

# The trade-off between short- and long-lived greenhouse gases under uncertainty and learning

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**Tittel: The trade-off between short- and long-lived greenhouse gases under uncertainty and learning**

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**Samandrag:** I ein optimal klimapolitikk må ein fordele utsleppskutta over fleire klimagassar. Det er stor uvisse knytt til framtidige skader av klimaendring, men vi vil lære meir dei neste tiåra. Klimagassane har ulik levetid i atmosfæren, noko som medfører at like store utslepp av ulike gassar har ulik klimaeffekt. Slike skilnader er viktige med tanke på uvisse og læring om framtidig skade, men den vanlege Global Warming Potential metoden ser bort frå dei. Vi har utvikle ein numerisk modell for å analysere korleis uvisse og læring påverkar dei optimale utsleppa av både CO<sub>2</sub> og CH<sub>4</sub>. I modellen fører utslepp av desse gassane til global temperaturstigning og produksjonstap i økonomien. Ny informasjon om kor alvorleg klimaskadane er kjem i 2010 og 2020. Vi finn at uvisse fører til reduserte utslepp for begge klimagassar samanlikna med tilfellet med sikker kunnskap om klimaskadane. Denne effekten fører til 0,08 °C mindre forventa temperaturstigning i 2200. Læring fører til mindre utsleppskutt for begge gassar fordi forventa framtidig marginal skade av utsleppa er redusert. Denne effekten er noko mindre for den kortliva CH<sub>4</sub>.

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**Abstract:** To find an optimal climate policy we must balance abatement of different greenhouse gases. There is substantial uncertainty about future damages from climate change, but we will learn more over the next few decades. Gases vary in terms of how long they remain in the atmosphere, which means that equivalent pulse emissions have very different climate impacts. Such differences between gases are important in consideration of uncertainty and learning about future damages, but they are disregarded by the conventional concept of Global Warming Potential. We have developed a numerical model to analyze how uncertainty and learning affect optimal emissions of both CO<sub>2</sub> and CH<sub>4</sub>. In the model, emissions of these greenhouse gases lead to global temperature increases and production losses. New information about the severity of the climate problem arrives either in 2010 or in 2020. We find that uncertainty causes increased optimal abatement of both gases, compared to the certainty case. This effect amounts to 0.08 °C less expected temperature increase by year 2200. Learning leads to less abatement for both gases since expected future marginal damages from emissions are reduced. This effect is less pronounced for the short-lived CH<sub>4</sub>.

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# 1 Introduction

Most cost-benefit studies of climate policy discuss options to reduce only emissions of  $\text{CO}_2$  (carbon dioxide) to achieve specified emission targets or to mitigate damage from climate change. The Kyoto Protocol includes, however, five gases or groups of gases, for which emission cuts are counted as means to meet the commitments of the Parties. Three of them,  $\text{SF}_6$ , PFCs and HFCs, are greenhouse gases emitted mainly from industrial processes. According to the IPCC, they contributed to approximately 2 percent of the global emissions of greenhouse gases in 1990, calculated in  $\text{CO}_2$ -equivalents. The other two,  $\text{CH}_4$  (methane) and  $\text{N}_2\text{O}$  (nitrous oxide) are emitted from different sources and contribute 20 and 9 percent, respectively, of total emissions. Although not nearly as important as  $\text{CO}_2$ , measures to reduce emissions of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , in particular, may turn out to be vital if the costs are to be kept moderate.

If the potential for reducing emissions of greenhouse gases other than  $\text{CO}_2$  is large, efficient (and cost-effective) policies to mitigate climate change may clearly be affected by the way emissions of different gases are compared. Unfortunately, there is no single answer as to how this comparison should be carried out. The main problem is that the time it takes before a pulse emission of a given gas has lost its impact on the radiative forcing in the atmosphere varies greatly among the gases. For example, it takes 100 to 200 years before the concentration of emitted  $\text{CO}_2$  is reduced to 1/3, as compared to only 12 years for  $\text{CH}_4$ . The comparison of a ton of  $\text{CO}_2$  emitted with a ton of  $\text{CH}_4$  therefore depends critically on how the future forcing of a gas is evaluated compared with the present forcing.

Over a period of, say, 20 years into the future, the knowledge about damages from global warming may have improved considerably. Over the same period, most of the radiative forcing from a ton of  $\text{CH}_4$  emitted has disappeared, while most of the forcing from a ton of  $\text{CO}_2$  still remains in the atmosphere. The fact that  $\text{CO}_2$  remains in the atmosphere long after new information has arrived may considerably affect the optimal policy if the aim is to control radiative forcing rather than emissions. With substantial uncertainty about future damages, and especially with more information about these damages arriving over the next decades, emission of a ton of  $\text{CH}_4$  is simply not equivalent to the emission of 21 tons of  $\text{CO}_2$ , which is the equivalent amount calculated from the Global Warming Potential (GWP) value of  $\text{CH}_4$  recommended by IPCC (1996). Converting emissions of other greenhouse gases into tons of  $\text{CO}_2$  equivalents by means of GWPs, as prescribed in the Kyoto Protocol, may thus lead to suboptimal policies.

This paper aims at a better understanding of how to balance abatement of various gases under uncertainty. We limit the focus to  $\text{CO}_2$  and  $\text{CH}_4$ , partly because they represent the largest contributions to greenhouse gas emissions, and partly because their lifetimes are significantly different.

In the next section we discuss optimal abatement of alternative gases in a very simple two-period model to get some sense of the structure of the problem. Section 3 presents a more elaborate empirical model. Numerical simulations using this model are presented in section 4. Much of the basic structure of the simple model reappears in the more elaborate model, but as the model is much more complex, so are the results. Section 5 concludes the paper.

## 2 Optimal abatement of different gases under uncertainty

To gain some insight into the basic structure of the problem, we consider a stylized model with only two periods. Emissions in period  $t$  of CO<sub>2</sub>,  $y_t$ , and CH<sub>4</sub>,  $x_t$ , causes damages  $D_t$  where:

$$D_1 = a \exp(y_1 + x_1)$$

$$D_2 = a \exp(y_1 + y_2 + x_2)$$

and benefits

$$B_1 = -\exp(-y_1) - \exp(-x_1)$$

$$B_2 = -\exp(-y_2) - \exp(-x_2)$$

The damages depend on the uncertain coefficient  $a$ . Only the expected level  $E(a) = \bar{a}$  is known when the emissions in the first period are determined. The uncertainty is fully resolved in the second period, where the true value of  $a$  is known.

We solve the problem using dynamic programming, starting from the last period.

Since  $a$  then is known, the optimization problem of the second period is thus:

$$V(y_1) = \max_{y_2, x_2} [-\exp(-y_2) - \exp(-x_2) - a \exp(y_1 + y_2 + x_2)].$$

Solving the first order condition we find:

$$x_2 = y_2 = \frac{-1}{3} [\ln(a) + y_1].$$

Inserting this solution back into  $V(y_1)$  we find:

$$V(y_1) = -3\sqrt[3]{a} \exp\left(\frac{1}{3}y_1\right)$$

In the first period  $a$  is yet unknown, so the problem then is:

$$\max_{x_1, y_1} [-\exp(-y_1) - \exp(-x_1) - E[a \exp(y_1 + x_1) - V(y_1)]] .$$

The first order condition for this problem gives:

$$\begin{aligned} x_1 &= -\frac{1}{2}(\ln \bar{a} + y_1) \\ \exp(-y_1) &= (\sqrt{\bar{a}})^{-1} \exp\left(\frac{1}{2}y_1\right) + E\sqrt[3]{a} \exp\left(\frac{1}{3}y_1\right) \end{aligned}$$

Given  $Ea = \bar{a}$ , how will increased uncertainty about  $a$  affect  $y_1$ ? In the last equation, the left hand side is decreasing in  $y_1$  while the right hand side is increasing in  $y_1$ .

By Jensen's inequality:

$$E\sqrt[3]{a} < \sqrt[3]{\bar{a}}$$

Hence increased uncertainty induces a negative shift on the right hand side and no shift on the left hand side. Thus increasing uncertainty increases  $y_1$ , and as a consequence reduces  $x_1$ .

To understand the background for this result, note first that uncertainty as such has no effect in this model. If  $a$  is equally uncertain in the second period, the model is formally identical to one with certain  $a = \bar{a}$ . The effect of uncertainty is thus due to learning. Note further that the damages from first-period  $\text{CH}_4$  emissions occur only in the first period. Hence, whether or not the uncertainty is resolved in the second period, it does not affect marginal benefits or damages from  $\text{CH}_4$  emissions. For first-period  $\text{CO}_2$  emissions, on the other hand, the damages occur in both periods, and hence marginal damages are affected by the resolution of uncertainty. The more we know in the future, the better decisions we will be able to make. This is shown by the

adjustment of  $y$  following the reduction of expected future damage when uncertainty is resolved. Reduced marginal damages and unchanged marginal benefits imply increasing emissions. On the other hand, current damages are increasing in total emissions,  $y_1 + x_1$ . When  $y_1$  increases, marginal damages of  $x_1$  increase and hence optimal CH<sub>4</sub> emissions drop.

The structure of this model reflects the difference in lifetimes of the two gases. But CH<sub>4</sub> actually has a non-zero lifetime and the model consequently oversimplifies the difference. At the other extreme, when second-period damages are:

$$D_2 = a \exp(x_1 + y_1 + x_2 + y_2)$$

we find that increased uncertainty implies increased first-period emissions of both gases. The intermediate cases, e.g. with:

$$D_2 = a \exp(bx_1 + y_1 + x_2 + y_2)$$

for some  $0 < b < 1$ , are more realistic but harder to solve analytically. Intuitively, we would expect that  $y_1$  will increase and emissions of CH<sub>4</sub>  $x_1$  may increase or decrease depending on the size of  $b$ . The size of  $b$  is an empirical question. With this conclusion, we now turn to the analysis of the numerical model.

### 3 The model

The model applied in this study is an extension of the model in Kverndokk (1994). Total output depends on energy use, which again is related to CO<sub>2</sub> emissions. Potential GDP, denoted  $P$  (GDP with no damages from climate change), consequently is a function of

emissions  $e$ :

$$P(e) = AE^\gamma - p\mu e - a(M - m)^\xi \quad (1)$$

$$E = [(\mu e)^\rho + z^\rho]^{1/\rho} \quad (2)$$

Here  $e$  denotes emission levels,  $\mu$  converts emissions to amount of fossile energy, and  $z$  denotes alternative (emission free) energy (measured in oil equivalents). Total energy  $E$  is a CES aggregate of fossil energy  $\mu e$ , and alternative energy  $z$ . The term  $\gamma$  is the output elasticity of energy, while  $p$  is the energy price, and  $A$  represents the exogenous elements in the production function, like real capital and labour supply. The expression  $a(M - m)^\xi$  is the abatement cost function, where  $M$  represents baseline emissions and  $m$  is the actual emissions of CH<sub>4</sub>. The terms  $a$  and  $\xi$  are parameters.

The world is divided into seven countries or regions: USA, Europe, Rest of OECD (ROE), Former Soviet Union (FSU), China, India and Rest of the world (ROW). Each region comprises countries that to some extent have similar economic structures and level of development. This allows for a more precise economic model. The parameters may vary across regions because various energy sources are not equally important in each region, while changes over time may be due to technological progress and changing availability of the various energy sources.

The parameters are chosen to produce “business as usual” (BAU) paths of optimal emission and corresponding production levels (meaning that possible damage from climate change is disregarded) consistent with those of the IPCC scenario IS92a (IPCC (1992)).



Following Kverndokk (1994), the production is reduced by a factor determined by the increase in the mean global temperature since pre-industrial time,  $T$ . Actual GDP is:

$$Y = \left[ 1 - K \left( \frac{T - T_{1990}}{\Lambda - T_{1990}} \right)^\phi \right] P.$$

note that with  $T = \Lambda$ , then  $Y = (1 - K)P$ , and  $K$  is therefore the relative GDP reduction due to climate change at temperature increase  $\Lambda$ . Following Kverndokk,  $\phi = 1.3$ . There is uncertainty about the size of  $K$ , but we learn about the value of  $K$  as time passes. We assume that a 3 °C temperature increase reduces GDP by 1.3% (see Kolstad (1994)). For this reason,  $\Lambda$  is chosen to be 3 in our model.

We want to maximize the expected utility of the total global production over a given time horizon. Although we do not know the factor  $K$ , we have initial probabilities for the damage scenarios, and these probabilities are later updated through a learning process. (See the next section.)

### 3.1 The climate model

Since the only control variable in this setting is the level of carbon emissions, we take other greenhouse gas emissions to be exogenous variables. We include carbon emissions from deforestation, cement production, etc. In addition to this, we consider the two most important greenhouse gases after CO<sub>2</sub>, namely CH<sub>4</sub> and N<sub>2</sub>O. Again we follow the IPCC IS92a scenario.

The calculations proceed through three steps. First, from the emissions we compute the atmospheric concentration of the gases. For CO<sub>2</sub> we follow Hasselmann et al.

(1997), using a weighted average of different mean lifetimes, ranging from infinite to 1.6 years. The weights are given as:

Lifetime	$\infty$	258.5	71.9	17.6	1.6
Weight	0.07	0.648	0.101	0.097	0.084

For atmospheric concentrations of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ , we assume mean lifetimes of 12 and 120 years, respectively.

Given concentrations  $w$ , we compute radiative forcing  $F$  at time  $t$  (IPCC (1997)):

$$\begin{aligned}
 F_{\text{CO}_2}(t) &= 6.30 \ln \left( \frac{w_{\text{CO}_2}(t)}{w_{\text{CO}_2}(t_0)} \right) \\
 F_{\text{CH}_4}(t) &= 0.036 \left( \sqrt{w_{\text{CH}_4}(t)} - \sqrt{w_{\text{CH}_4}(t_0)} \right) \\
 F_{\text{N}_2\text{O}}(t) &= 0.14 \left( \sqrt{w_{\text{N}_2\text{O}}(t)} - \sqrt{w_{\text{N}_2\text{O}}(t_0)} \right).
 \end{aligned}$$

where  $t_0$  denotes preindustrial time (1750). We also take into account the radiative forcing from sulphur,  $F_S$ . Emissions of sulphur are taken to be exogenous in the model.

The radiative forcing from sulphur is:

$$F_S(t) = \frac{e(t)}{e(1990)} F_{dir.S}(1990) + \frac{\log(1 + e(t)/e_{nat})}{\log(1 + e(1990)/e_{nat})} F_{indir.S}(1990) \quad (3)$$

where the first right hand side component is the direct radiative forcing and the second component is the indirect radiative forcing from sulphur particles (Fuglestvedt and Bernsten (1999)). The term  $e(t)$  is the release of sulphur particles in year  $t$  measured in TgS per year,  $e_{nat}$  is natural sources of sulphur (equal to 42 TgS per year), and  $e(1990)$  is sulphur release in 1990 (equal to 76 TgS (IPCC (1994))). The term  $F_{dir.S}(1990)$  is

direct radiative forcing (equal to  $-0.3 \text{ W/m}^2$ ), and  $F_{indirS}(1990)$  is the indirect radiative forcing in 1990 (equal to  $-0.8 \text{ W/m}^2$ ). The total radiative forcing now becomes:

$$F(t) = F_{CO_2}(t) + F_{CH_4}(t) + F_{N_2O}(t) + F_S(t)$$

where the sign of  $F_S(t)$  is negative due to the cooling effect of sulphur in the atmosphere.

Finally, we find the temperature increase from the formula (Hartmann (1994)):

$$T = \int_{t_0}^t c^{-1} F(t) e^{-(t-t')/\tau_R} dt'$$

where  $c$  is the heat capacity of sea water, equal to  $3.15 \times 10^8 \text{ JK}^{-1} \text{ m}^{-2}$ , and the temperature response time of the climate system  $\tau_R$  is equal to 6.3 years.<sup>1</sup> These parameters were chosen to give a  $2.5 \text{ }^\circ\text{C}$  global temperature increase in an equilibrium with the atmospheric concentration of  $\text{CO}_2$  doubled from preindustrial time (to a level of 550 ppmv). Thus the temperature increase from emission of other greenhouse gases is additional to the effect of  $\text{CO}_2$ . Data on concentrations are taken from Wigley et al. (1997). The temperature response in this simple model corresponds reasonably well with the output from global climate models that incorporate heat transfer across the ocean-atmosphere interface.

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<sup>1</sup>The temperature response time in Hartmann (1994) is 10 years, which corresponds to 6.3 years in our model due to calibration. Hasselmann et al. (1997) employ a temperature response time of the climate system of 36.8 years (which is a weighted average of the temperature response time constants 2.1, 12.0, and 138.6 years).

## 3.2 Abatement costs

The model defines output as a function of the use of fossil fuels, measured in terms of input of CO<sub>2</sub> emissions. The cost of CO<sub>2</sub> abatement is thereby represented indirectly by the calibration of the model. As a basis for calibration, we estimated the costs in terms of percentage reductions in GDP following a given percentage reduction in CO<sub>2</sub> emissions for each region. The point of reference for the estimates is IPCC (1996), but it must be emphasised that IPCC presents estimates over a wide range for each region. Moreover, for most of the developing regions there are no proper estimates.

The abatement costs for each region change over time. This is because the cost of capital, for example, that associated with increased energy efficiency, is likely to be reduced because old capital equipment has been depreciated. The main differences in abatement cost across regions are found between the OECD regions and the other regions. Among the OECD regions, the USA exhibits the highest costs, approximately 400 USD per ton of carbon for moderate reductions in the short term. This can be debated, and some studies assume that abatement costs of CO<sub>2</sub> in the USA are at approximately the same level as in the EU, and definitely lower than in the ROE. Other studies argue that the energy technology is more efficient in the USA than in most other regions, and that abatement costs therefore are high.

CH<sub>4</sub> is emitted from a variety of sources, and some of them are only indirectly related to economic activities. The composition of emission sources also varies greatly from region to region. A major source is agriculture, where the emissions stem from both livestock and grain production. Emissions from rice fields are significant in Asian

countries. In Russia, one of the main sources is the leakage from pipelines for oil and gas. In addition, emissions of  $\text{CH}_4$  are related to energy use, and the emissions from landfills are significant in most countries.

Despite the many options to reduce emissions of  $\text{CH}_4$ , little is known about the costs of the measures on a regional or world scale. Some country studies indicate, however, that because of the limited attention emissions of  $\text{CH}_4$  has had prior to the Kyoto agreement, there are potential measures at very low costs in several countries. For other measures the costs may turn out to be very high. Due to the uncertainty of the costs, we have chosen a logarithmic abatement cost function, which allows between 10 and 35 percent of the emissions to be reduced at relatively low costs. Beyond this level, the marginal costs are assumed to increase substantially.

The parameters of this study were calculated on the basis of a study by the Norwegian State Pollution Authority on potential measures to reduce emissions of  $\text{CH}_4$  in Norway. The measures were divided into two classes depending on whether emissions were related to combustion, production, and industrial processes, on the one hand, or bio fuel, land use, and waste on the other. Then the cost function for each region was calculated on the assumption that the marginal cost of reducing the same percent of emissions is equal in all regions. Variations across regions then occur because of different compositions of the emission sources in present emissions.

The resulting parameteres give low costs in China, India, and the Rest of the World, particularly for small cuts. For larger cuts, the variations in marginal costs level out. The USA and the EU, in particular, exhibit relatively low costs for large cuts. The calibration gives relatively high costs for the Former Soviet Union. This is probably

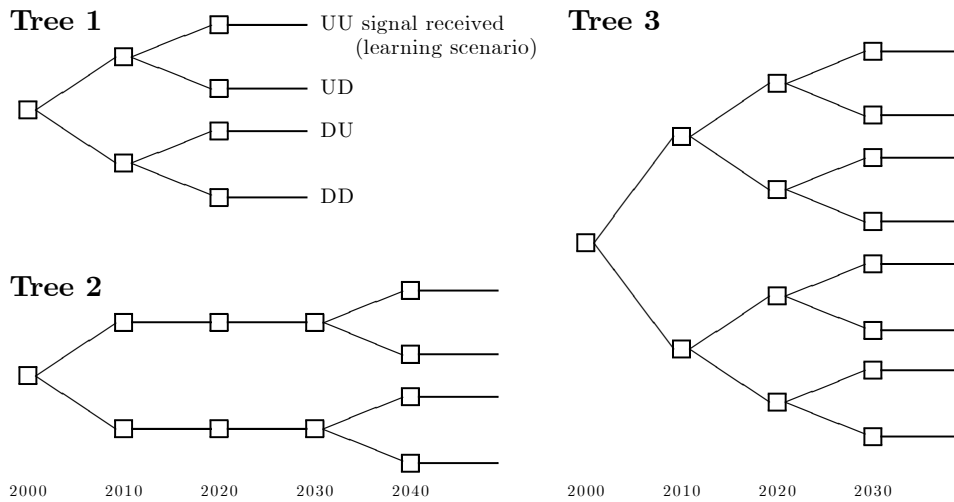
incorrect, and may be due to a significant under-reporting of emissions, particularly from pipelines.

The difficulty in calibrating global models like the one applied in this study suggests the numerical figures should be interpreted with caution. However, the principles for abatement of  $\text{CH}_4$  versus  $\text{CO}_2$  depend only to a small degree on the absolute level of parameters chosen in the study, as long as they satisfy requirements about relative levels.

## 4 Numerical analysis

### 4.1 Presentation of scenarios

The numerical analysis of the model is based on the tree depicted in Figure 1. There are two periods: one where new information on the severity of the climate problem arrives in the first period (2010), and one where it arrives in the second period (2020). The new information either indicates that the damage costs of climate change are larger than earlier anticipated (case U), smaller than earlier anticipated (case D), or the same as earlier anticipated (case M). One may interpret case M as sustaining the expected value of the damage cost. Again following Kolstad, we limit ourselves to *star-shaped spreading of beliefs*. (See Kolstad, 1992.)



Decision trees: At each node in the tree, the carbon emission must be determined. Damage probabilities are updated after new information has arrived. An upward sloping branch implies an "up" signal, indicating severe damage. Downward sloping branches: "down" signals; no slope: no new information.

Figure 1. Decision tree

## 4.2 Results

Numerical simulations were made using a 230-year horizon, starting in 2000. Compared with the case of no damage, a reference scenario with damage from global warming and no uncertainty gives an optimal abatement of total emissions in year 2000 at approximately 24 percent for  $\text{CO}_2$  and 15 percent for  $\text{CH}_4$ . The abatement of  $\text{CO}_2$  peaks at approximately 49 percent in 2100, whereas the abatement of  $\text{CH}_4$  reaches 100 percent in 2090 and stays at this level till the end of the time horizon.

The reference scenario is compared with several other scenarios, one with uncertainty and no learning and several with uncertainty and different learning rates. Note that in the simple two-period model above, there is no difference between certainty and uncertainty with no learning. In the present model there are much more non-linearities

and hence uncertainty does affect the optimal policy.

We find that with uncertainty, optimal abatement increases for both CO<sub>2</sub> and CH<sub>4</sub>. In year 2000 the increase is equal to 0.7 percent for CO<sub>2</sub>. Optimal CO<sub>2</sub> abatement in 2100 peaks at approximately 52 percent. Consequently uncertainty leads to slightly more abatement than in the case of certainty in the present model. The adjustment corresponds to a 0.08 °C lower expected increase in temperature by year 2200. Both gases are abated at a slightly higher rate over time than in the case of certainty. Extending the time horizon until 2330 leads to increased CO<sub>2</sub> abatement and reduced CH<sub>4</sub> abatement in 2000, which can be interpreted as CH<sub>4</sub> abatement being substituted for CO<sub>2</sub> abatement due to the increased effect of reducing emissions of the longlived greenhouse gas CO<sub>2</sub>.

The effect of adding learning however, is more in line with the results for the simple two-period model. We found that for the longlived gas CO<sub>2</sub>, optimal emissions in 2000 would increase with learning, and this is clearly the case also in our simulations, although the effect of approximately 3 percent emission increase is not very strong.

For CH<sub>4</sub> on the other hand, the predictions from the two-period model were more mixed. First, we would expect a substitution such that CH<sub>4</sub> emissions would be reduced as CO<sub>2</sub> emissions are increased. On the other hand, CH<sub>4</sub> does have a non-zero lifetime, and reduced future marginal damages due to learning induces increased optimal emissions. Looking at our simulation results, we find that increased learning does imply a small increase in emissions, as abatement in 2000 falls by approximately 1 percent.

In the case that learning is postponed till 2040, the abatement of both greenhouse



gases is increased in 2000. This result is due to a relatively lower reduction in future marginal damages caused by the postponement of learning.

## 5 Conclusions

We find that uncertainty and learning both affect the optimal mix of CH<sub>4</sub> versus CO<sub>2</sub> abatement even if the effects are rather small. With uncertainty, the optimal abatement of both gases is increased compared to the certainty reference case. This effect amounts to 0.08 °C less than the expected temperature increase by year 2200. Adding learning means less abatement for both gases since future marginal damages from emissions of these gases are reduced. This effect is less pronounced for CH<sub>4</sub> since some CH<sub>4</sub> emissions are substituted for CO<sub>2</sub> emissions as the latter are increased.

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