A risk hedging strategy for the 2°C target and the Copenhagen Accord

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Preface

This report presents the results from a research project “Long term impact of the Copenhagen accord regarding the 2 degree target”, done at VTT Technical Research Centre of Finland during autumn 2010 and winter 2011 for the Nordic Working Group for Global Climate Negotiations (NOAK). It highlights the need for more ambitious early action in order to close the emission gap related to the Copenhagen Accord outcomes.

The report portrays greenhouse gas emission pathways that would minimize the costs of reaching the 2 degree target, while simultaneously taking into account the uncertainty of and future learning on climate sensitivity. The report argues that it is not possible to assert that the 2 degree target would be reached with certainty with a predetermined emission pathway. Instead, climate policy should be readjusted during the century as new information on climate sensitivity becomes available.

The study estimates that the emission level resulting from the Copenhagen Accord would be at least 5 Gt CO₂-eq higher than the cost-effective level in 2020. In line with e.g. what is calculated by Nicholas Stern, the report states that the mitigation costs would be higher should the 2020 emission level be that of the Copenhagen Accord. Therefore future climate negotiations should aim for more ambitious emission reductions, both in and after 2020, which of course will also affect the effort sharing between parties to a great extent. If the global emission target for e.g. 2050 is formed in a bottom-up manner from the pledges of individual parties, it might be challenging to ensure that the parties adjust their emission pledges harmoniously to suit this new information on climate sensitivity.

The Nordic Working Group for Global Climate Negotiations (NOAK) is a working group under the Nordic Council of Ministers, whose aim is to contribute to a global and comprehensive agreement on climate change with ambitious emission reduction commitments. To this end, the group prepares reports and studies, conducts meetings and organizes conferences supporting the Nordic negotiators in the UN climate negotiations. The steering group for the project consisted of Harri Laurikka (Finland), Marjo Nummelin (Finland), Olle Björk (Sweden), Daniel Johansson (Sweden), Håvard Toresen (Norway) and Carsten Eskebjerg (Denmark). The authors wish to sincerely thank the steering group for their comments, and NOAK for the funding of the project.

The Nordic Council of Ministers is proud to be able to contribute to the knowledge base so crucial for the future of the global climate negotiations through this report and the ongoing work of NOAK.

A handwritten signature in black ink, appearing to read 'Halldór Ásgrímsson', written over the printed name.

Halldór Ásgrímsson,
Secretary General

Nordic Council of Ministers

Summary

- This report examines greenhouse gas emission pathways up to 2100 that aim to reach the 2°C target, with a special focus on the uncertainty of climate sensitivity and hedging the risk in mitigation costs. The report describes a new way for calculating optimal emission pathways, compares the results with previously estimated outcomes of the Copenhagen Accord, and discusses the implications of the proposed pathways for effort sharing beyond 2020.
- Given that there currently exists large scientific uncertainty around climate sensitivity, – i.e. the question of how much temperature will rise with rising greenhouse gas concentrations – it is not possible to assert that the 2°C target would be reached with certainty with a predetermined emission pathway. Instead, climate policy should be readjusted during the century as new information on climate sensitivity becomes available.
- The uncertainty of climate sensitivity and future learning about climate sensitivity can be taken into account in the decision making for near-term emission targets, resulting with a *hedging strategy* against the uncertainty of climate sensitivity. The hedging strategy seeks to avoid excessive future mitigation costs if it turns out that climate sensitivity is stronger than what has been assumed previously. As a result, hedging the risk against the uncertainty of climate sensitivity implies more ambitious early action than a scenario that disregards the uncertainty.
- This report describes a simplified and transparent model for determining a hedging strategy that minimizes the mitigation costs for reaching the 2°C target during the century. The resulting optimal strategy suggests an emission level of 42.8 Gt CO₂-eq for Kyoto gases in 2020. This is at least 5 Gt less than the lower range of estimates for the outcome of the Copenhagen Accord.
- A sensitivity analysis of the model, using different assumptions for mitigation costs and discount rates, suggested that the optimal emission level might vary from 37.8 to 47.8 Gt CO₂-eq. The high end of this range overlaps only slightly with the lower range of estimated emissions under the Accord. Therefore the results reported here reinforce the previous arguments about the emission gap related to the Copenhagen Accord outcomes.
- A case where 2020 emissions correspond to the Copenhagen Accord outcomes and the hedging strategy is followed only after 2020 was also studied. The comparison of the Accord case and the first, cost-optimal case showed that the 2°C target could be achieved also under

the Accord, by compensating the higher 2020 emission level by further reductions of 1.6 Gt per year, on average, between 2030 and 2080. This would result with an increase of mitigation costs by 2.5%, assuming that the cost-minimizing pathway is indeed followed after 2020. However, if the optimal pathway is not followed already in 2020, it is difficult to assure that it would be followed later on.

- Our final consideration deals with effort sharing after 2020. If the global emission targets need to be readjusted to suit new information about the level of climate sensitivity, this would also affect the effort sharing between parties to a great extent. If the global emission target for e.g. 2050 is formed in a bottom-up manner from the pledges of individual parties, it might be challenging to ensure that the parties adjust their emission pledges harmoniously to suit this new information on climate sensitivity.
- Last, some shortcomings of the model were noted that might affect the presented results. The model uses a simplified module for calculating the climatic consequences from the emission pathways, and the emission levels presented here are slightly higher than pathways that have been reported to achieve the 2°C target with a 50% to 66% probability in a recent report by UNEP (2010). Also, in our scenario cases with the highest realization of climate sensitivity the level of emissions should become negative already by 2060. Whether such emission levels would be achievable is debatable, and avoiding such situations would justify even more ambitious early action than what our scenario suggests

1. The Copenhagen accord and the 2°C target

Following the 15th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) at Copenhagen in 2009, 140 parties to the UNFCCC have agreed to the Copenhagen Accord (UNFCCC, 2010) (later the Accord). The Accord states the understanding that deep reductions in global greenhouse gas emissions are required to hold the increase in global mean temperature increase below 2 degrees Celsius. In addition, 115 parties have submitted their communications as annexes to the Accord. These communications include quantified emission targets from Annex I parties and nationally appropriate mitigation actions from non-Annex I parties, and vary considerably by their level of ambition regarding substantive emission reductions.

The resulting global level of emissions in 2020 due to the emission pledges of the Accord are however ambiguous, as the pledges include conditionalities – such as more ambitious targets being conditional on the level international effort, or emission intensity targets. Also, a large number of developing countries have not committed to any emission reductions, and the commitments extend mainly only to 2020.

Due to this ambiguity, estimates on the emission level in 2020 following the Accord have been made in a number of studies (Lowe, J.A. et al., 2010; Stern and Taylor ,2010; den Elzen, M. et al. ,2010a; den Elzen, M. et al. ,2010b; Rogelj, J. et al ,2010). The range of possible emission levels is wide, ranging from 47 Gt CO₂-eq to 54 Gt CO₂-eq, depending on the assumptions used for e.g. economic growth, whether parties' low or high pledges are used, and whether the surplus emission units from the Kyoto protocol may be carried over to the next commitment period. A summary of estimates from the referenced studies is given in Table 1.

Table 1. A summary of estimated global greenhouse gas emissions in 2020 due to the pledges in the Copenhagen Accord.

Study	Low value	High value	Reference
	Gt CO ₂ -eq	Gt CO ₂ -eq	
AVOID	48	49.4	Lowe, J.A. et al. (2010)
CCCEP/Grantham	48.2	49.2	Stern and Taylor (2010)
PBL/Ecofys	48.7	50.1	den Elzen, M. et al. (2010a)
UNEP	47	53	den Elzen, M. et al. (2010b)
Rogelj, J. et al	47.9	53.6	Rogelj, J. et al (2010)

For assessing whether or not the pledges in the Accord are compatible with the 2°C target, the referenced studies compare the above emission levels with emission pathways aiming for the 2°C target. Past mitigation

scenarios with a “likely”¹ change of meeting the 2°C target have presented an emission levels from 39 to 44 Gt CO₂-eq in 2020 (den Elzen, M. et al., 2010b). Based on this, most of the above mentioned studies conclude that estimated emissions under the Accord exceed the 2°C-compatible range by some 4 to 10 Gt CO₂-eq.

As the increase in global temperature is indeed dependent mainly on the cumulative emissions during the whole century – rather than on the 2020 level – the emission level of 2020 does not yet determine the temperature increase in e.g. 2100. However, as the economic system, and thus the emission reductions, involves inertia, early action is necessary to reach the long-term climate targets.

Moreover, even if high emissions during the early part of the century could be wholly compensated with higher reductions later on, this might be an uneconomic course of action due to the steeply rising abatement costs with very high emission reduction levels. Therefore an economically sound balance between mitigation efforts during early and late years should be found, i.e. the reductions should be cost-optimal.

Although past studies have mainly concluded that the emission reductions of the Accord are inadequate in pursuing the 2°C target, a look at e.g. recent scenarios of the Energy Modelling Forum (EMF) might give us more perspective. Figure 1 presents four scenarios from the EMF-22 scenario exercise that correspond to cost-optimal emission pathways to remain below 450 ppm-eq, i.e. a radiative forcing of 2.6 W/m² (Krey and Riahi, 2009; van Vliet et al., 2009; Gurney et al., 2009). In the figure, the range of assumed outcomes of the Accord from Table 1 is also presented. The figure shows that, depending on which scenario we look at, the Accord might be already on a cost optimal track for 450 ppm-eq concentration target, which would roughly imply a 50% change of meeting the 2°C target. Nevertheless, this conclusion rests on the technology assumptions made in the different scenarios, and still leaves only a 50% change of meeting the 2°C target.

¹ Over 66% probability.

Figure 1. Global emissions of Kyoto-gases in four scenarios limiting radiative forcing to 2.6 W/m² (450 ppm-eq). The scenarios of the MESSAGE model (Krey and Riahi, 2009) are presented with two different technological assumptions, either with (solid blue line) or without (dashed blue line) bio-CCS.

2. A cost-optimal pathway for the 2°C target

The controversy on whether we can say that the projected emissions in 2020 or a pathway until 2100 would be a cost-optimal solution to reach the 2°C target rests on the end of the century rests on two major uncertainties: we don't know what kind of emission reductions will be possible, on what costs and at what time; and – being even more important – how sensitive the climate actually is to rising greenhouse gas concentrations in the atmosphere. The latter issue, that of the climate sensitivity, has been a matter of scientific debate for long, and there still exists significant uncertainty on the level of the sensitivity. But as we don't know what kind of an emission pathway would lead to at most 2°C warming, how a cost optimal pathway for the 2°C target could then be specified?

Past mitigation scenarios have usually aimed at the 2°C target either by using the most likely value of climate uncertainty parameter, thereby bypassing the uncertainty altogether; or targeted instead a concentration target that would yield a “likely” probability, for example 66%, to remain below 2°C warming. These approaches, however, ignored that the level of uncertainty regarding climate sensitivity is likely to decrease throughout the century. Then, as time progresses and new information becomes available, we can adjust climate policy to reflect this new information.

Including this type of dynamic decision making in climate change mitigation scenarios solves the issue of uncertainty on climate sensitivity. As we come closer to the 2°C limit, we have greater understanding on the sensitivity and may decide to push for more ambitious emission reductions, thereby never exceeding the 2°C limit. Therefore, if global political will is sufficient, the 2°C can be reached with certainty².

In this dynamic decision making framework, we have to decide now the level of emission reductions in the near future, at the same time considering what we might know in the future and what our options would then be, given the actions that we take now. Then after some time, e.g. 10 years, we face this problem once again, but then with new information. If this new information suggests that the climate sensitivity is likely to be higher than previously thought, an optimal solution at that point of time would be to aim for lower emission levels than was earlier

² In this context we have ignored technological considerations completely, and assumed that there is no lower technological limit for global emissions; although the cost of required emission reductions might in extreme cases of climate sensitivity be enormous.

planned. On the other hand, if the new information allows us to rule out the higher estimates of climate sensitivity, optimal climate policy would be to relax our previously projected emission pathways. With this stochastic problem setting, our chosen policy would be an optimal hedging strategy against the uncertainty in the climate sensitivity.

An important effect of the dynamic formulation of the problem is that the uncertainty and its gradual resolving affect our actions already at the first time steps. The main driver for this is the steeply rising marginal abatement costs with increasing emission reduction levels. If we later discover that the climate sensitivity is higher than the most likely estimate we have now, the increase in costs required to meet the 2°C target would be far higher than the decrease in costs if the sensitivity is found out to be actually lower than now presumed. Therefore a cost optimal solution would then be to prepare for the worst, with the appropriate probability, with early mitigation action.

Earlier scenario literature has considered this type of dynamic climate policy only in few papers (Syri et al., 2007; Johansson et al., 2008; Webster et al., 2008; Loulou et al., 2009), and in a very simplified setting, where the uncertainty is resolved in its entirety suddenly at a single point of time, usually in 2040. In this report we present a more sophisticated treatment of the dynamic climate policy problem, using a simplified, stochastic model using marginal abatement cost curves.

3. Model description

The model used here to solve the stochastic, dynamic cost-optimization problem of limiting global mean temperature increase at most to 2°C is, apart from the stochastic formulation, a simple cost-optimization model with predetermined marginal abatement cost (MAC) curves gathered from literature.

Although some aspects, such as the lifetime of capital used for the emission reductions, is not covered by the model, the simplified formulation requires far less assumptions, and therefore improves transparency of the model. In addition, using a large scale integrated assessment model, such as ETSAP-TIAM, MESSAGE or IMAGE, in the stochastic setting would be impossible due to computational limitations.

The assumptions made in the model are:

- Global mean temperature increase is limited to 2°C
- Baseline emissions of Kyoto-gases grow from 53 Gt CO₂-eq in 2020 to 80 Gt CO₂-eq in 2050 and 100 Gt CO₂-eq in 2100
- Cost minimizing emission reductions using a 5% discount rate
- Marginal abatement costs curves fitted to the results reported by Krey and Riahi (2009) van Vuuren et al. (2010) and Gurney et al. (2009)
- The probability distribution of climate sensitivity in 2010 corresponds to higher-mean estimate of (Knutti and Hegerl, 2008)
- The uncertainty of climate sensitivity decreases gradually over time along a binomial lattice with 10 year period length

The details of model parameterization regarding the uncertainty and abatement costs are provided in the following subsections. Sensitivity analysis on the discount rate and MAC parameterization assumptions are provided in section 5. The climate module used in the model is described in Appendix A.

3.1 The uncertainty of climate sensitivity

Our stochastic optimization setting consists of two components: the probability distribution in the beginning of the scenario and the way the uncertainty is gradually resolved.

The distribution used in the initial years of the scenario, specifically up to 2020, corresponds to the current level of uncertainty, as we currently are trying to negotiate the level of emissions in 2020. Very different distributions of the climate sensitivity have been presented in the

past, and a review by Knutti and Hegerl (2008) assembled the differing lines of evidence into two distinct distributions. Of these two, we have used the version with a higher mean value. Due to the computational formulation of our problem, the distribution had to be discretized into separate steps, instead of using the original continuous distribution. The two distributions of Knutti and Hegerl (2008) and our discretized version are presented in Figure 2.

Figure 2. Two probability density distributions (red and blue lines, left axis) for the climate sensitivity parameter that combine different lines of evidence for potential sensitivity values (Knutti and Hegerl, 2008); and a discretized version (violet points with ranges, right axis) of the blue distribution that has been used in the scenarios of this study.

After 2020, new information on the sensitivity is assumed to be available, allowing us to exclude either the highest or lowest value in our discretized distribution, both with a 50% probability. Similar resolving of the uncertainty is assumed to occur every 10 years up to 2080, when the true value of the climate sensitivity is assumed to be known with certainty. In total, this yields a binomial lattice, depicted in Figure 3. The lattice has 64 separate paths on how the uncertainty gradually decreases, with all paths having equal probabilities. With the information available in the beginning of the scenario, the probabilities for the known value of climate sensitivity in 2080 correspond to the distribution specified in Figure 2.

Following the reasoning in the beginning of the section, using the described lattice causes an emission pathway to split into two at each junction of the lattice. Therefore the solution to the stochastic, dynamic cost-optimization problem is not a single scenario, but a set of 64 equally probable scenarios that separate gradually from each other at each junction of the lattice.

Figure 3. A binomial lattice describing the assumed evolution of climate sensitivity probability. At each junction, once every ten years, either the highest or lowest value in the probability distribution is ruled out, both with a 50% probability. The true value will be known in 2080, with the values of C_s and their probabilities presented on the right hand side of the lattice diagram. The values and probabilities correspond to the discretized distribution of Figure 2. One possible path through the lattice, with the true value of C_s at 3.0°C, is marked with red arrows.

3.2 Marginal abatement cost curves

The marginal abatement costs were taken from recent mitigation scenario analysis with large-scale integrated assessment models. For this purpose, only scenarios that considered the global emissions of all Kyoto gases were selected, as otherwise the reduction potential would have been underestimated.

The selected studies were Krey and Riahi (2009), van Vuuren et al. (2010) and Gurney et al. (2009), which all provided multiple scenarios and thus multiple points to the marginal abatement curves at each point of time. In addition, Krey and Riahi (2009) and van Vuuren et al. (2010) reported scenarios with different technological assumptions. Combined, the emission level - marginal cost pairs formed a rather wide range of MAC curves, especially for the end of the century. Due to this variance in reported MAC levels, two different MAC curves to be used in our model were fitted to the data points, one corresponding to the higher cost envelope and the other to the lower cost envelope of the original data points.

Although the MESSAGE (Krey and Riahi, 2009) and IMAGE (van Vuuren et al., 2010) scenarios included emission levels below zero in 2100, with the corresponding marginal costs in excess of 1000 $\$/_{2005}/t_{CO2}$, the reported emission reduction potentials were insufficient for reaching the 2°C target with the two highest levels of climate sensitivity ($C_s = 4.5^\circ C$ and $C_s = 5.4^\circ C$). Therefore the MAC curves used in the model had to be extrapolated to allow even higher reduction levels in the latter part of the century. Corresponding to the steeply rising costs in the original data, the marginal costs with these extrapolated emission reductions are enormous, reaching 3000 $\$/_{2005}/t_{CO2}$ in 2100.

The original data points from Krey and Riahi (2009), van Vuuren et al. (2010) and Gurney et al. (2009), and the two fitted MAC curves used in our model are presented in Figure 4.

Figure 4. Marginal abatement costs for years 2030, 2050 and 2100 from recent IAM analyses (Krey and Riahi, 2009; van Vuuren et al., 2010; Gurney et al, 2009), split to high and low cost envelopes; and the fitted high and low cost marginal abatement curves used in this study.

4. Stochastic scenarios for reaching the 2°C target

In order to compare whether the Copenhagen Accord is on a cost-optimal track two different scenario settings are analyzed:

A cost-optimal hedging strategy for the 2°C target starting from 2020. Assume that emissions in 2020 are comparable to the Accord pledges (here 48.8 Gt CO₂-eq), and cost optimization starts only in 2030.

4.1 A cost optimal pathway with full cost optimization

A cost-optimal hedging strategy for the 2°C target, in which the optimal emission reductions start from 2020, is presented in Figure 5. The optimal strategy with the assumptions made in the model would imply an emission level of 42.8 Gt CO₂-eq in 2020. After this, as new information on the climate sensitivity is assumed to be available, the optimal strategies split, depending on the realization of the new information. The average of the 64 individual stochastic scenarios shows a relatively linear path of reductions in global emissions towards the end of the century.

For comparison, the figure also includes a cost optimal deterministic strategy with an assumed climate sensitivity of 3°C. The difference between emissions in the optimal deterministic and stochastic scenarios shows clearly the effect of hedging against uncertainty: due to the risk of extreme costs with high values of climate sensitivity the optimal hedging strategy involves more ambitious early action than the optimal deterministic scenario, in which such risk doesn't exist.

Figure 5. Global emissions in the baseline (red); a deterministic 2°C scenario (green) with 3°C climate sensitivity; and the stochastic 2°C scenarios (gray) with climate sensitivity distributions corresponding to Figure 3. The average of the stochastic scenarios is noted with a blue line.

4.2 A cost optimal pathway under the Copenhagen Accord

In the second case the stochastic cost-optimization was assumed to start only in 2030, while the emissions in 2020 would be determined by the Copenhagen Accord. The results for this case are presented in Figure 6. The figure also shows the average emission pathway of the full cost optimization case from Figure 5.

As the emissions under the Accord are higher than the optimal hedging strategy in 2020 by 6 Gt CO₂-eq, the strategy of the second case has to compensate the higher 2020 emissions in later periods, on average by 1.6 Gt CO₂-eq per year between 2030 and 2050. At most, the maximum compensation between the 2030 to 2050 period was 2.3 Gt CO₂-eq per year.

Figure 6. Global emissions in the baseline (red); the average of stochastic 2°C scenarios under the Copenhagen accord (dark blue); and the average of cost optimal stochastic scenarios from Figure 5.

4.3 A comparison of mitigation costs

As the level of 2020 emissions in the Copenhagen Accord case differs from those of the cost-optimal case, the mitigation costs are higher in the Copenhagen Accord case. Figure 7 presents the average costs in both cases between 2020 and 2100. Corresponding to the difference in average emissions in Figure 6, the mitigation costs are lower in the Copenhagen Accord case in 2020 and higher between 2030 and 2080. As an aggregate measure, the net present value (NPV) of mitigation costs between 2020 and 2100 was 2.5% higher. Such a small difference seems intuitively reasonable, as the emission level of 2020 is only a small part of the century, i.e. our total timeframe under consideration. Using a slightly suboptimal strategy around 2020 doesn't largely affect the NPV of costs, if a cost-optimal strategy is followed from 2030 onwards.

Figure 8 compares the NPV of costs in individual stochastic scenarios. The figure indicates that in the scenarios with high realizations of climate sensitivity, i.e. the scenarios with high mitigation costs, the costs are somewhat higher (up to 13%) in the Copenhagen Accord case. On the other hand, with low realizations of climate sensitivity the costs are lower in the Copenhagen Accord case, although the absolute value of the difference is small. As a result, on average the cost NPV is indeed slightly higher, by the mentioned 2.5%, in the Copenhagen Accord case.

Figure 7. Average annual mitigation costs [Bln. \$₂₀₀₅/t_{CO2}] in the cost-optimal and Copenhagen accord cases.

Figure 8. The net present value of mitigation costs [Bln. \$₂₀₀₅/t_{CO2}] from 2020 to 2100 compared between the individual stochastic scenarios in the cost-optimal (x-axis) and Copenhagen Accord (y-axis) cases. The grey diagonal line indicates equal costs in a scenario between the two cases.

4.4 Comparison to past mitigation scenarios

In order to gain further insight from our stochastic scenario formulation, the emission pathways in the cost-optimal case were compared to previously reported emission scenarios. A recent report (UNEP, 2010) compiles a large number of emission pathways that reach the 2°C target with 50% to 66% probability. The range of annual emission in these scenarios is wide, due to both the probability range and differing temporal profiles of emission reductions.

When stochastic scenarios in our setting are compared to deterministic ones in e.g. the UNEP (2010) report, the distinction between the approaches should be borne in mind. The UNEP report declares a probability with which the temperature target is reached, based on the current level of knowledge on climate sensitivity, whereas each stochastic scenario realization in Figure 5 reaches the target with certainty. A stochastic scenario realization in which the climate sensitivity is found out to be 3°C would reach the 2°C target with – given the current level of knowledge – a 50% probability, i.e. the low end of the probability range in the UNEP report. Therefore the stochastic scenario realizations with climate sensitivity of 3°C should be roughly comparable to the UNEP emission range.

Figure 9 presents these individual stochastic scenarios along with the range of UNEP's stylized emission pathways. Based on the figure, the average of the selected stochastic scenarios lies mostly inside the UNEP's range and involves more ambitious early action than most of the UNEP's pathways, although it exceeds the range between 2050 and 2080. The cumulative emissions of the stochastic scenarios were estimated to be slightly, around 10%, higher than those of the UNEP's pathways. Should a more detailed climate module been used, the scenarios calculated in this report might thus involve somewhat deeper emission reductions.

Figure 9. Global emissions in individual stochastic scenarios of Figure 5 with climate sensitivity realizations at 3°C (grey lines) and their average (orange line) compared to a range of emissions from stylized emission pathways (green area) that are reported to reach the 2°C target with 50% to 66% probability (UNEP, 2010).

5. Sensitivity analysis for the pathways

As the model used involved a very limited number of assumptions, it is relatively easy to assess how much the assumptions affect the main results. Two easily comparable numerical results that are analyzed here are the emission level in 2020 with full cost-optimization; and the increase in the NPV of mitigation costs between 2020 and 2100 due to not following the cost-optimal hedging strategy in 2020, i.e. the relative difference between NPV's of the Copenhagen Accord and cost-optimal cases. The analyzed assumptions are the discount rate and the MAC curves, whether the lower or higher cost envelope in Figure 4.

The effect of discount rate and MAC curve on the optimal hedging strategy in 2020 is presented in Figure 10. The range extends from the 2% and high cost case, in which emissions were 37.8 Gt CO₂-eq, to 47.8 Gt CO₂-eq in the 8% and low cost case. The default case, 5% discount rate with low cost curves, lies right in the middle of the range. If compared to the estimates of 2020 emissions under the Accord, presented in 0, only the highest of our sensitivity cases reaches the lower end of assumed emissions under the Accord.

Figure 10. Sensitivity analysis for the optimal global emissions [Gt CO₂-eq] in 2020. The bars indicate cases of full cost-optimization with either high or low mitigation cost curves, and discount rates (DR) of 2%, 5% and 8%.

The sensitivity of the difference in the NPV of mitigation costs between the Copenhagen Accord case and full cost-optimization case is presented in Table 2. In all cases the relative difference in the NPV between the two cases is small, ranging from 1% to 4%. This implies that the difference in NPV is rather robust to our assumptions.

Table 2. Sensitivity analysis for the difference in the NPV of mitigation costs between the Copenhagen Accord case and full cost-optimization case, with discount rates of 2%, 5% or 8%, and high or low mitigation cost curves.

Discount rate	Marginal cost curve	NPV increase
2%	Low cost	2.4%
	High cost	2.8%
5%	Low cost	2.5%
	High cost	4.1%
8%	Low cost	1.0%
	High cost	3.3%

6. Effort sharing

The stochastic model described above considers the emission reductions only on the global level. Yet, emissions on the national level have often more practical importance on the political level, as the negotiation process has, at least so far, concentrated on a bottom-up approach, where the emission targets of the individual countries make up the global total. On contrast, a top-down approach would mean dividing predetermined global emissions, e.g. the expected emissions suggested in Figure 5, to the parties. Regardless of the approach, this raises up the question of equitable burden sharing.

6.1 Effort sharing in 2020 between Annex I and non-Annex I

The UNFCCC classifies developed countries as Annex I and non-Annex I countries. Annex I countries have emission targets under the Kyoto Protocol, while non-Annex I countries do not. Greenhouse gas emissions in non-Annex I countries have been rising rapidly and grew bigger than Annex I emissions already in 1991. The biggest non-Annex I countries have already given emission reduction pledges in the Copenhagen Accord. Most of the non-Annex I pledges are measured in emission intensity, and as an example China pledged to “lower its carbon dioxide emissions per unit of GDP by 40-45% by 2020 compared to the 2005 level”.

Due to these different ways for measuring the reductions and possible conditionalities in the pledges, it is rather complicated to estimate the absolute emissions for non-Annex I, as was already mentioned in section 1. Nevertheless, several studies listed in Table 1 have given different estimates of Annex I and non-Annex I pledges. Figure 11 shows GHG emissions of Annex I and non-Annex I, their estimated baselines, range of Copenhagen pledges and IPCC’s emission levels for the 2°C target.

As Figure 6 and Figure 10 suggested, it is very unlikely that Copenhagen pledges would be the cost-optimal path to limit global warming to 2°C. This message can be seen also from Figure 11, which shows that the emissions under the Accord are some 2 to 4 Gt CO₂-eq larger for Annex I, and 3 to 9 Gt CO₂-eq larger for non-Annex I than what the IPCC has suggested. This gap is in global level very similar to the gap between the Accord emissions and the cost-optimal strategies in Figure 10.

Figure 11. Greenhouse gas emissions of Annex I and non-Annex I, estimated baselines from 2010 to 2020, range of Copenhagen pledges in 2020 and IPCC's emission levels for 2 degree target in 2020.

6.2 Effort sharing after 2020

The cost-optimal hedging strategy in Figure 6 does not provide a single emission level beyond 2020. Therefore the effort sharing after 2020 may, in the stochastic context here, done either by using the average 2050 emissions, or by allocating the emissions for Annex I and non-Annex I with some simplified allocation procedure. For the basis of our analysis we take that the emissions of Annex I countries should be reduced by 80% to 95% from 1990 levels in 2050, as has been suggested by the IPCC (Chapter 13, 2007).

The average emissions in the cost-optimal case of Figure 5 were 31.1 Gt CO₂-eq, and in the Copenhagen Accord case of Figure 6, 29.5 Gt CO₂-eq. If we combine the range of Annex I reductions, 80% to 95%, to the average emission levels in Figure 5 and Figure 6, we would get 2050 emission targets shown in Table 3. In terms of absolute emissions, the suggested Annex I target would imply reducing emissions in Annex I very close to zero. As the remaining amount of emissions from the assumed global total would be from non-Annex I countries, their emissions would be allowed to be from 71% to 101% above their 1990 levels.

Table 3. Emissions of Annex I and non-Annex I country groups in 2050, if the global level of emissions is the average shown in Figure 5 and Figure 6, and if Annex I countries reduce their emissions by either 80% or 95% from their 1990 levels.

Annex I target	From 1990 levels (in Gt CO ₂ -eq)	-80%	-95%
		3.9	1.0
	Cost-optimal (in Gt CO ₂ -eq)	+81%	+101%
		27.2	30.1
Non-Annex I target	Copenhagen Accord (in Gt CO ₂ -eq)	+71%	+90%
		25.6	28.5

In the stochastic scenario setting, the emission level in 2050 is dependent on the new information that will be gained during the following decades. As the global level of emission varies between individual scenario realizations, it is not realistic to assume a fixed emission level for either Annex I or non-Annex I. It could be assumed instead that the -80% target of Annex I should hold for the expected emissions, i.e. to the stochastic scenario average.

Therefore, we fix that the -80% reduction target of Annex I should hold for the stochastic scenario average, and use a simplified effort sharing procedure for any departures from this average. Specifically, the difference in global emissions between an individual stochastic scenario and the average is divided between Annex I and non-Annex I in a ratio of 1 to 3. For example, if a scenario has an emission level 4 Gt CO₂-eq lower than the scenario average in some given year, the target of Annex I in absolute terms would be 1 Gt lower and that of non-Annex I would be 3 Gt lower.

The results of this simplified effort sharing procedure in the stochastic scenarios are presented in Figure 12. The scenario averages for Annex I and non-Annex I equal the -80% case in Table 3. In the individual scenarios, the emissions of non-Annex I have a wide range, from 12 to 45 Gt CO₂-eq, while in worst cases the Annex I emissions should already be negative in 2050.

Figure 12. Emission levels of Annex I and non-Annex I countries with a simplified effort sharing in the stochastic scenarios. In the stochastic scenario average, the Annex I emissions are set at -80% from 1990 levels in 2050, as was also presented in Table 3.

There are yet only few country specific estimates of 2050 emissions. Figure 13 and Table 4 compare historical emissions, Copenhagen pledges and -80% from 1990 Annex I emissions. To sum up the presented data, industrialized countries have planned extensive reductions while developing countries have just started. With current pledges from Copenhagen, China's share of the global GHG emissions will rise dramatically by 2020. Figure 13 tries to clear the scale of estimated emissions in 2020 and projected future to the 2050. Darker area (1990–2009) in the picture is historical emissions and lighter area (2010–2050) future speculations. Numbers behind Figure 13 are printed out in Table 4.

Figure 13. Greenhouse gas emissions of Annex I countries, China and India. Emissions between 1990 and 2009 are statistics from IEA, 2020 corresponds to Copenhagen pledges, and 2050 to -80% reductions from 1990 levels by Annex I countries. The remaining emissions in 2050 in the average cost-optimal stochastic case and deterministic case are allocated to non-Annex I.

Table 4. Historical emissions, Copenhagen pledges and estimates for 2050 emissions for Annex I countries, China and India.

	1990	2005	2020	2020	2050	2050
Annex I	[IEA]	[IEA]	Copenhagen pledge low	Copenhagen pledge high	-80 % from year 2000	-95 % from year 2000
	GtCO2	GtCO2	GtCO2	GtCO2	GtCO2	GtCO _{2eq}
United States of America	6.1	7.0	5.8	5.8	1.4	0.34
European Union	5.5	5.1	4.4	3.8	1.0	0.25
Russian Federation	3.2	2.3	2.7	2.4	0.5	0.12
Japan	1.3	1.4	1.0	1.0	0.3	0.07
Canada	0.6	0.8	0.6	0.6	0.1	0.04
Australia	0.5	0.6	0.6	0.4	0.1	0.03
Ukraine	0.9	0.4	0.7	0.7	0.1	0.02
Turkey	0.2	0.3	0	0	0.06	0.016
Belarus	0.2	0.1	0.2	0.1	0.02	0.004
New Zealand	0.06	0.08	0.05	0.05	0.014	0.003
Norway	0.056	0.066	0.039	0.034	0.013	0.003
Switzerland	0.055	0.056	0.044	0.038	0.010	0.003
Croatia	0.041	0.029	0.038	0.038	0.005	0.001
Iceland	0.004	0.003	0.003	0.003	0.001	0.000
China	3.8	7.7	13.0	11.4	-	-
India	1.4	2.1	5.3	4.4	-	-

7. Conclusions

This report has reassessed the question of an optimal pathway for reaching the 2°C target from the viewpoint of hedging against the risk of uncertain climate sensitivity. The report describes a simplified stochastic model, which uses marginal abatement curves for emission reductions and takes the uncertainty of climate sensitivity into account when considering optimal pathways for reaching the 2°C target. The optimal hedging strategy calculated with the model was compared to the assumed level of emissions under the Copenhagen Accord. Using the results from the model, mitigation costs between the optimal strategy and the Copenhagen Accord case were compared, and potential impacts on effort sharing after 2020 were considered.

Past deterministic mitigation scenarios, i.e. those that do not take the uncertainty of climate sensitivity explicitly into account in the scenario formulation or decision making, have a drawback that for a given emission scenario they either describe a probability with which the 2°C target is reached, or disregard the uncertainty altogether. However, as new information on climate sensitivity is likely to be available in the future, climate policy can be readjusted to suit this new information. Then if we eventually will learn the true value of climate sensitivity – e.g. during the last decades of the century – the target can be achieved with certainty through this readjusting, should sufficient political will be present.

The stochastic scenario approach used in this study incorporates this possibility for readjustments in calculating cost optimal strategies for reaching the 2°C target. In the scenarios, the uncertainty around climate sensitivity is assumed to be gradually decreasing. Then, in some given future point of time, if climate sensitivity is found out to be higher than expected the emissions will have to be reduced more in the future than previously anticipated, and vice versa. Yet, with increasing levels of emission reductions, the costs will rise significantly. A risk hedging strategy for minimizing expected emission reduction costs would take the uncertainty on the necessary level of future emission reductions, including the resulting costs, into account. Our finding was that this optimal hedging strategy would imply more ambitious emission reductions during the next decades than what a deterministic cost-optimal scenario with a fixed, known level of climate sensitivity would imply.

As the level of emissions with the optimal hedging strategy, 42.8 Gt CO₂-eq in 2020, was compared to different estimates on emissions under the Copenhagen Accord, a difference of at least 5 Gt CO₂-eq was noted. A sensitivity analysis showed that by varying the marginal abatement curves and the discount rate from 2% to 8%, the optimal

emission level in 2020 ranges between 37.8 and 47.8 Gt CO₂-eq. This overlaps only slightly with the range of estimates for 2020 emissions under the Accord, 47 to 53.6 Gt CO₂-eq. Therefore it can be concluded that global emissions implied by the Copenhagen Accord do not follow the optimal hedging strategy for remaining below 2°C.

Yet, as the emission pledges in the Accord concern mainly the year 2020, it would be possible to start following the hedging strategy after 2020. This would imply only slightly deeper emission reductions than in the optimal strategy, on average by 1.6 Gt CO₂-eq between 2030 and 2080. The effect of not following the optimal path already in 2020 on the net present value (NPV) of mitigation costs between 2020 and 2100 would also only be minor, resulting with an increase of 2.5%.

As the global emission level depends on the new information regarding climate sensitivity, so obviously does also effort sharing. Using a simplified approach for effort sharing, with which the emissions of Annex I were set at -80% from 1990 levels in the 2050 stochastic scenario average, it was shown that the range of possible emission in 2050 levels for the Annex I and non-Annex I country groups was wide. Based on this, it should be borne in mind in the effort sharing debate that significant readjustments on individual countries' emission targets would be required if new information on climate sensitivity necessitates adjustment on the global emission target.

The findings of this study are, however, susceptible for interpretation. Although the comparison of the optimal hedging strategy and the Copenhagen Accord case showed that the emission gap in 2020 could be compensated later on – and in doing so the net present value of mitigation costs would not increase much – it is interesting to ask that if we are not following the optimal strategy in 2020, how can we be sure that the optimal path is followed after 2020. Also, recalling the result of our effort sharing experiment adds some more insight. The global emission level under the Copenhagen Accord is comprised of pledges from the parties in a bottom-up manner. If this approach is maintained, instead of setting a global target which would be then split between the parties, is it a feasible assumption that individual countries would harmoniously update their pledges to accommodate to the new, arising information on climate sensitivity, as suggested by the hedging strategy and our effort sharing experiment. Given this difficulty, reaching more ambitious targets already in 2020 than what is expected to result under the Accord is more important than what the results reported here as such might imply.

Finally, it should be noted that the model used in the study has obviously its limitations. One point of improvement would be to use a more detailed climate module, as is discussed in Appendix A. Also, two notable shortcomings are that the rate at which emissions are reduced or increased is not limited, and that on worst realizations of climate sensitivity the model is forced to use extrapolated emission reductions. The former would have a two-way effect, as the model would try to balance

between avoiding too high emission increase or decrease rates. The latter issue is, however, very critical with the highest realizations of climate sensitivity. In the worst-case scenario, negative emissions were required already by 2060, with our effort sharing exercise involving negative Annex I emissions already in 2050. Whether such emission levels would be achievable is debatable, and avoiding such situations would justify even more ambitious early action than what our scenario suggests.

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Sammanfattning på svenska

- I den här rapporten undersöker vi de olika stigarna växthusgasutsläppen kan ta för att uppnå 2°C målet, med särskild fokus på osäkerheten i klimatkänslighet och risken med utsläppsminskningarna. Rapporten beskriver ett nytt sätt för beräkning av optimala utsläppstigar, jämför resultaten med tidigare uppskattningar av Köpenhamnsöverenskommelsen, och diskuterar konsekvenserna av de föreslagna stigarna för insatsfördelning efter 2020.
- Det finns en stor vetenskaplig osäkerhet kring klimatkänsligheten - dvs frågan om hur mycket temperaturen kommer att stiga med stigande halter av växthusgaser – och därför är det inte möjligt att hävda att 2°C målet skulle uppnås med säkerhet med en förutbestämd utsläppstyg. I stället bör klimatpolitiken omformuleras när ny information om klimatkänslighet blir tillgänglig.
- Osäkerheten i klimatkänsligheten och framtida kännedom om den kan ändå beaktas i beslutsprocessen för också kortsiktiga utsläppsmål, vilket resulterar i en *säkringsstrategi* mot osäkerheten i klimatkänslighet. Denna strategin syftar till att undvika för stora framtida kostnader för utsläppsminskningar om det visar sig att klimatkänsligheten är större än vad som antagits tidigare. Det innebär att den säkringsstrategin har mer ambitiösa tidiga utsläppsminskningar än ett scenario som bortser från den osäkerheten.
- Denna rapport beskriver en förenklad och transparent modell för att bestämma en säkringsstrategi som minimerar de förväntade kostnaderna för att uppnå 2°C målet. Den resulterande kostnadsoptimala strategin pekar på en utsläppsnivå på 42,8 Gt CO₂-ekvivalenter av Kyoto-gaser år 2020. Detta är minst 5 Gt mindre än de lägsta uppskattningarna av följderna av Köpenhamnsöverenskommelsen.
- En känslighetsanalys av begränsningskostnader och diskonteringsräntor visar att den optimala utsläppsnivån kan variera mellan 37,8 och 47,8 Gt CO₂-ekv. Övre delen av detta intervall överlappar bara något med den nedre delen för de tidigare beräknade utsläppen under Köpenhamnsöverenskommelsen. Våra resultat förstärker därför de tidigare argumenten om en för låg ambition i Köpenhamnsöverenskommelsen.
- Ett fall där utsläppen år 2020 motsvarar Köpenhamnsöverenskommelsen och säkring strategin följs bara därefter också har studerats. Jämförelsen av detta fall och det första, kostnadsoptimala fall visade att 2°C målet skulle kunna uppnås även med Köpenhamnsöverenskommelsen, om den högre utsläppsnivån år 2020 ska kompenseras genom ytterligare sänkningar i genomsnitt på 1,6 Gt

per år mellan 2030 och 2080. Detta skulle leda till en ökning av utsläppsminskningarkostnaderna med 2,5 %, förutsatt att den kostnadsminimerande vägen verkligen följs efter 2020. Men om den optimala vägen inte följs före år 2030, är det kanske svårt att säkerställa att den skulle följas senare.

- Till sist ve behandlar insatsfördelning efter 2020. Om det globala utsläppsmålet måste justeras för att passa ny information om klimatkänsligheten, skulle detta påverka också insatsfördelning mellan länderna. Om det globala utsläppsmålet för t.ex. 2050 bildas via en bottom-up-procedur med utfästelser från enskilda parterna, kan det vara utmanande att säkerställa att parterna anpassar sina egna utsläppsmål.

Appendix A – The climate model

The climate module used in the model is that of the TIMES Integrated Assessment Model (TIAM), a global integrated assessment model developed under the IEA's Energy Technology Systems Analysis Program (ETSAP). The model incorporates a linear three reservoir model for the CO₂ concentration, and a single reservoir models for CH₄ and N₂O. The temperature increase is calculated with linearized radiative forcing equations and a two reservoir temperature model, differentiating between temperature increase in the atmospheric layer (atmosphere and surface ocean) and the deep ocean. Full description of the climate module is given in (Loulou and Labriet, 2008).

The MAC curves in the model were based on literature. As the cited sources did not report emissions separately for different gases, but only for the aggregate amount measured in CO₂-equivalents, there was not enough information to estimate separate MAC curves for each of the gases. Yet, full emissions and reductions of all Kyoto gases are required for analyzing the 2°C target. This lack of information would leave two options: either use assumptions for the shares of gases both in the baseline and the MAC curves; or measure all gases as CO₂-equivalents with GWP₁₀₀ weighting. The latter option was chosen as it is more transparent, although it somewhat distorts the calculation of the temperature increase.

In order to estimate the magnitude of this distortion, a reference scenario with explicit CO₂, CH₄ and N₂O emissions was constructed. The GWP weighted aggregate emissions in this scenario were set at a level corresponding to one stochastic scenario of Figure 5 with climate sensitivity realization at 3°C, while the emissions of CH₄ and N₂O were taken from our past study with the TIAM model (Ekholm et al., 2010). The global mean temperature increase in the original stochastic scenario of Figure 5 and the constructed reference case are presented in Figure 14, and the difference between the scenarios is relatively small.

The similarity of the cases can however be explained by comparing the warming effect of each gas after a release of 1 t CO₂-eq of the gas. CH₄ has a short lifetime, and therefore it causes large radiative forcing during the first decades after the emission, and a negligible forcing after 50 years. N₂O has, on the other hand, more similar warming characteristics compared to CO₂. In 100 years, by the definition of GWP₁₀₀, the warming induced by each gas is however equal. Now, in the scenario with CO₂-only emissions, the warming effect from the CH₄ that is treated as CO₂-equivalent is, roughly speaking, spread over a 100 year period instead of a few decades. Therefore the CO₂-only scenario underestimates radiative forcing in the early decades of the scenario, but overestimates it in the

latter decades. As a result, the temperature increase is relatively similar after 100 years.

It should however be noted, that this is a feature of the simplified structure of the climate module used. Should a more complex model be used, the aggregation of emissions into CO₂-equivalents-only could have larger effects, due to e.g. carbon cycle feedbacks. Yet, as such feedbacks are not considered in our model, the aggregation provides a reasonable approximation for calculating potential emission reduction strategies.

Figure 14. Global mean temperature increase in two scenarios with equal CO₂-equivalent emissions. The “CO₂-only” case corresponds to a single stochastic scenario of Figure 5 with climate sensitivity realization at 3°C, and the “All gases” has equal aggregate CO₂-eq emissions but explicit emissions for CH₄ and N₂O from (Ekholm et al., 2010). The difference in the temperature between the scenarios, due to the emission aggregation to CO₂ only, is relatively small.