. This does not mean that charges cannot be used to reduce the

Figure 4.4 Reductions of emissions of methane originating from charges and direct measures. 1000 t. CH_4.

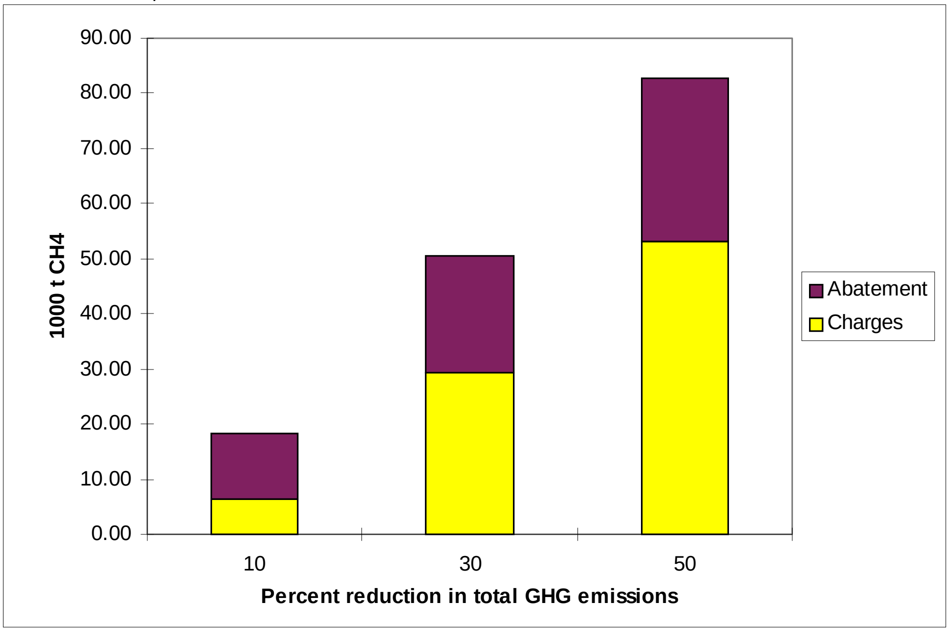
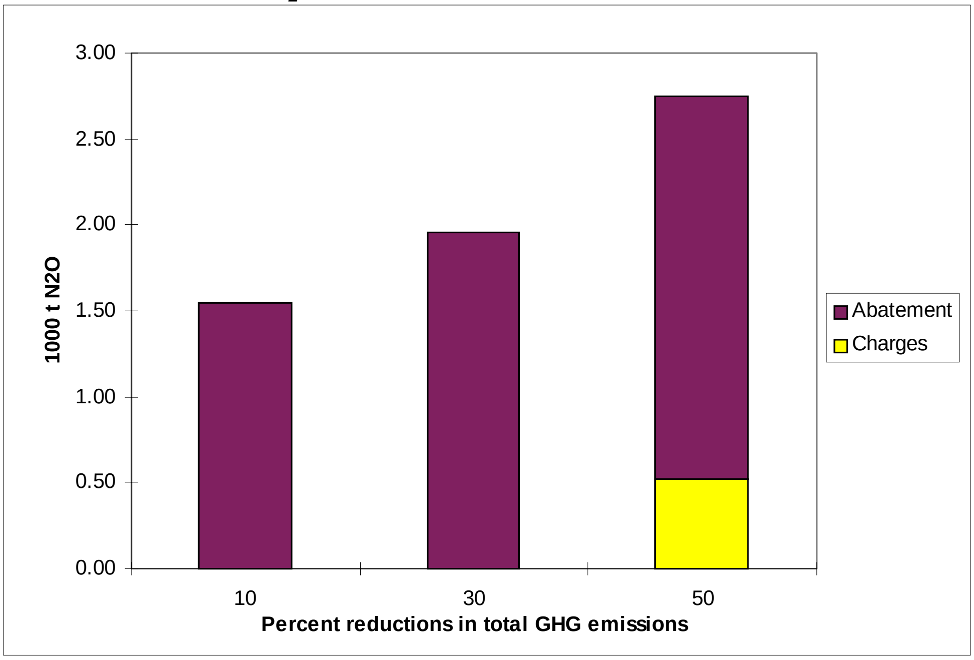


Figure 4.5 Reductions of emissions of nitrous oxide originating from charges and direct measures. 1000 t. N_2O.



emissions of N_2O. However, the charge considered here is a charge on energy. Thus, the reductions are due to reductions in energy-related activities. Charges on fertilisers may be an adequate measure to achieve the reductions grouped under 'direct' measures.

Figure 4.6 Charges on energy per NOK energy price free of charge at alternative targets for reductions of greenhouse gas emissions.

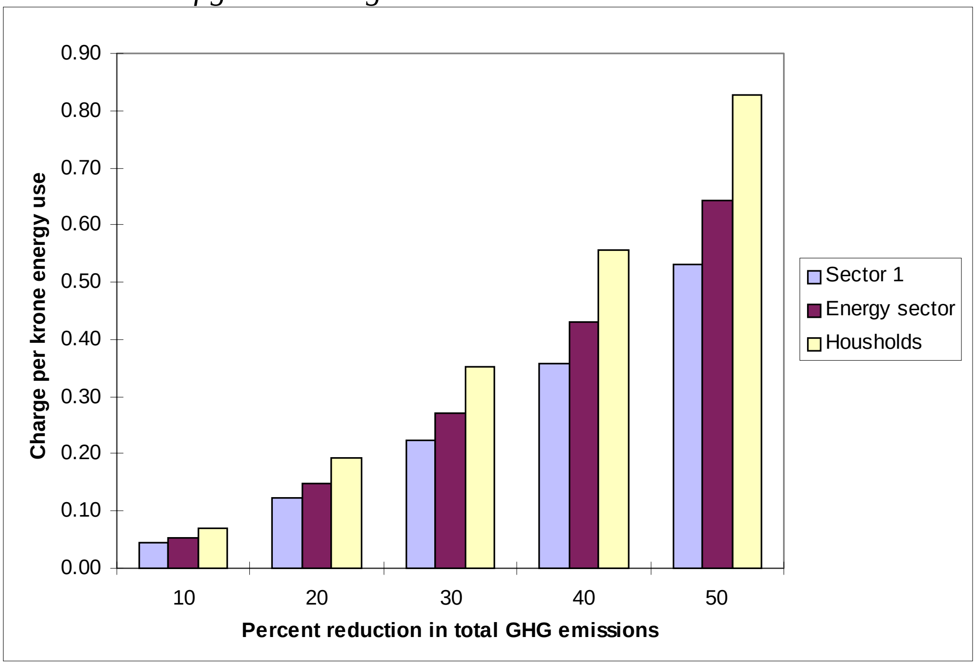
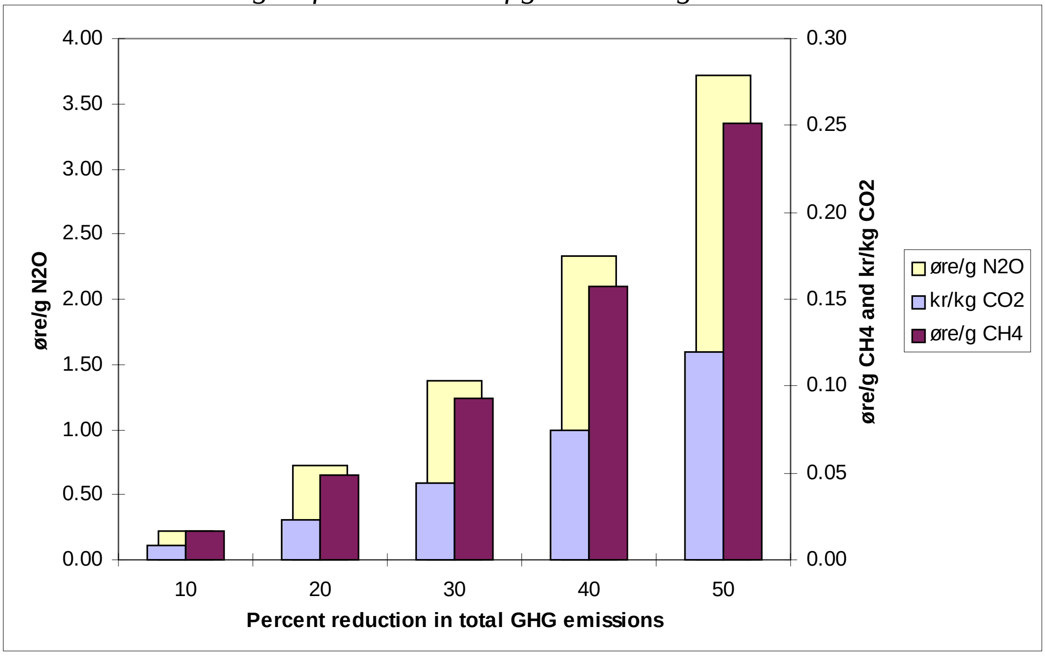


Figure 4.7 Admissible marginal costs of direct measures to abate climate change at alternative targets for reduction of greenhouse gas emissions.



It was pointed out in section 3 that the costs in terms of reductions in GDP are low in this study compared with other studies. Another indicator for the costs of emission reductions is the required charge. Figure 4.6 shows the energy charge per NOK spent on energy (free of charge) in the three sectors of the model. The differences are due to the fact that the emission coefficients differ among sectors. Thus, the household sector is the most emission intensive, then comes the energy sector, which probably is atypical compared with the energy sectors of other countries, while the commodity and service sector have "cleanest" activities. A rule of thumb for moderate and medium targets seems to be that the charge adds to the energy price with the same percent as the percentage reduction in emissions. For 10 to 25 percent reductions, a charge adding 10 to 25 percent, respectively, to the energy price seems appropriate. For higher emission reductions, more have to be added. A 50 percent reduction target implies a nearly doubling of the energy price.

The marginal cost of direct abatement measures at alternative emission targets show what it is optimal to pay in terms of net abatement costs. According to the equilibrium conditions discussed in section 3.1, these may be interpreted as cost-benefit rules for an evaluation of marginal projects not included in this study. Thereby, a link between so-called bottom-up studies and top-down-studies is established. Bottom-up studies seldom manage to capture how sensitive the social benefits of the projects are to a change in emission targets. In this analysis, this sensitivity is shown in figure 4.7. The net admissible cost for CO_2 abatement ranges from about 1.5 øre/kg CO_2 if the emission reduction is 10 percent to 22 øre/kg CO_2 at a 50 percent target. The corresponding figures are 0.03 to 0.45 øre/g for methane and 0.42 to 6.7 øre/g for nitrous oxide. In other words, how attractive a measure to reduce the emissions are turns out to be very sensitive to what target for the policy is. The advantage of implementing the bottom-up studies in a macroeconomic model is that it is possible to calculate this sensitivity.

5 INTERTEMPORAL ANALYSIS OF CLIMATE POLICY

Climate policy aims at regulating expected climatic effects in the far future. A discussion of climate policy in a static context, such as in the previous section, is therefore insufficient when designing a strategy to combat climate change. This section aims at pointing out how important the aspect of time may be. In this section we concentrate, first, on the implications of shifting policy targets from emissions to concentrations. Second, we show how an initial redistribution of abatement from some gases to others gases with different life-times affect the solution.

It should be noted that the properties of the solution of optimal growth models often make it difficult to establish a realistic growth path. This is particularly problematic in very aggregated models such as the one applied in this study, where the initial variables are calibrated to observed data. The long-term properties of the optimal solution leads to either declining consumption with enormous saving/investment or ever increasing consumption and deterioration of real capital. In order to balance these ‘forces’ and to permit parameters which allow the consumption path to pass through the observed level in the base year, the period under consideration is limited to 50 years. The average growth in consumption of the model turned out to be as high as 3 percent per year over this period. Energy growth is nearly 10 percent annually with no climate policy. This leads to extremely high concentrations. The paths must therefore clearly be considered as being unrealistic, even though it is reasonable to expect a ‘business-as-usual’ scenario to include at least some climate measures, and therefore to yield lower energy consumption that the no-intervention alternative, used as the baseline scenario in this report. However, the calculations indicate the effects we want to focus on, and how the distribution between the different gases and between the available measures develops.

Table 5.1 Main macroeconomic figures in base case. Mrd. NOK

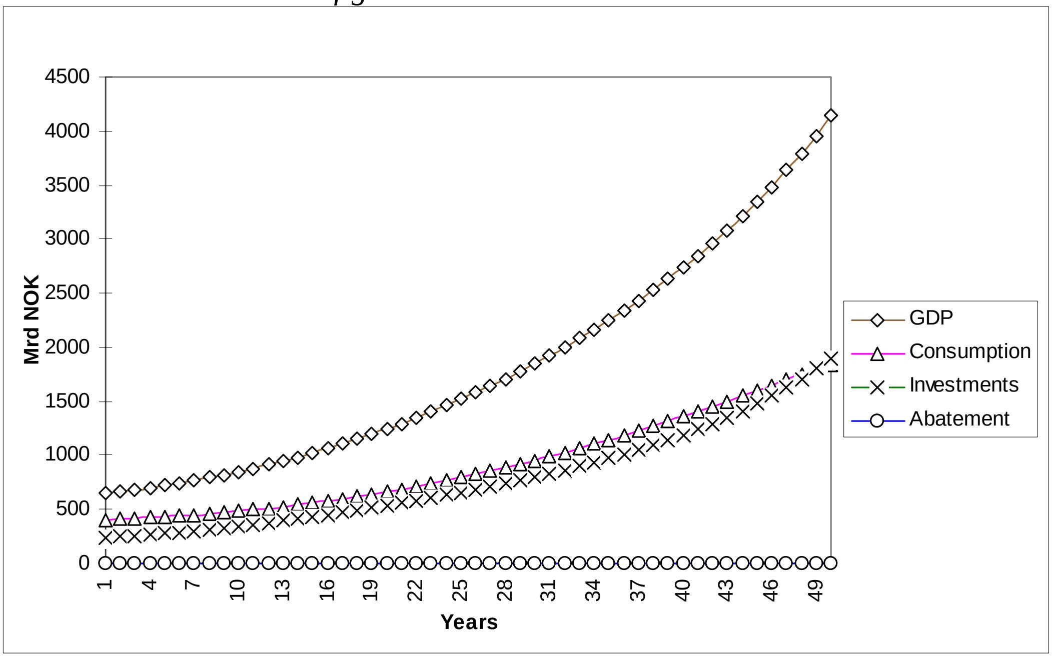


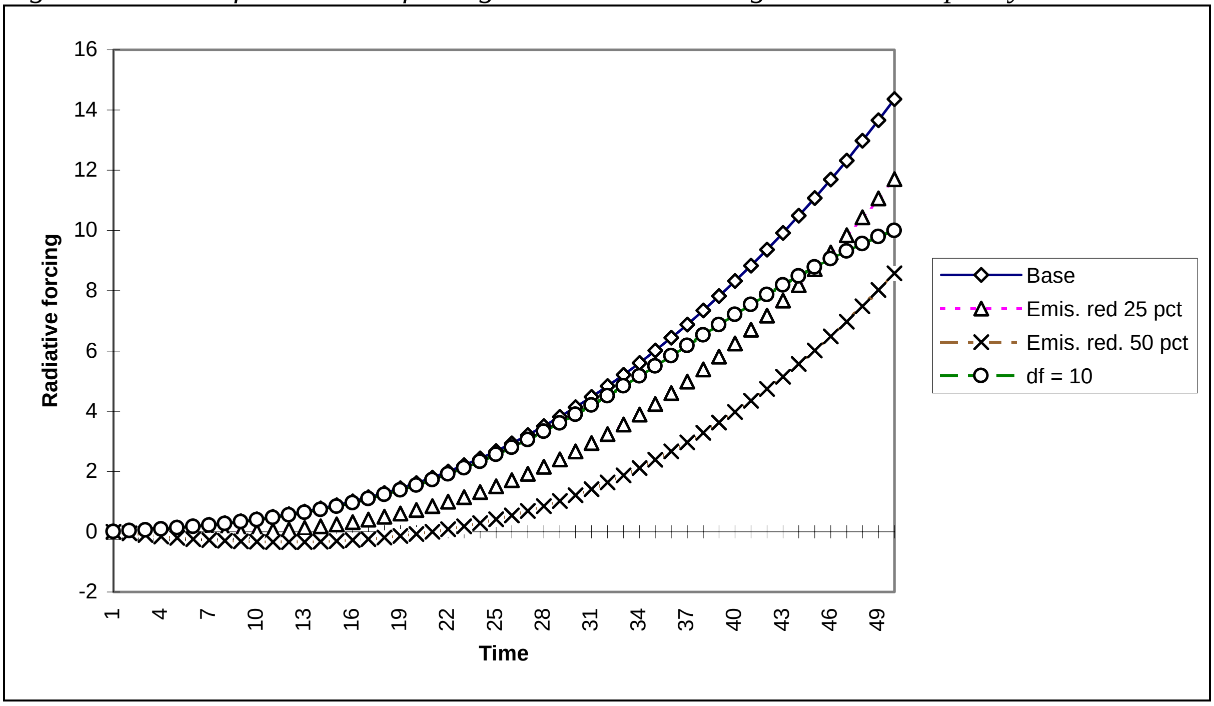
Figure 5.1 shows the development of some main macroeconomic figures in the base case. The high growth rate is due to a high rate of capital accumulation, which to some extent follows from the observed level of consumption in the base year. Measures to reduce emissions of

greenhouse gases are practically speaking not implemented in this case. As mentioned earlier, the base case leads to extremely high emissions over the next 50 years. The main explanation is that the price of energy, which is endogenously determined, decreases by 3.6 percent per year on the average over the simulation period. Recall also that even if no climate measures are initiated over this period, other measures to reduce energy consumption might be implemented for different reasons, and thereby reduce also the emissions of greenhouse gases. Thus, the base case should *not* be considered as a 'business-as-usual'-scenario. Most of the increase in emissions takes place in the commodity sector, while the emissions from the energy sector is moderate. Not surprisingly, the emissions of CO_2 increase the most. This is because parts of the emissions of CH_4 and N_2O are exogenous, with a relatively moderate increase.

The targets for the climate policy we consider are set on radiative forcing relative to the base year (*t=0*). Radiative forcing is an accurate measure for the warming potential, and is calculated on the basic of the concentrations of greenhouse gases (see also page 14). In the base case, the increase in the concentrations over the period (1994 - 2044) is from 353 to 1708 ppmv for CO_2, 1720 to 3786 ppbv for CH_4 and from 310 to 622 ppbv for N_2O.[4] The change in radiative forcing over the period is then 14.26.

The costs of implementing an emission target relative to a target on radiative forcing requires that the static equilibrium is estimated for each year. This has not been done. Hence we cannot directly compare the costs of implementing an emission target with the cost of implementing a

Figure 5.2. Paths for radiative forcing with alternative targets in climate policy



target on the radiative forcing.[5] To illustrate the difference between an optimal, intertermporal policy and a policy with fixed emission targets, figure 5.2 compares the forcing

[4] The IPCC scenarios IS92 ranges from approximately 450 ppmv to approximately 550 ppvm for concentrations of CO2, 2224 ppbv to 3038 ppbv for CH_4, and 364 ppbv to 376 ppbv for N_2O in year 2050.
[5] Richels and Edmonds (1994) makes a tentative comparison of these two kinds of targets.

over time for emission targets at 25 and 50 percent reductions relative to the baseline scenario and the consequence of an optimal policy to meet targets for radiative forcing (denoted *df*) at *df = 10* at *T = 50.*

The difference between the two types of policy targets is that a target on concentrations, or radiative forcing, allows for a more moderate climate policy in the first period, by allocating the bulk of climate policy measures to the second half of the simulation period. Actually, the optimal path almost coincides with the base case over the first 25 years. After that, emission reductions become substantial, and we end up with a level of concentrations corresponding to a target of emission reductions at approximately 35 percent over the whole period. As pointed out by Richels and Edmonds (1994), the economic advantage is that a delay of climate measures allows for alternative investments in the early period, which again contribute to capital accumulation. In addition, technical advancement may allow for less costly abatement in the future.

To start with, assume that the abatement cost of different gases are distributed at *t=0* in the same way as in the static case. That is, the marginal cost of reducing one GWP is to be the same for all the gases. Figure 5.3 shows the cost in terms of initial consumption equivalents of different targets on radiative forcing at *T = 50. df = 0* implies a stabilisation of the concentrations of the greenhouse gases to the present level. In order to compare the costs of different alternatives, we have defined the 'initial consumption equivalent', which expresses the economic loss of introducing a climate target in terms of present consumption. The initial consumption equivalent is the reduction of consumption today necessary to give the same reduction in present welfare as the total welfare loss from the whole consumption path. Roughly speaking, one may say the initial consumption equivalent is the average percentage reduction in consumption over the whole period.

Figure 5.3 Percent reduction in initial consumption equivalent at alternative targets for radiative forcing.

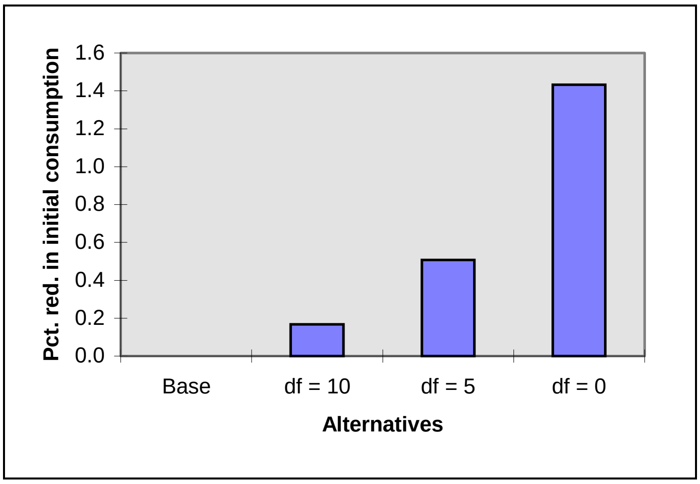
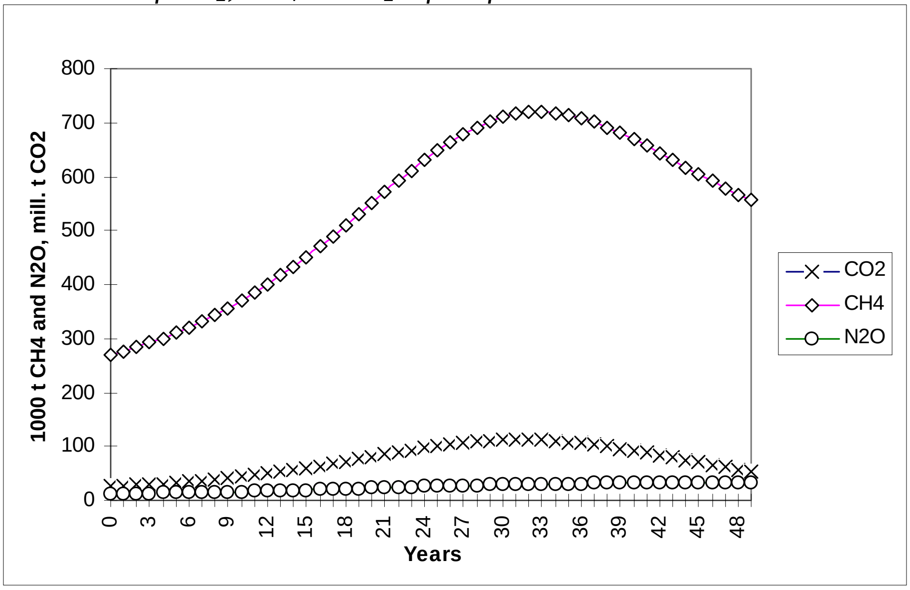


Figure 5.4. Emissions of CO_2, CH_4 and N_2O for df = 5 at T = 50



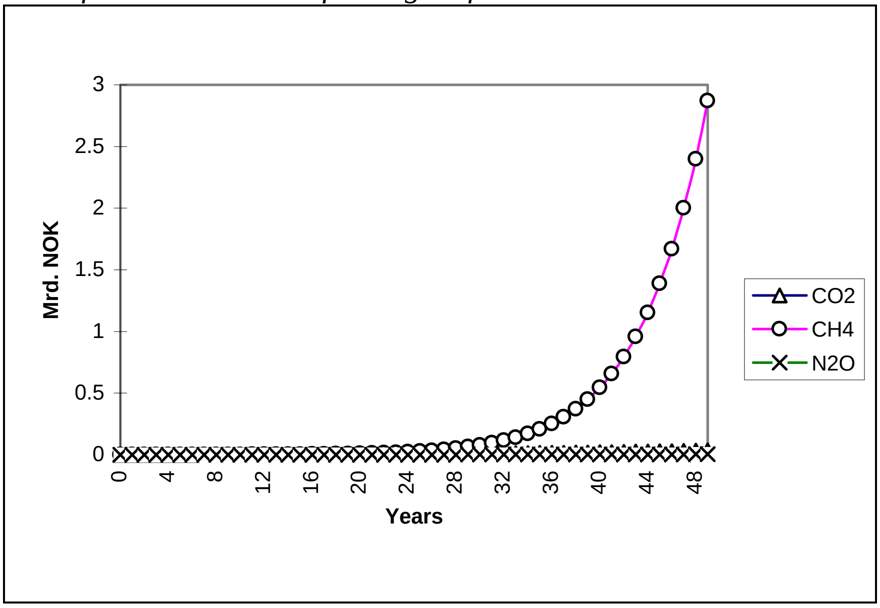
The costs of the alternatives are clearly lower than realistic. This is again partly due to the energy price path. Under the target *df = 10* the energy price falls by 1 percent per year on average. Another explanation for the low costs may be that the flexibility of the production structure is exaggerated, although it is somewhat less flexible than a Cobb-Douglas technology would imply. As pointed out above, the base case is extremely optimistic with respect to economic growth. A target of *df = 5* corresponds to a moderate to high emission scenario, as in e.g. the IPCC (1992). We will therefore use *df = 5* as the benchmark for further analysis of the optimal policy.

The emissions from the path with *df = 5* are shown in figure 5.4. The trends show the same pattern as pointed out above, that is the main abatement efforts are to be implemented towards the end of the period. The main reductions are to take place in the production sectors, while the reductions in emissions from the households are more moderate. This is due to the formulation of the utility function, which assumes a certain subsistence level for energy consumption.

The implementation of abatement measures exhibits a rather different picture from the conclusions given in the static analysis. Figure 5.5 and 5.6 shows the paths for direct abatement and charges. Nearly all the direct abatement costs are spent on reducing the emissions of methane. This is partly due to the short life-time of methane in the atmosphere, which indicate a higher rate of increase in the expenditures to direct abatement measures, but is also related to the marginal effect on radiative forcing from methane. The relation between charges and direct abatement is determined from the static set of conditions, and is therefore the same as in the static case.

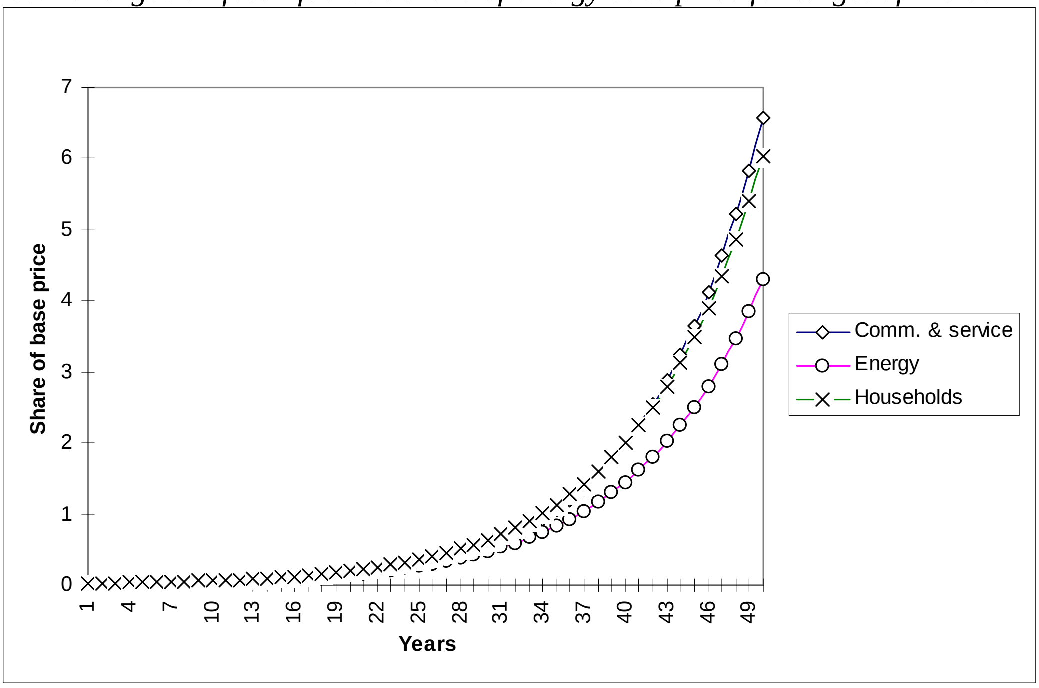
The emission charges across sectors are shown in figure 5.6. Recall that the differences reflect the emission coefficients and the composition of gases in the different sectors. As in the atemporal case, the charge is highest in the household sector, and lowest in the commodity and service sector at *t = 0*, but they are very small in all the sectors, less than 3 percent of the basic price. Energy use peaks between the years 27 and 33, dependent on sector.

Figure 5.5. Costs of direct abatement for target df = 5 at T = 50



The paths described above rests on two fundamental assumptions. One is the assumed shadow price of the target, and the other is the initial allocation of abatement costs on CO_2, CH_4 and N_2O which is given from the intuitive 'static' condition. This condition is not a part of the solution of the model. The choice of a shadow price for the target has implications for the level of initial abatement costs. Charges are implemented already at *t = 0* with rates between 1.5 percent in the commodity and service sector and 3 percent in the household sector. This is not necessarily optimal. A higher shadow price leads to lower initial abatement and charge,

Figure 5.6 Charges on fossil fuels as share of energy base price for target df = 5 at T = 50.



and higher abatement activity towards the end of the period. Only the alternative whereby abatement efforts were practically speaking absent at *t=0* were tested. This yielded a lower total utility.

The necessity of testing for alternative initial allocation of abatement efforts follows from the dynamic optimum conditions for the increase in abatement costs, which give individual paths for the abatement of each gas. The life-time of each gas explains some of these differences, but also the marginal abatement cost and implicitly the shadow price of the emissions are decisive. It is, therefore, difficult to say whether abatement of a gas should be advanced or delayed compared with the 'static' assumption. The intertemporal conditions demand that the rate of increase in the abatement is for the short living gases, such as methane. In an intertermporal context, short-lived gases yields a more rapid response to radiative forcing, and thus global warming in the atmosphere. Hence, more emphasis on abatement of methane may contribute to a delay of the policy initiatives, and still enable the target *df = 5* to be achieved. Since a delay of such initiatives in general implies an economic yield, one should probably put more emphasis on the abatement of methane compared with CO_2 and N_2O.

Figure 5.7 shows alternative amounts of direct abatement costs for CO_2 and CH_4 at $t = 0$ which all lead to an achievement of the target *df = 5*. The two bars at the left indicate initial abatement costs when allocated according to the static conditions. Total abatement costs are then 0.89 mill. NOK at $t = 0$, of which more than 0.75 mill NOK are spent on CO_2-abatement. The figure shows that the total costs may be reduced to 0.239 mill. NOK if approximately 0.22 mill. NOK is spent on the abatement of methane. By the end of the period, the annual abatement costs of CO_2 and CH_4 are somewhat higher after the reallocation has taken place.

Nevertheless, the reallocation of initial abatement also yields a welfare surplus. This can be explained by the fact that a small increase in the abatement of CH_4 compensates a large

Figure 5.7 Alternative initial abatement of CO_2 and CH_4 with df = 5.

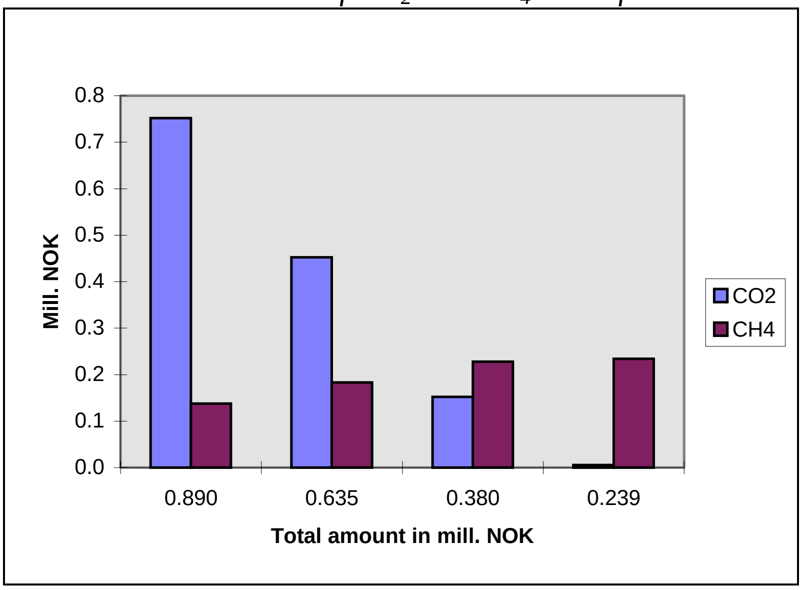
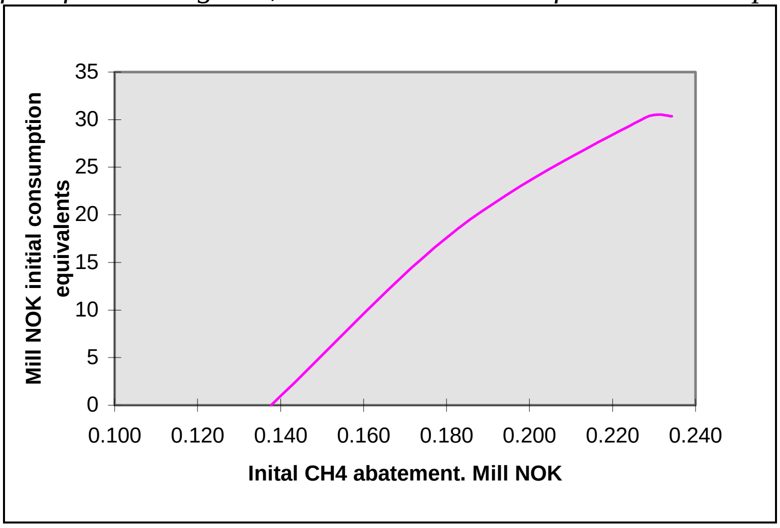


Figure 5.8 Benefits of advancing CH_4 abatement in terms of initial consumption.



decrease in the abatement of CO_2. Figure 5.8 shows the benefit in terms of mill. NOK initial consumption equivalents by carrying out this substitution of initial abatement. The substitution is beneficial up to a point where the abatement of CH_4 is nearly 0.23 mill NOK. At this point abatement of CH_4 constitutes nearly the whole amount of total, initial abatement costs, which is about 0.24 mill NOK. This indicates that it is optimal to start with CH_4 abatement, and use other measures at a later stage. In other words, the comprehensive approach with targets on concentrations seems to allow for a further delay of abatement measures compared with a policy which focuses on emission targets.

One may of course claim that the benefits of a better allocation of initial abatement efforts on gases are extremely small, being less that 30 mill. NOK out of a total consumption of 406 mrd NOK. On the other hand, if we compare this with the amount of initial abatement efforts, which is less than 1 mill. NOK, the effect may be considered substantial. This is mainly due to the different paths of consumption and abatement that are being initialised by the reallocation.

ANNEX

Model:

The model maximises total utility over the period *(0,T):*

$$\max_{x_h,u_h,a_i} \int_{t=0}^{T} B(x_h-\gamma_h)^{\sigma\varepsilon}(u_c-\gamma_u)^{\sigma(1-\varepsilon)}e^{-\delta t}dt$$

subject to the following constraints:

Capital formation equals output in sector 1 less households' consumption of goods and services, total abatement (*i = 1,2,h)* and capital depreciation:

$$\dot{k} = e^{\tau_1 t}(A_1+\alpha_{11}u_1^{\rho_1}+\alpha_{12}k_1^{\rho_1})^{\frac{1}{\rho_1}} - x_h - \sum_i a_i - \Delta(k_1+k_2)$$

Energy supply equals energy demand from commodity and service sector, energy sector and households:

$$e^{\tau_2 t}(A_2+\alpha_{21}u_2^{\rho_2}+\alpha_{22}k_2^{\rho_2})^{\frac{1}{\rho_2}} = u_1+u_2+u_c$$

Concentrations of greenhouse gases declines according to their 'natural' decay rate, increases by emissions, which are considered to increase proportionately due to energy consumption in each sector, but may be abated according to abatement efforts. For gas *i* (*i* = CO_2, CH_4 and N_2O) the following differential equation applies:

$$\dot{c}_i = l_i c_i + \sum_{j=1,2,c}\beta_{ij}u_j - C_i a_i^{\eta_i}$$

Note that β_{ij} includes emission coefficient, a constant that scales national emissions to world emissions and a conversion factor which transforms emissions to concentrations (beta-value). The policy target is expressed in terms of radiative forcing which measures the change in forcing relative to a base year, which is set to *t=0* in the calculations:

$$df_t = 6.3\ln(\frac{c_{CO_2t}}{c_{CO_20}}) + 0.036(c_{CH_4t}{}^{1/2} - c_{CH_40}{}^{1/2}) + 0.14(c_{N_2Ot}{}^{1/2} - c_{N_2O0}{}^{1/2})$$

The results are based on the analytical solution of the model. A set of equilibrium conditions are fulfilled at each point in time. The intertemporal conditions fixes the paths of x_h and a_i (*i* = CO_2, CH_4 and N_2O) from a given starting point. The reference path was found by starting with x_{h0} = observed value and $a_i = 0,\ \forall i$. Alternative paths are compared such as to end up with the same stock of total capital ($k = k_1 + k_2$) at $T = 50$.

Variables and parameters (in order of occurrence)

ENDOGENOUS VARIABLES

x_h	=	Household's consumption of ordinary goods and services
u_h	=	Household's consumption of energy
a_i	=	Abatement costs of greenhouse gas i (i = CO_2, CH_4 and N_2O)
k	=	Total stock of capital
u_1	=	Energy use in commodity and service sector
k_1	=	Stock of capital in commodity and service sector
k_2	=	Stock of capital in energy sector
u_2	=	Energy use in energy sector
c_i	=	Concentration of greenhouse gas i (i = CO_2, CH_4 and N_2O)
df	=	Radiative forcing relative to base year ($t = 0$)

PARAMETERS

B	=	Scale factor for utility
γ_h	=	'Subsistence' level for consumption of commodities and services
σ	=	1 - (Intertemporal elasticity of substitution)
ε	=	Atemporal marginal cost of consumption goods
γ_u	=	'Subsistence' level for energy consumption
δ	=	Pure rate of time preference
τ_1	=	Rate of technology advancement in commodity and service sector
A_1	=	Contribution from labour in commodity and service sector (constant)
α_{11}	=	Distribution parameter for energy in commodity and service sector
ρ_1	=	Indicator for the constant rate of substitution between energy and commodity input in commodity and service sector.
α_{12}	=	Distribution parameter for commodities and services in commodity and service sector
Δ	=	Rate of capital depreciation
A_2	=	Contribution from labour in energy sector (constant)
τ_2	=	Rate of technology advancement in energy sector
α_{21}	=	Distribution parameter for energy in energy sector
ρ_2	=	Indicator for the constant rate of substitution between energy and commodity input in energy sector
α_{22}	=	Distribution parameter for commodities and services in energy sector
l_i	=	Rate of natural decay for the concentrations of greenhouse gas i
β_{ij}	=	Contribution to the concentrations of gas i from one unit of energy use in sector j (emission coefficient)
C_i	=	Initial reduction in emissions from one unit of direct abatement
η_i	=	Elasticity of emission reductions from abatement

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