

Methane emissions and permit prices for greenhouse gases

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The Kyoto Protocol restricts emissions of five greenhouse gases in addition to CO₂. An international permit price for tradable quotas of greenhouse gases will depend on the costs of reducing emissions of all these gases. A cost-effective reduction both nationally and internationally entails that the marginal cost of further reductions must be the same for all measures and all gases in all countries. Methane from landfills is one of the largest sources of emissions besides CO₂. In order to ensure a cost-effective implementation of climate policy, it is necessary to evaluate the costs of the various measures aimed at landfill gases against reductions in other greenhouse gases, and implement the least expensive measures first. Moreover, the total costs of abatement for Norway will depend on those sectors of the economy that might be exempt from cost-effective taxes.

Introduction

Studies that have attempted to provide estimates of the permit price for tradable quotas of greenhouse gases indicate that the inclusion of additional gases in the climate protocol will result in substantially lower permit prices. Methane is the most important greenhouse gas besides CO₂. This means that the cost of reducing emissions of methane may have an important influence on the permit price for greenhouse gases as a whole. In this article, we look more closely at the marginal costs of reducing methane emissions. Methane accounts for about the same proportion of total greenhouse gas emissions in Norway as in the rest of the world, and the importance of methane gas emissions for the permit price in Norway may therefore provide some indication of the importance in other countries.

Many studies show that there are increasing marginal costs associated with reducing greenhouse gas emissions. This means that the stricter the requirements are, the more expensive it is per unit to reduce emissions. This in turn implies that the necessary permit price will depend on perceptions of emission changes without permit prices. With a sharp rise in emissions, the necessary permit price will be relatively higher than in the case with lower growth. Some studies show that analyses made prior to the Kyoto negotiations may have been optimistic with regard to how low emissions would be without restrictions.

In this article we will first look at emissions in Annex B Parties and then cite some studies of international permit prices in connection with emission reductions. We present projections of methane gas emissions in Norway, and ana-

lyze the costs of various measures aimed at reducing these emissions. The importance of including methane in the Kyoto Protocol for permit prices will depend on the change in the marginal costs of reducing emissions of other gases. Three calculations have been made for Norway under different assumptions concerning the possibilities of replacing or reducing the use of fossil fuels both on the supply side and the demand side in the energy market. Using these calculations as a basis, we discuss the degree to which these can serve as an illustration of the permit price which is necessary internationally in order to achieve the targets in the Kyoto Protocol.

Emissions of greenhouse gases

Total emissions of the six greenhouse gases in Annex B Parties came to 16.5 billion tonnes CO₂ equivalents in 1990, see table 1. We see that CO₂ is the dominant greenhouse gas in all countries, with a total share of 83 per cent in 1990, while methane accounted for 13 per cent and nitrous oxide 4 per cent. This indicates that the inclusion of other gases in the determination of permit prices may be of some significance in an initial Kyoto Protocol. The importance, however, may be more limited if the Protocol later includes more restrictive requirements.

The largest countries with regard to greenhouse gas emissions are the US, Russia, Japan and Germany. About 35 per cent of greenhouse gas emissions is generated in the US and just under 20 per cent in Russia. These two countries can thus block an agreement, which requires that the Kyoto Protocol must be ratified by Parties with combined emissions equal to 55 per cent of emissions by Annex I Parties.

Total emissions in most countries increased from 1990 to 1995. Total emissions for the 10 countries explicitly mentioned in table 1 nevertheless declined by 2.3 per cent, pri-

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Table 1. Emissions of greenhouse gases in selected countries of participants in the Kyoto Protocol and total for Annex B. Million tonnes CO₂ equivalents. 1990

	CO ₂	N ₂ O	CH ₄	HFC/PFC/SF ₆	Total	Total 1995 ¹
USA	4 957.0	127.5	567.0	92.2	5 680.2	6 149
Russia	2 388.7	27.8	567.0	..	2 983.5	2 165
Germany	1 014.2	65.4	119.3	20.6	1 205.3	1 065
Japan	1 155.0	17.1	29.0	..	1 201.1	1 347
United Kingdom	577.0	33.6	95.2	2.1	706.3	654
Canada	462.6	29.6	64.8	9.1	559.9	618
France	366.5	54.8	60.8	..	482.1	498
Sweden	61.3	4.7	6.9	1.4	73.4	69
Denmark	52.0	3.2	8.5	0.2	63.9	75
Norway	35.5	4.7	6.1	4.8	47.4	55
Other country	2 605.2	246.2	623.3	9.1	3 483.8	
Total	13 675.1	614.5	2 148.0	139.5	16 486.9	
Share	0.83	0.04	0.13	0.01	1.00	

¹ 1994 for Russia, Japan og Denmark.

Source: Climate Secretariat. There are some differences in these figures and final statistics for the various countries, including Norway, see later overview of Norway's figures. However, this does not alter the overall picture described here. The total figures are the combined figures for those countries that have reported figures to the Secretariat.

marily due to lower emissions in Russia and the other former Eastern bloc countries.

The table indicates that Norway's emissions of greenhouse gases accounted for about 0,3 per cent of total greenhouse gas emissions among participating countries in the Kyoto Protocol as these were reported prior to the negotiations. Norway accounted for a good 3 per cent of emissions of HFCs/PFCs/SF₆ and about 0.8 per cent of nitrous oxide emissions. Norway's emissions of methane accounted for about 0.3 per cent of emissions of this gas in Annex B Parties. A reasonable reduction potential for additional gases will thus have a slightly greater impact for Norway than for Annex I Parties combined. Important sources of methane emissions are livestock and the decomposition of waste. Emissions of nitrous oxide primarily come from the production of fertilizer, where Norway is an important world market participant. Livestock production is also an important source, but in this case Norway is more on a par with other countries throughout the world. Even though Norway has a relatively high share of emissions of HFCs/PFCs/SF₆, the importance of this has declined sharply in recent years with emissions reduced to half in Norway.

We also see that the US accounts for nearly 70 per cent of total emissions of CFCs, HFCs and SF₆. If the US can substantially reduce its emissions of these gases at low costs, this may influence the permit price for the other gases. These emissions, however, do not account for a particularly higher proportion of total emissions in the US than in other countries. The reason, of course, is that the US dominates in the overall picture of emissions by Annex B Parties.

The US, Germany and Japan have a lower proportion of methane emissions than their share for total greenhouse gases. Russia has a substantially higher methane share than

its share for greenhouse gases due to considerable reductions in CO₂ emissions as a result of the economic downturn following the breakup of the former Soviet Union.

This may imply that Russia has a potential for reducing its emissions at low costs in addition to those emissions which have already been reduced, provided that it is less expensive to reduce methane than the other gases. France, Germany, Norway and Sweden have relatively high nitrous gas emissions.

Permit prices for CO₂

Many studies carried out in the early 1990s, prior to the Kyoto negotiations, analyzed the level of taxes or permit prices for CO₂ which would be necessary to stabilize emissions of CO₂ at the 1990 level, globally or within the OECD area. The estimates in these studies, and the underlying assumptions concerning the rise in total emissions, have varied considerably¹, see table 2. There have been two new elements in the development of these studies. The estimates for necessary taxes/permit prices have become increasingly lower, and the increase in base scenario emissions has been steadily reduced. Early international studies in this area were reviewed in the KLØKT project (see Moum 1992). These studies then estimated that the taxes necessary to stabilize emissions ranged between Nkr 700-10 000 per tonne CO₂. The accompanying emission reductions ranged between 20-60 per cent. The KLØKT study assumed that the most realistic estimate was Nkr 1400 per tonne CO₂ with an accompanying reduction in emissions of 35 per cent.

The Green Tax Commission (NOU 1996:9) made use of the OECD's global model GREEN to analyze the consequences of introducing a tax which on a global basis was sufficient to stabilize emissions at the 1990 level in 2010

¹ See, for example, Bye (1997) and Hourcade et al. (1996) for a review of these studies.

Table 2. Estimated tax to achieve stable emissions at 1990 level in 2010, Nkr per tonne CO₂, and projected growth in total greenhouse gas emissions 1990-2010, per cent

	Year of study	Tax	Year	Rise in emissions
SIMEN ¹	1989	1 000	2000	16
Nordhaus	1990	3 325	2020	50
IEA	1990	350	2025	12
ECON	1990	1 400	2000	18
KLØKT	1992	1 400	2025	35
Jorgenson and Wilcoxon (1990)	1990	420	2020	32
Grønn skattekomisjon (NOU 1996:9)	1996	360	2020	45
Energiutvalget (NOU 1998:1)	1998	200	2020	45
St meld nr 29 (1997-98)	1998	50-200	2010	23
Alfsen, Holtsmark og Torvanger (1998)	1998	50-100	2010	6.5
Grubb and Vrolijk (1997)	1998	35-70	2010	6.5

¹ Bye, Bye and Lorentsen (1989).

and maintain emissions at this level until 2030. A tax of Nkr 360 per tonne CO₂ was sufficient to achieve this stabilization, or a reduction in carbon emissions of about 45 per cent compared with the baseline scenario in 2020. With linearity in the effect, this means that each 5 per cent reduction in emissions requires an additional tax of about Nkr 40. Against this background, it is estimated that a 5 per cent reduction in emissions would require a tax of about Nkr 400 per tonne CO₂.

A number of national studies show that relatively strong instruments would be necessary in order to stabilize greenhouse gas emissions in *Norway* from 1990 to 2010-2020.

Calculations carried out by the Energy Commission² indicate that even a tax of Nkr 400, where considerable emission reductions are achieved by subjecting energy-intensive industries to sharply rising electricity prices, will not be sufficient to achieve Norway's Kyoto commitment without buying permits (see later section on tax calculations for the Norwegian economy). Although the costs of reducing emissions in Norway may be high compared with other countries, when disregarding a dramatic adaptation of the structure of industry, these calculations - which include an adaptation of manufacturing - indicate that also in the rest of the world the shadow price of greenhouse gases may be high under the Kyoto Protocol's targets for total emissions. In the Energy Commissions Report, Nkr 200 is used as an illustration of a necessary permit price internationally in order to achieve the Kyoto targets.

Studies referred to in Report no. 29 to the Storting (1997-98) indicate a low international permit price. The report states: *A number of institutions both in Norway and other countries, including CICERO and the OECD, have evalua-*

ted potential permit prices. Under different assumptions the price estimates vary from Nkr 50 to about Nkr 200 per tonne CO₂. References to studies in the report are not precise, but the estimates are primarily based on a study by Grubb and Vrolijk (1997), see Alfsen, Holtsmark and Torvanger (1998). Compared with the Green Tax Commission's analyses and national studies, a price of Nkr 50 seems very low.

The low estimates may be ascribable to several factors: in part the inclusion in the Kyoto Protocol of a number of gases in addition to CO₂, which may be cheaper to reduce, and in part the very slow rise in emissions in the baseline projection. Grubb and Vrolijk (1997), however, *assumes* that a 10-15 per cent reduction of CO₂ emissions and a 30 per cent reduction in other greenhouse gases may occur at no cost. The basis for this assumption is not documented.

Based on the data used in connection with the negotiations, Alfsen, Holtsmark and Torvanger (1998) indicate that total emissions of greenhouse gases by Annex B Parties will rise by 6.5 per cent from 1990-2010. This is very low compared with the OECD study used by the Green Tax Commission where emissions grow by 45 per cent up to 2020. By way of comparison, Norway's second communication to the climate convention indicated an increase in Norway's emissions of 19 per cent from 1990 to 2010, see Alfsen (1998). The Energy Commission indicates a 15 per cent increase in emissions up to 2010 in its baseline scenario, while Report no. 29 to the Storting indicates a 23 per cent increase³. A recent study by Schmalense, Stoker and Judson (1998) shows that projections of global CO₂ emissions, which were used as a basis for the Kyoto negotiations, may be highly underestimated. The emission projections from Schmalense et al. are nearly 25 per cent higher than the IPCC's estimates of emissions for 2020, see also Hourcade et al. (1996).

The marginal cost of reducing greenhouse gas emissions to a stabilization level is very dependent on the level of emissions in the baseline projection, i.e. on how much emissions must be reduced, see e.g. Johnsen, Larsen and Mysen (1997) and Dean and Holler (1992). Underestimated emissions in the baseline projection may thus indicate that the shadow price of greenhouse gases, given the Kyoto Protocol's targets, may be substantially higher than the level suggested by the studies used so far.

Greenhouse gases excluding CO₂ account for 17 per cent of total greenhouse gases in countries participating in the Kyoto Protocol. There is thus reason to assume that the introduction of additional gases, combined with the continued objective of stabilization, may have some bearing on the permit price which will be generated in an international permit market. This particularly applies in an initial phase where a reduction of these gases may constitute a high

² See, for example, Energy and Power Balance in the period to 2020 (NOU 1998:1) as a most recent example of this.

³ It is particularly with regard to CO₂ emissions that the Report to the Storting is considerably higher than those of the Energy Commission.

share of total emission reductions. It is not certain, however, that the importance is considerable. The most important gas next to CO₂ is methane. Due both to its size and the lower potential for reducing other gases, we will in addition to CO₂ focus in particular on methane in the following.

Calculations of methane gas emissions

Methane is the main greenhouse gas besides CO₂, also in Norway. Emissions from agriculture account for 22 per cent of total methane gas emissions, and most of these emissions stem from animal digestion. According to Report no. 29 to the Storting, measures aimed at reducing these emissions are not considered relevant. The methane emissions which are relevant in a climate policy context are thus emissions of gases from landfills, which are estimated at 67 per cent of total methane gas emissions and about 12 per cent of total greenhouse gas emissions in Norway.

There is considerable uncertainty surrounding the quantities of methane that are actually generated at landfills, the quantities that are released, and the effect of burning methane gas. First, there is uncertainty concerning the actual level of emissions. More recent studies indicate that the level may be lower than assumed earlier, partly because methane naturally decomposes into CO₂ on its way out of the landfill. Tests of methane emissions from landfills with a soil cover indicate that methane emissions from Norwegian landfills may be far lower than the level on which earlier calculations have been based (Slyngstad 1998a). With optimal conditions in the top layer of the landfill, the landfill may have negative emissions, since in addition to the methane from the landfill itself it decomposes other methane from the surrounding air.

On the other hand, updated estimates of future economic developments indicate that the *growth* in waste generation is underestimated, with the decline in methane gas emissions thereby overestimated, see below. Another question is the cost of reducing methane gas emissions. New research seems to conclude that methane gas emissions can be reduced using relatively simple means and at low costs. A major Swedish project (Lagerkvist 1998) concerning landfill gas concluded that the problem of landfill gas is highly overestimated and that emissions can be kept at a low level through relatively simple means.

Projections of waste and methane gas emissions in Norway

Earlier projections of municipal waste for Norway in the period to 2010 are based on waste statistics from 1992 (Bruvoll and Ibenholt 1995). The projections are based on an assumption that waste quantities increase with rising production and use of materials. Economic developments

Table 3. Projections of municipal waste, 1 000 tonnes (growth from 1992 in per cent)

	1992 ¹	1995	2010 (new projections)	2010 (previous projections)
Industrial waste	1 135.4	1 460.2	1 773.8 (56)	1 778.9 (57)
Household waste	1 087.4	1 262.0	1 815.1 (67)	1 429.1 (31)
Total	2 222.8	2 722.2	3 588.8 (61)	3 208.0 (44)

¹ Figures for 1992 include 93.6 tonnes of unknown/mixed waste distributed proportionally on industrial and household waste.

Table 4. Projections of total disposed of waste quantities, 1 000 tonnes (growth from 1992 in per cent)

	1992	1995	2010
Municipal industrial waste	862.9	919.9	1 117.5 (29)
Household waste	826.4	795.0	1 143.5 (38)
Other industrial waste	938.0	1 000.0	1 214.8 (29)
Total	2 627.4	2 715.0	3 475.7 (32)

in the macroeconomic model MSG, which is also used for energy and emission calculations, are used as the basis for waste projections⁴. The projections have now been updated using updated waste figures from 1995 and new forecasts for economic developments in MSG⁵, see table 3.

The new projections in table 3 show a far higher growth in waste generation than assumed earlier. Whereas the previous projection showed a rise of 44 per cent in the period to 2010, the current statistics imply that the growth may be a good 60 per cent. This is primarily ascribable to higher growth in registered quantities of household waste in recent years, and thus higher waste generation per consumption unit than assumed earlier. As much as 23 per cent of the previously estimated growth of 44 per cent was reached in the period 1992-1995. Moreover, new projections of macroeconomic developments contribute to changes in waste generation in the various sectors. Industrial waste is expected to show a lower growth from 1995 compared with earlier projections.

In the Norwegian Pollution Control Authority's forecasts, industrial waste, excluding municipal waste assumed to be about 1 million tonnes (Norwegian Pollution Control Authority 1988). We use this estimate for 1995, and assume that the quantities change in pace with municipal industrial waste.

Table 4 shows estimates of future *quantities of landfilled waste* which follow from projected waste quantities. In 1992, 76 per cent of municipal waste was disposed of in

4 See Bruvoll and Ibenholt (1997) for a description of the model.

5 The economic projections largely correspond to the calculations used as a basis by the Energy Commission.

Table 5. Potential methane emissions in millions of tonnes (CO₂ equivalents)

Methane potential kg methane/tonne waste	1992	1995	2000	2010
83 (Holdhus 1998)	0.218 (4.6)	0.205 (4.3)	0.213 (4.5)	0.218 (4.6)
130 (St meld nr 29)	0.342 (7.2)	0.321 (6.7)	0.333 (7.0)	0.341 (7.2)
<i>Memo: St meld nr 29</i>	1990 0.302 (6.3)	1996 0.327 (6.9)		2010 0.248 (5.2)

landfills, whereas the share was 63 per cent in 1995 (Statistics Norway 1994, 1988). We assume an unchanged landfill rate from 1995-2010 for both municipal waste and other industrial waste. This means that additional measures aimed at a higher percentage of materials and energy recovery will result in corresponding reductions in landfill.

Given these assumptions, landfilled quantities show a rise of 32 per cent from 1992 to 2010. These figures provide a basis for new projections of methane emissions. Methane is emitted over a period of many years following disposal, and emissions and the timing of these will depend on dampness, disposal method, cleaning technology, etc. The methane potential, the total future potential quantity of methane from disposed of waste in one year, will differ from actual annual emissions, which arise from the waste quantities of the previous year and earlier years. There is also considerable uncertainty associated with this methane potential. Report no. 29 to the Storting points out that a project has been initiated to evaluate the level of methane gas from landfills in Norway, and various studies will be compared.

The estimates for methane emissions in Report no. 29 to the Storting are based on an assumption of 130 kg methane per tonne waste. This report refers to calculations from the Norwegian Pollution Control Authority which show 100 kg methane per tonne waste. Studies carried out by the Centre for Soil and Environmental Research indicate an even lower methane potential. According to Holdhus (1998), maximum emissions might be 83 kg methane per tonne waste. In order to illustrate the uncertainty in the figures, we present calculations based on the assumptions applied in both the Report to the Storting and by the Centre for Soil and Environmental Research (Holdhus).

It is assumed that the proportion of landfilled waste in facilities with methane recovery systems rises from 45 to 70 per cent. Moreover, it is assumed that the burning effect of the facilities rises from 20 to 35 per cent in the period 1995 to 2010 (cf. Report no. 29 to the Storting). This means that we assume that 25 per cent of the methane gas from waste which goes to landfills in 2010 will be burned. Table 5 shows the potential methane emissions in excess of what is burned under different assumptions on the methane potential. Under Holdhus' assumptions on maximum methane emissions, the emissions are far lower than assumed earlier.

The new projections result in higher emissions than in the Report to the Storting for different assumptions on the met-

hane potential. The deviation is primarily ascribable to the fact that the Report to the Storting assumes that additional recycling/recovery measures will reduce disposed of waste quantities in 2010, an assumption which is not made in our projections. We will now instead evaluate the costs of several measures, including recycling (composting of wet organic waste).

Costs of reducing methane

Reduced quantities of organic waste for disposal will contribute to lower methane emissions. The actual methane gas which arises can also be burned so that the gas is converted into CO₂ (which has a far lower climate effect). Moreover, during methane oxidation microorganisms can convert methane into CO₂ when the gas on its way to free air passes through a layer of soil/bark with a certain organic composition.

The potential for reducing methane through other methods than burning is 4.6-7.2 million tonnes CO₂ equivalents in 2010, depending on the methane potential (see table 5). Our figures on costs indicate that methane can be reduced at relatively low marginal costs (see table 6). It is likely that the marginal cost rises with the share of methane that is reduced, and it is uncertain when the marginal cost exceeds the marginal cost of CO₂ reductions. Even though it appears that methane can initially be reduced relatively cheaply, it is thus not certain that it is profitable to make use of the entire potential.

Materials recovery

A main strategy for the Government for reducing methane emissions is to initiate an increase in the proportion of waste that is recycled. Report no. 29 to the Storting refers to agreements on recycling packaging waste that have been entered into with the business sector and consumer waste in municipalities.

Composting wet organic waste is one possible policy for increasing the rate of recycling. Several counties have introduced a ban on the disposal of wet organic waste. A recent study by InterConsult ASA (1998), based on the composting of wet organic waste in the county of Sogn og Fjordane, indicates that composting provides few climate gains compared with the social costs, see table 6. Their figures show that the costs per tonne CO₂ will range between NKr 1150-1300 per tonne CO₂. As pointed out by Bruvold

(1998a), the recycling of materials in many cases may be a costly alternative to waste treatment, which indicates that more cost-effective measures for reducing methane gas emissions should be evaluated.

Waste incineration

Increased waste incineration will also reduce emissions of landfill gases. The power market is decisive when evaluating incineration for energy purposes versus disposal. In the baseline scenario in the Energy Report, gas-generated power is the marginal energy source in the long term. An increased supply of energy from waste incineration will not alter the marginal cost of electricity within the current interval of 25 TWh for gas-generated power in the Energy Report's baseline scenario. Energy from waste will therefore replace gas-generated power instead of increasing total electricity consumption. For fossil waste materials, such as plastic, this means that the climate effect of CO₂ from plastic waste is reduced substantially, and that burning paper through reduced gas consumption contributes to lower greenhouse gas emissions.

The costs of incinerating paper and plastic waste can illustrate the costs of waste incineration as a climate policy instrument. Because some of the statistics are based on foreign data, they should only be used as an indication of Norwegian conditions.

The costs for paper and plastic (including environmental costs but excluding climate costs) are estimated on the basis of Bruvoll (1998a). If the greenhouse gas saving is taken into account, the incineration of *paper* (instead of disposal without methane burning) may result in greenhouse gas reductions to about NKr 50 per tonne CO₂ (about NKr 60 if it is not assumed that the energy replaces gas-generated power).

Plastic at landfills decomposes very slowly, while CO₂ is released immediately with incineration. In a market where the marginal energy source is based on non-fossil fuels, the incineration of plastic does not appear to be a relevant climate policy instrument. However, under the Energy Commission's assumptions concerning the power market, the cost per tonne CO₂ will be negative for plastic incineration compared with disposal as incineration entails lower econo-

Table 6. Costs of reducing methane gas emissions in NKr per tonne and reduction potential in millions of tonnes CO₂ equivalents

Measure	Cost
Composting wet organic waste	1 150 - 1 300 NKr
Waste incineration	Paper: 50 NKr Plastics: negative
Burning methane	Paper: about 60 NKr Plastics: about 400 Nkr
Methane oxidation	20 - 50 NKr

mic costs. In addition, there is a positive climate effect in that the organic material replaces other emissions, something which only partially takes place for the methane gas that is burned at landfills. Plastic, however, accounts for only a small share of total waste quantities, and plastic incineration therefore represents a limited potential for greenhouse gas reductions.

Reduced waste generation

Another way to reduce the landfilled waste is to promote waste minimization. Possible instruments in this connection are taxes which in various ways provide an incentive to reduce the use of materials which sooner or later end up as waste. For example, municipalities have been urged to use differentiated waste fees in order to encourage a reduction in the quantity of waste for final treatment. These appeals have not been sufficient to influence waste quantities, since the waste fees provide no reward for lower waste production by households (Hass 1997). The final treatment fee for waste can also promote reduced waste generation.

Taxes to reduce waste generation may result in a lower level of waste disposal, but will also result in costs for other sectors of the economy. Bruvoll (1998b) shows that a general tax on raw materials (paper and plastic) not only reduces waste quantities but also other environmental discharges. The total environmental gain, which primarily stems from emissions other than those from the waste sector, is higher than the costs in the form of reduced production and consumption. The greenhouse gas effect, however, is unclear. A tax on the use of materials is an indirect instrument in relation to landfill gases, and relatively high taxes are probably necessary to produce a relevant effect on greenhouse gases alone.

Methane burning

Today 40-50 per cent of the waste is disposed of at landfill sites with methane burning. In Report no. 29 to the Storting it is assumed that most larger landfills will have installed gas recovery systems in the course of 1999 and that about 70 per cent of the waste disposed of annually will then be placed in landfills with gas recovery facilities. Existing technology captures about 20 per cent of methane emissions from facilities with methane burning, and it is assumed that the effect in 2010 can increase to 30-40 per cent. According to Bruvoll (1998b), it will be possible to achieve greenhouse gas reductions to about NKr 60 per tonne CO₂ for paper waste, assuming that methane burning replaces fossil fuels (NKr 70 per tonne if the energy does not replace fossil fuels). For plastic waste, the methane gas emissions are small due to low degradability, and the cost is thereby relatively high, about NKr 400 per tonne CO₂.

Methane oxidation

The covering layer of landfills which initially has been placed there for aesthetic reasons has proven to function as an oxidation layer for some of the methane that is formed

at landfills. An optimal covering layer consists first of a porous material which distributes the methane gas equally before it passes through the oxidation layer. The oxidation layer shall provide favourable conditions for methane-oxidizing microorganisms. Experiments are under way where a compost of bark and sewage sludge appears to be promising (Slyngstad 1998b)⁶. When conditions permit safe gas handling, the emissions of methane during landfilling do not have to be very high. The method is relatively new and is being tested, and the effect of the method is therefore uncertain.

Methane oxidation may be less expensive than methane burning. Slyngstad (1998a) maintains that a medium-sized municipality can save a total of NKr 4-7 million (investment and operating expenses) using methane oxidation instead of methane burning. Holdhus (1998) estimates the cost of the covering layer, including purchases and the spreading of materials to which nutrients have been added, at a maximum NKr 1200 per cubic metre. However, for suitable waste, such as garden waste/demolition refuse with nutrient-rich sewage sludge added, the cost in practice will be eliminated for the material itself, and the cost will be linked to the actual costs of mixing and spreading, estimated at NKr 200-300 per cubic metre. With a landfill of 10 metres and with a covering layer of 0.5 metre at a cost of NKr 1200 per cubic metre, the cost of reducing methane will vary between NKr 25 and 45, measured per tonne CO₂ equivalents. These relatively low figures for costs are supported by other studies. In an extensive review of the literature concerning landfill gases, Haarstad (1998) concludes that methane gas emissions from landfills can be reduced or even eliminated using relatively simple techniques for methane oxidation.

The figures on costs (NKr 25 and 45 per tonne CO₂ equivalents) presuppose a methane potential of 130 and 83 kg, respectively, per tonne waste, see table 5. This means that the higher the methane potential is, the higher will be the share of greenhouse gas reductions that can be achieved on the waste side and at even lower costs per tonne. However, if

the methane potential and the problems associated with methane are overestimated, as is argued by a number of observers, the greenhouse gas reductions that can be achieved through landfills will be lower and the cost per unit higher.

Calculations of taxes for the Norwegian economy

We showed in table 1 that methane accounted for about the same share of total greenhouse gas emissions in Norway as in other Annex I Parties. The importance of including methane in the Kyoto Protocol will depend on the change in the marginal costs of reducing emissions of other gases. In connection with the Energy Commission's report, Statistics Norway made some calculations of the consequences for the Norwegian economy and greenhouse gas emissions as a result of the introduction of different tax levels for CO₂ in Norway (Bye, Johnsen, Aune and Hansen 1998). In the following we discuss three calculations from this study, where we analyze the effect of an international permit price of NKr 200 under different assumptions concerning exemptions and targets for emission reductions, see table 7. We also make some evaluations of which of these are likely to be the most comparable with other countries on average.

Emissions of greenhouse gases in the *baseline scenario* in the Energy Commission based on new projections of methane emissions are lower than indicated by Report no. 29 to the Storting. Emissions of greenhouse gases rise by a good 22 per cent from 1990 to 2020. Emissions of CO₂ show a particularly sharp rise (40 per cent). According to the revised estimates, emissions of methane decline slightly, particularly in relation to the current level. CO₂ thus accounts for a steadily rising share of total greenhouse gas emissions. If the same applies to other countries, this may imply that a reasonable reduction in emissions of other gases are offset by a sharp rise in CO₂ emissions. This also indicates that with any stricter requirements in the Kyoto Protocol at a later time, the marginal cost of CO₂ reduc-

Table 7. Norway's greenhouse gas emissions in different scenarios, millions of tonnes CO₂ equivalents

	1990	1996	2000			
			Reference	Cost Effective	Industry exempt	Stricter requirements
CO ₂	35.5	41.1	49.8	39.5	42.1	38.4
Methane ¹	9.3	7.7	7.8	7.7	7.7	7.7
N ₂ O	5.7	5.6	5.3	5.3	5.4	5.3
Other gases	4.7	2.1	4.5	4.5	4.5	4.5
Total	55.1	56.5	67.4	57.0	61.1	55.9

¹ Total quantities of methane from landfills and other sources. 1990 figures from Statistics Norway (1998). Based on the new projections of waste quantities, the methane forecasts differ from those presented in the Energy Report. A methane potential of 83 kg/tonne waste is assumed, see table 5. The methane potential is very uncertain.

⁶ Experiments with other masses are being planned in a joint project between the Institute of Soil and Water Studies at the Norwegian College of Agriculture and Hjeltnes COWI.

tions will be of greater importance to the permit price for greenhouse gases.

In the *cost-effective* scenario, it is assumed that all CO₂ emissions in Norway are subject to a tax of Nkr 200 per tonne. This means that those sectors which today have a tax higher than Nkr 200 will see a reduction in their tax, while those sectors which have a lower tax or are exempt from the tax will experience a rise in the tax. The macroeconomic calculations then showed virtually unchanged economic growth. Emissions of greenhouse gases are reduced by nearly 10 million tonnes, or 21 per cent, which results in an increase in greenhouse gas emissions from 1990 of about 3.5 per cent. The main reason for the sharp reduction is that in the baseline scenario there is a relatively large element of gas-generated power with sizeable CO₂ emissions, whereas gas-generated power will not be profitable in the cost-effective scenario. The demand for energy will be covered through slightly greater hydropower development. The greatest effect, however, comes through the reduction in electricity consumption, particularly in power-intensive manufacturing sectors, which will face higher electricity prices.

A reduction in methane emissions by an estimated 50 per cent in relation to table 7 will mean a further reduction of about 3.8 million tonnes. Total emissions in 2020 will then be about 3.5 per cent lower than the 1990 level. This may indicate that a permit price of Nkr 200 will be too high to achieve an international reduction of 5.2 per cent, as it is common to assume that it is more expensive to reduce emissions in Norway than the average internationally. On the other hand, the cost-effective scenario reflects a situation with relatively large substitution possibilities in the Norwegian economy, both on the supply side for electricity (hydro and other renewable sources versus gas) and on the demand side for electricity (power-intensive manufacturing industry is reduced sharply). Substantial substitution possibilities entail low marginal costs for reducing greenhouse gas emissions.

If *power-intensive manufacturing sectors are exempt* from taxes on greenhouse gases, the reduction in emissions will be smaller (see manufacturing exempt in table 7). Emissions, however, may still be reduced by a considerable margin with the elimination of gas-generated power. Electricity is instead imported from other countries. Changes in emissions in these countries will depend on their climate policy. Here it has been assumed that all countries introduce a tax of Nkr 200 per tonne CO₂. With a 50 per cent reduction in methane emissions, Norway's emissions will rise by 4 per cent from 1990. This is a situation where substitution possibilities on the demand side are considerably less than in the cost-effective scenario, but where there are still substantial substitution possibilities on the supply side for electricity.

If it is more expensive to reduce emissions in Norway than in other countries, one can conclude that an international permit price may be lower than Nkr 200 per tonne CO₂,

assuming that the targets in the Kyoto Protocol are to be achieved. However, it is far from certain that the assumption of cheaper adaptation in other countries is correct with the high level of gas-generated electricity included in the baseline scenario and with the considerable substitution possibilities on the demand side which are assumed in one of the scenarios. It is therefore interesting to see what can be achieved at the margin in Norway without including gas-generated electricity. In the scenario involving *stricter requirements in the Kyoto Protocol* a cost-effective tax of Nkr 400 has been introduced. This can illustrate a situation where gas-generated electricity is excluded - it is eliminated with a tax of Nkr 200 - but where there is still considerable flexibility on the demand side in that a large proportion of power-intensive manufacturing sectors are still included. We see that in this case total greenhouse gas emissions are only reduced by about 1 million tonnes in relation to the cost-effective scenario with a tax of Nkr 200.

It is not obvious that it is considerably more expensive to reduce emissions of greenhouse gases in Norway than in other countries in the long term. First, gas-generated power will be replaced relatively easily by alternative technology with taxes on greenhouse gas emissions. Second, we make it unnecessarily expensive to eliminate greenhouse gas emissions in Norway by sheltering large parts of the economy from the costs of emissions. With considerable substitution possibilities, a permit price of about Nkr 200 per tonne CO₂ equivalents will be close to the permit price necessary for achieving stabilization or a 5 per cent reduction in greenhouse gas emissions. This particularly applies if methane can be reduced by a considerable extent at a cost which is lower than this. Fewer substitution possibilities, however, result in substantially higher costs or a substantially smaller effect on emissions with the same permit price.

Summary

There is considerable uncertainty concerning the international permit price which is necessary to achieve the Kyoto Protocol's emission targets. The marginal costs of various pollutants in Norway in the period ahead are therefore also uncertain. Many early studies have calculated relatively high costs for stabilizing CO₂ emissions internationally. The Kyoto Protocol, however, has introduced additional gases, and more recent studies indicate very low costs for stabilizing *total* greenhouse gases. This is also indicated in Report no. 29 to the Storting.

There are two new elements in more recent studies. First, the projection in the baseline scenario shows lower emissions than earlier. Moreover, it is assumed that gases other than CO₂ can be reduced considerably and at low costs. This particularly applies to methane, which is the largest of these.

More recent projections for Norway show that municipal waste quantities are rising at a faster pace than assumed earlier. At the same time, methane emissions from landfills may be overestimated, and the importance of methane in a

greenhouse gas context may be somewhat less than previously estimated for Norway.

Based on Norwegian analyses, there is also reason to assume that methane emissions can be reduced substantially at relatively low costs. This may result in low permit prices in the short term. In the longer term, it is conceivable that stricter emission requirements will be introduced, thereby resulting in higher permit prices. CO₂ will then be of greater relative importance to the permit price in relation to other gases.

Recent projections of global emissions show a substantially stronger increase in emissions than assumed prior to the Kyoto negotiations. The baseline calculations for emissions in the years ahead will be decisive for how high permit prices in the tradeable permit market will be given the restrictions on emissions stipulated in the Kyoto Protocol.

Calculations for two "worlds" - one with considerable and one with limited substitution possibilities - indicate very different necessary permit prices for achieving stable emissions of greenhouse gases. It is not certain that Norway in every respect is an expensive country in which to reduce greenhouse gas emissions. On the contrary, there are elements on the supply and demand side which may indicate that it is inexpensive to reduce emissions in Norway. It is argued that an international permit price of Nkr 200, which is used in the Energy Report, may be a good illustration of what will be necessary to achieve the Kyoto Protocol's emission targets internationally.

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