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Lyngfelt, A., Johansson, D., Lindeberg, E. (2019)
Negative CO 2 emissions - An analysis of the retention times required with respect to possible carbon leakage
International Journal of Greenhouse Gas Control, 87: 27-33
http://dx.doi.org/10.1016/j.ijggc.2019.04.022

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Final manuscript submitted, *International Journal of Greenhouse Gas Control*, ***87*** *(2019) 27–33*

Negative CO_2 Emissions - An Analysis of the Retention Times Required with Respect to Possible Carbon Leakage

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Abstract

With present emissions the global CO_2 budget associated with a maximum temperature increase of about 1.5 to 2ºC will likely be spent within a few decades, Thus, it will be very difficult or perhaps even impossible to meet the climate targets agreed upon in Paris only by decreasing emissions of greenhouse gases. Scenarios presented in the IPCC reports accommodate for this by introducing so-called negative CO_2 emissions. The idea is that the cumulative CO_2 emission budget will be exceeded, but that massive negative emissions, especially during the latter part of the century, will remove the surplus of CO_2 in the atmosphere.

A number of different Negative Emissions Technologies (NETs) have been proposed, including Biomass Energy with Carbon Capture and Storage (BECCS), afforestation/reforestation, altered agricultural practices, biochar production, enhanced weathering and direct air captured. However, many of the options proposed could be associated with carbon leakage which could compromise the purpose of negative emissions, e.g. storage in of carbon in growing/dead biomass that leaks to the atmosphere. Furthermore, it may be difficult to safely assess the long-term leakage rates. To reach the large negative emissions needed it is expected to require a mix of approaches having different expected retention times, and different safety in terms of leakage rates.

Could the risk of leakage mean that we are just delaying the problem and transferring the problem to coming generations? The short answer to this is that it all depends on the leakage rates. Different leakage rates and mixes of leakage rates are investigated in the paper. For the case of a mixture of leakage time scales of 300, 1000 and 10,000 years and assuming that 80% or more was permanently stored, the contribution to the atmospheric stock was small, peaking at about 3 ppm CO_2. It was concluded that leakage would not significantly compromise the benefits of negative emissions unless leakage is substantial and rapid. To quantify what could be meant by substantial and rapid, an example would be if 100% of the CO_2 stored would leak out at a rate of the order of 1%/year.

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Keywords: Negative CO2 emissions; Negative Emission Technologies; NETs; BECCS; CO_2 Leakage

1. Background

With present emissions the global CO_2 budget associated with a maximum temperature increase *well below* 2ºC will likely be spent within a few decades. Thus, it will be extremely difficult or perhaps even impossible to meet the climate targets agreed upon in Paris only by decreasing fossil CO_2 emissions.

The concept of CO_2 budgets is used to show the total amount of CO_2 emissions that would still be allowed for meeting climate stabilization targets. The basis for the budget reasoning is the near linear relationship between cumulative emissions of CO_2 and global mean surface temperature change referred to as the Transient Climate Response to cumulative CO_2 Emissions (TCRE), [1], The carbon budgets available for a maximum warming to 1.5 or 2ºC are uncertain,[2],[3] since the budget does not only depend on the uncertainty in the TCRE, [1], but also on future emissions and climate response of non-CO_2 forcers, such as other greenhouse gases and aerosols, and the accepted risk, e.g. 33 or 50%, of not meeting the target.

For the discussion in this paper the exact numbers are not crucial, but for the sake of clarity global climate stabilization targets to restrict the warming to 1.5 or 2ºC correspond to about 420 and 1170 gigatonnes (Gt) of carbon dioxide (CO_2), from 2018 and onwards if we have an accepted risk of about 33% to not meeting the targets, [4]. These budgets are specifically for the greenhouse gas CO_2, whereas the budgets for total greenhouse gas emissions in CO_2 equivalents are larger. Thus, the CO_2 budgets are calculated by subtracting the assumed warming of non-CO_2 greenhouse gases.

As the anthropogenic emissions of CO_2 were 41.4 Gt/a in 2017, [5], the budgets for 1.5- 2ºC correspond to around 10-30 years of present emissions. It would be possible to delay the point in time when CO_2 emissions have to be completely stopped if we would be able to start reducing emissions rapidly. However, there is little to indicate an imminent decrease of emissions, instead the so-called INDCs (Intended Nationally Determined Contributions) submitted to the United Nations suggest emissions will continue to rise at least until 2030.

For the 2ºC target, 114 different scenarios have been investigated by the IPCC (Intergovernmental Panel on Climate Change) in their fifth assessment report (AR5), [6]. The vast majority of these use massive so-called negative emissions to be able to meet the budget target as a consequence of the small CO_2 budget still available. However, most of the negative emissions come during the second half of this century. Thus, the budget will indeed be exceeded, causing an overshoot of the temperature target, but the massive negative emissions eventually remove the surplus of CO_2 in the atmosphere so that the temperature target is eventually met. This is illustrated in Figure 1, which represents a median of the scenarios included in IPCC AR5. What Figure 1 actually shows is that the gross budget for fossil CO_2 emissions of the 2-degree target is approximately doubled by including -700 Gt of negative emissions. In fact, the gross negative emissions start to roll out already in 2030 to reach around -7 Gt/y already in 2050 and -15 Gt/yr at the end of the century.

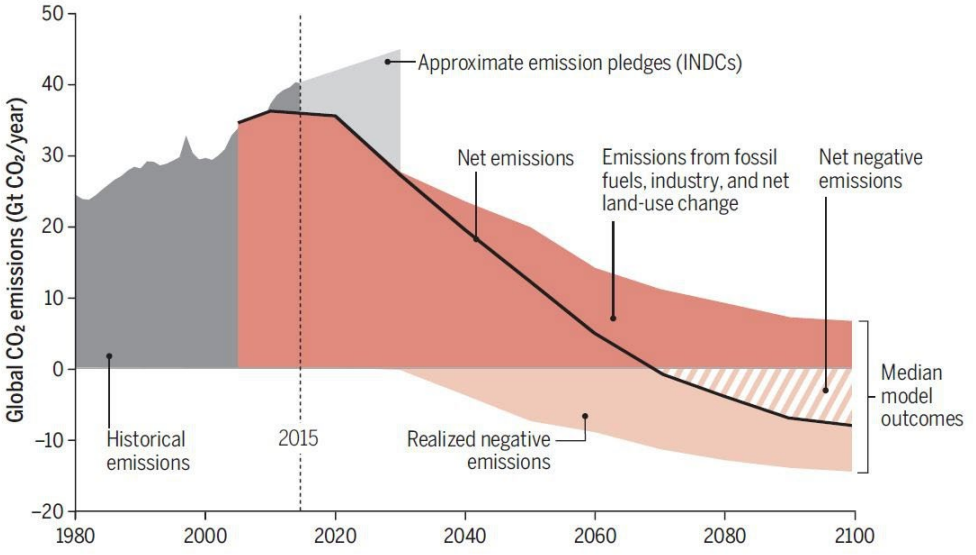

Figure 1. A median IPCC emission scenario for meeting the 2 ℃ target. From [7]

A number of different Negative Emissions Technologies (NETs) have been proposed, including BECCS, afforestation/reforestation, altered agricultural practices, biochar production, enhanced weathering and direct air captured. However, many of the options proposed could be associated with carbon leakage which could compromise the purpose of negative emissions, e.g. storage of carbon in growing/dead biomass. Furthermore, it may be difficult to safely assess the long-term leakage rates. Reaching the large negative emissions needed is expected to require a mix of Negative Emission Technologies having different expected retention times, and different safety in the assessment of leakage rates.

Could the concept of leakage mean that we are just delaying the problem and transferring the problem to coming generations? The simple answer to this is that it all depends on the leakage rates. This is because there are several processes in the natural global geochemical carbon cycles with varying time constants that remove carbon dioxide from the atmosphere. Because of these processes the “normal” carbon dioxide concentration over the last million years has been around 180-280 ppm and the ensuing normal state of the earth is ice age. However, our concept of normal is rather interglacial conditions, and from that perspective these carbon cycles will eventually lead to a deficit in CO_2, i.e. too low atmospheric concentrations of CO_2. This is in a very long time perspective, and is not in disagreement with the need to assure that the rapid rise in atmospheric CO_2 content is quickly stopped and allowed to stabilize at, or preferably fall to, a level that provides adequate climate safety.

An important question is if the NETs may also include technologies with higher leakages, in a mixture of NETs with different retention times. The paper will analyse the effect of different retention times, different total amounts of stored CO_2, and mixes of retention times.

2. The model

The carbon cycle model used in this study is based on the linear impulse response for CO_2 emissions used in IPCC AR5 to estimate Global Warming and Global Temperature change Potentials,[8]. The impulse response function is based on a sum of exponential terms with different removal time constants, see equation 1 and table 1, The parameters in the impulse response function are determined so that they fit the impulse response of more advanced biogeochemical carbon cycle models, [9] . The atmospheric stock of CO_2 can with the impulse response function be determined by convolution of emissions of CO_2.

$$f(t) = A_0 + \sum_i A_i e^{-t/\tau_i} \quad (1)$$

Table 1. Parameters in Impulse Response Function [8] (Myhre et al, 2013)

i	A_i	τ_i [yr]
0	0.217	-
1	0.186	1.186
2	0.338	18.51
3	0.259	172.9

The linear impulse response function from, [9], does not include the long-term removal processes of CO_2 from the atmosphere such as dissolution of seafloor carbonates, weathering of terrestrial carbonate rocks and silicate weathering, [10]. For the time horizon we are interested in we cannot neglect these sinks and for that reason we deal with it by letting the constant A_0, representing a fraction of CO_2 emissions that remains indefinitely in the impulse response function estimated in [9], decay in accordance with time constants of the slow carbon removal processes presented in, [10]. This is achieved by reformulating the impulse response function according to equation 2.

$$f(t) = A_0 \cdot \left(\sum_j B_j \cdot e^{-t/\tilde{\tau}_j}\right) + \sum_i A_i \cdot e^{-t/\tau_i} \quad (2)$$

B_j is estimated from [10], while $\tilde{\tau}_j$are directly taken from [10], see table 2.

Table 2. Parameters representing the slow removal CO_2 process used in equation 2.

j	B_j	$\tilde{\tau}_j$ [yr]
1	0.54	5.5 k
2	0.14	8.2 k
3	0.32	200 k

A modelling similar to ours has previously been used by Lindeberg, [11], for estimating needed residence times for Carbon Capture and Storage (CCS) .

3. Results and discussion

3.1 Effect of leakage time scale

Fig. 2 shows the effect of leakage for different leakage time scales, when storing 800 Gt of CO_2. The time scales range from very rapid i.e. 100 years, to slow 100 000 years. The effect is shown as the difference in atmospheric CO_2 stock caused by the leakage, i.e. compared to no leakage. It is also compared to the case of emitting 800 Gt, which leads to an increase of the atmospheric stock by approximately 400 Gt at the highest peak. After the peak the amount of CO_2 remaining falls gradually, and after 12 000 years there is 75 Gt left, or 10 ppm. As can be seen the effect of storage under increasing time scales both lowers and delays the peak, cf. Table 3. Thus, even the very rapid leakage, i.e. τ = 100 years, delays the peak generated from the contribution of these 800 $GtCO_2$ by 150 years and reduces the peak by 39%. For τ = 1000 years, the peak comes after more than 2000 years and is reduced by two thirds, whereas for τ = 100,000 years, the increase after 100,000 years is around 1 ppm.

Thus, it can be concluded that increased leakage time scales both lower the peaks and delay the peaks. Further, long time scales are needed to get to a negligible effect of the atmospheric content. On the other hand, even short time scales give a reduction in the atmospheric stock at the peak and also delays the peak.

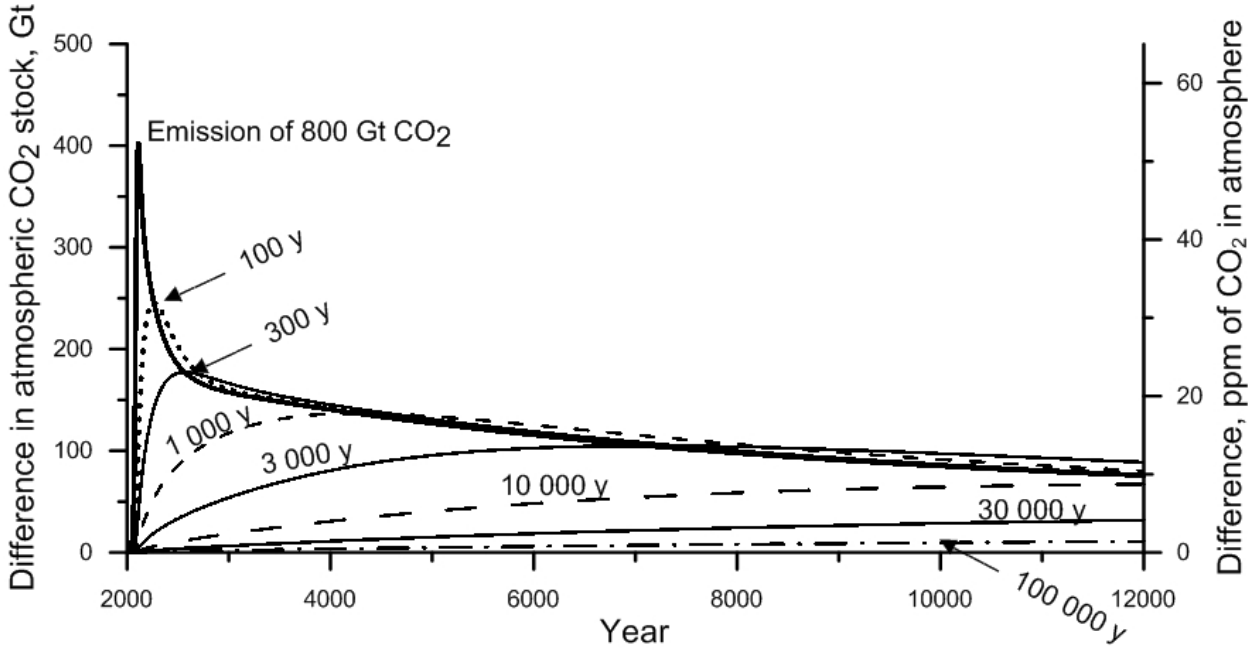

Figure 2. Increased stock of atmospheric CO_2 from 800 Gt of CO_2 for different leakage rates. For comparison emission of 800 Gt is also shown.

Table 3. Peaks reached for the different leakage time scales shown in Fig. 2.

Leakage case	CO_2 peak, Gt	CO_2 peak, ppm	Peak year	Fraction at peak year
No capture	402	52	2111	100%
Leakage time scale, years				
100	246	32	2263	61%
300	177	23	2568	44%
1000	137	18	4265	34%
3000	105	14	7125	26%
10000	67	9	14262	17%
30000	32	4	46588	8%
100000	11*	1*	100000*	3%*

* at 100 000 years peak not reached

3.2 Effect of total amount leaked

Figure 3 shows the effect of the total amount leaked with a time scale of 1000 years. The effect of increasing the total amount of CO_2 stored is trivial, more CO_2 stored means larger amounts will leak, leading to more CO_2 in the atmosphere. The highest amount stored, 8 000 Gt, is an extreme amount corresponding to using up a large part of the available fossil fuel resources, or 200 years of today's emissions of around 40 Gt/year. It gives a peak of 180 ppm, as compared to the 18 ppm peak for storing 800 Gt. It is worth noting though that the estimated atmospheric peaks obtained with large amount of CO_2 storage and corresponding leakage is likely to be underestimated by our model since it is based on a linearization of the carbon cycle. Hence, for instances with large amount of leaked CO_2 our model gives an estimate of potential impacts at the lower end of the plausible range.

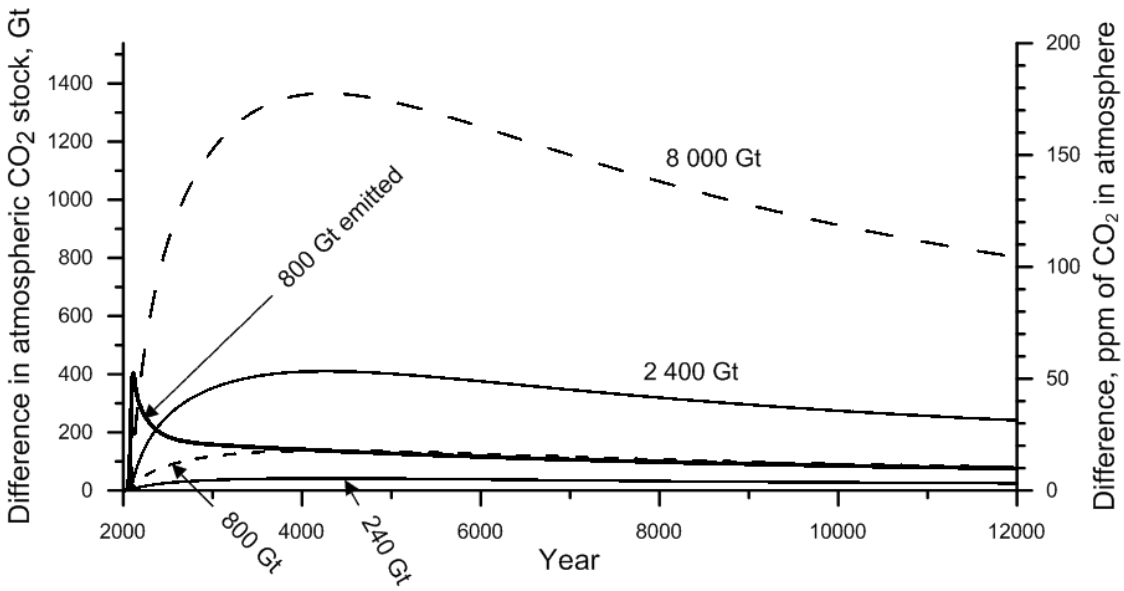

Figure 3. Increased stock of atmospheric CO_2 from 800 Gt of CO_2 for different total amount stored. Leakage time scale is 1000 years

Figure 4 shows the effect of total amount, with a time scale of 10 000 years. Even with 10 000 y time scale, the large amount of CO_2 leaking out will give high concentrations in the extreme scenarios, cf. Table 4. The larger amount we store, the longer leakage time scale is needed to avoid large increases in the CO_2 concentration.

The conclusions from the study by Lindeberg, [11], looking at a storage of 8000 and 24 000 Gt, was that a retention time of 10 000 years would be acceptable for geological storage. This does not really agree with the results in this study. An important difference is that Lindeberg's model was more realistic in the modelling of geological storage, as it included the effect of CO_2 becoming gradually, albeit slowly, permanently trapped. These trapping mechanisms involve residual trapping, where CO_2 is immobilized in fine pores, dissolution trapping, where CO_2 is dissolved in the water of the aquifere, and mineral trapping, where CO_2 reacts with minerals in the porous rock.

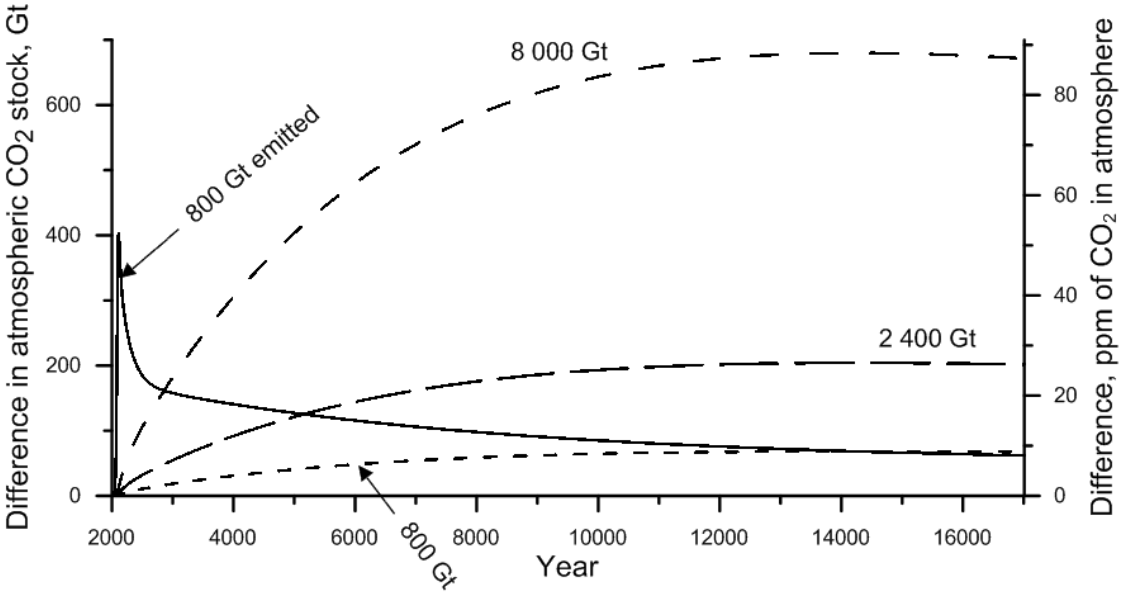

Figure 4. Increased stock of atmospheric CO_2 from 800 Gt of CO_2 for different total amount stored. Leakage time scale is 10 000 years

Table 4. Peaks reached for the different total amounts stored, as shown in l Figs. 3-4.

Leakage case	CO_2 peak, Gt	CO_2 peak, ppm	Peak year	Fraction at peak year
No capture, 800 Gt	402	52	2111	100%
Total stored, Gt (τ=1000 years)				
240	41	5	4265	10%
800	137	18	4265	34%
2400	409	53	4265	102%
8000	1366	178	4265	340%
Total stored, Gt (τ=10,000 years)				
240	20	3	14259	5%
800	68	9	14259	17%
2400	204	27	14259	51%
8000	680	88	14259	169%

3.3 The mixed case

The mixed case of the model includes capture of 800 Gt of atmospheric CO_2 and storage with leakages in three different time-scales. These are rapid, median and slow, see Table 3. They could also represent storage with low, median and high safety, or perhaps also the uncertainty of storage safety. Following the precautionary principle it would be reasonable to describe a storage with high uncertainty with respect to storage safety as having a short leakage time scale.

The three time-scales could also correspond to different principles of storage with different storage safety, e.g. afforestation/reforestation, biochar and geological storage (BECCS). However, the numbers were chosen more to see the effect of a mixture of different leakage time scales, than to represent any actual estimated values of these principles of storage. For example geological storage is here given a leakage time scale of 10,000 years, whereas estimations of a proper storage suggest a leakage time scale above 100,000 years [12]. The actual leakage time scales are very uncertain for afforestation and biochar. A forest can burn down, but on the other hand it can be restored, leading only to a temporal loss of CO_2 to the atmosphere. Thus, the assumptions on storage safety would reflect our expectations on the future society, will it be able and willing to preserve the forests? Or, if not, will it be able and willing to substitute loss of such storage with other kinds of storage?

Table 5. Assumptions for the mixed case.

Leakage case (type)	CO_2 stored, Gt (fraction)	Fraction leaked	Leakage time scale, years
Rapid ("afforestation/reforestation")	300 (37.5%)	20, 50 and 100%	300
Median ("biochar")	200 (25%)	20, 50 and 100%	1000
Slow ("geological storage")	300 (37.5%)	20, 50 and 100%	10000

The mixed case assumes that in each form of storage a certain fraction is safely, i.e. permanently, stored. Thus, the fraction leaked is 20%, 50 and 100%. The results are shown in Figure 5. For the case with 100% leakage, the peak is reduced by 75%, Table 6, corresponding to a peak of 13 ppm with its maximum 1800 years from now. As can be seen the peak is in fact very flat, within the narrow range of 10-13 ppm all through the years from 2300 up to 12 000. The two other leakage cases 50 and 20% are similar in behaviour, except that the added CO_2 stock becomes two and five times lower, yielding reductions of 88 and 95% compared to emitting the 800 Gt. This corresponds to an increase of a few ppm.

For the mixed case, it can be concluded that

- peaks become less pronounced, i.e., the impact of the atmospheric CO_2 stock/concentration of leaked emissions is more flat over time, when storage with different time scales are mixed
- a rather stable level is reached after a few hundred years
- the peak for 100% leakage is reduced by four times as compared to emitting 800 Gt. This is a similar reduction as for the unmixed case with 3000 year leakage time scale shown in Fig. 2 and Table 2. Obviously, mixing leakages having different peak years, will give a lower maximum peak than the added maximum peak of the three individual cases.
- mixing of different time scales in combination with a significant fraction of permanent storage resulted in a small impact on CO_2 atmospheric stock/concentration.

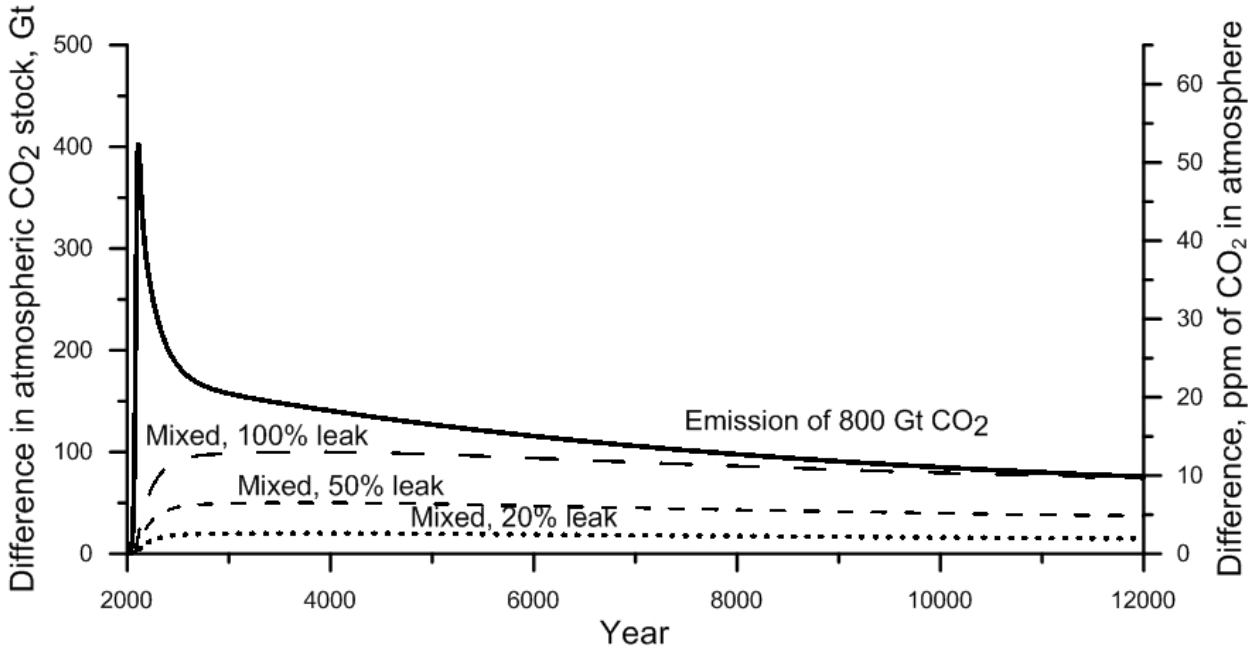

Figure 5. Increased stock of atmospheric CO_2 from 800 Gt of CO_2 for the three mixed cases, cf. Table 5.

Table 6. CO_2 peaks reached for the three different mixed scenarios, as shown in Fig. 5

Leakage case	CO_2 peak, Gt	CO_2 peak, ppm	Peak year	Fraction at peak year
No capture	402	52	2111	100%
100% leakage	100	13	3802	25%
50% leakage	50	7	3802	12%
20% leakage	20	3	3802	5%

3.4 Implications for the actual stock of atmospheric CO_2

Except for the most extreme cases, like 100% leakage and τ=300 years, CO_2 storage gives a very significant reduction of the contribution to the atmospheric CO_2 stock, and especially to the peak levels. Nevertheless, a minor, or very minor, contribution to the stock is not avoidable. So what will this mean in the context of the actual CO_2 stock in the future?

If we assume that a carbon neutral period will eventually follow, i.e. no net CO_2 emissions, this will give a slow fall in the atmospheric CO_2 stock. The data from Lindeberg, [11], for his 2 and 1.5°C scenarios are shown in Table 7. They both indicate a significant decrease in atmospheric CO_2 concentration during the coming millennium, i.e. a fall by 60-90 ppm. The line "Reference" in Fig. 6 shows the results from our model where we have used a CO_2 emissions scenario virtually identical to the gross positive CO_2 emissions in Figure 1 and where the CO_2 emissions drop towards zero the during first decades of the 22nd century. We observe a peak in the CO_2 concentration of about 460 ppm in year 2065, with a relatively rapid drop to about 390 ppm by year 2400 due to uptake in the biosphere due CO_2 fertilisation and ocean absorption. The continued decline beyond 390 ppm is primarily due to dissolution of

seafloor carbonates and weathering of rocks. A return to preindustrial CO_2 concentrations would need a time period in a quite different order of magnitude than the ones shown here. The slowest component, i.e. the weathering of rocks removes CO_2 from the atmosphere with a time scale of 200 000 years.

A comparison of our model with Lindeberg's data shows that the drop in CO_2 concentration differs somewhat. The drop (in relative terms) in Lindeberg [6] seems to be somewhat slower in the near-term while larger in the long-term compared to the response in our model. However, the difference is not more than what should be expected from the difference in CO_2 emissions scenarios and carbon cycle model representation.

Table 7. Atmospheric CO_2 concentration, assuming future net CO_2 emissions to be zero.

Year	Year	CO_2, ppm	ΔCO_2, ppm
2°C scenario			
Peak		510	
	3000	420	90
	8000	340	170
	15000	335	175
1.5°C scenario:			
Peak		410	
	3000	350	60
	8000	320	90
Our model			
Peak		460	
	3000	371	89
	8000	336	124
	15000	317	143

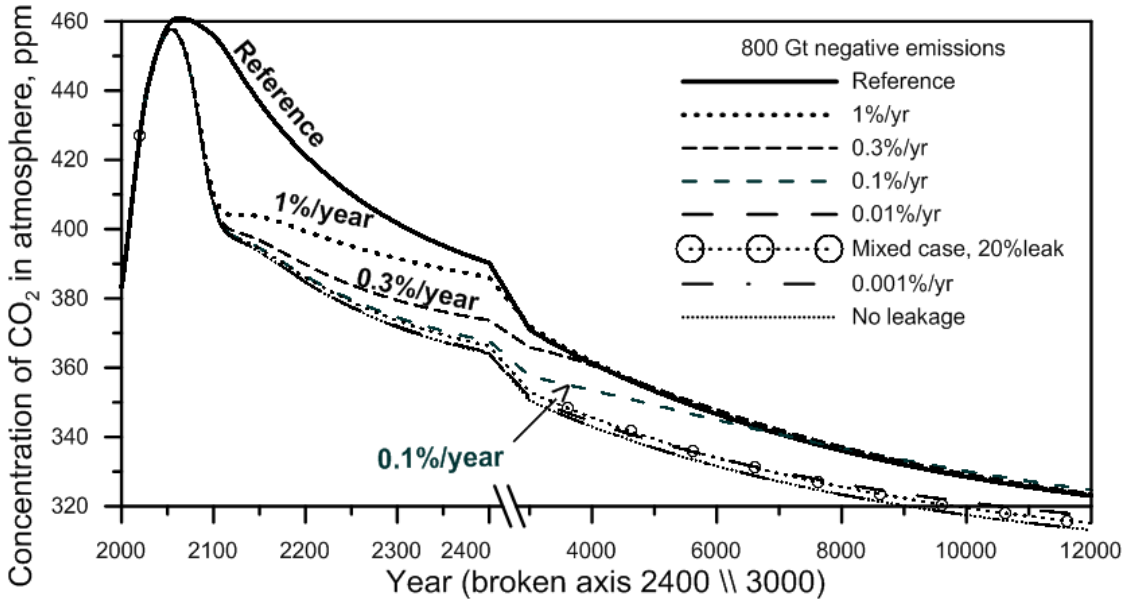

Figure 6. Atmospheric CO_2 concentration with, and without (Reference), negative emissions having various leakage rates.

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Even with rather pessimistic assumptions on leakage rates and storage time scales, e.g. the mixed case with as much as 50% total leakage, the storage of 800 Gt gives a contribution to the atmospheric CO_2 stock of less than 10 ppm which is smaller than the expected decrease in the atmospheric CO_2 concentration due to natural CO_2 removal process. In Figure 6 the effect of negative emissions with different leakage rates is included. As can be seen even the highest leakage rates are efficient in reducing the atmospheric concentration down to around 400 ppm, although the positive effect wears off in a few hundred years to coincide with the reference scenario. For cases with lower leakage and no leakage a small but distinct effect of the negative emissions remains even after 10 000 years.

4. Conclusions

The purpose of the paper was to analyse the consequences of carbon leakage for negative emissions technologies. A leakage will always result in more CO_2 in the atmosphere as compared to no leakage. However, a slower leakage will give a smaller contribution to the stock of carbon dioxide in the atmosphere. Even under the most extreme assumptions, i.e. 100% leakage, negative emissions would be better than allowing the CO_2 to be emitted and stay in the atmosphere. From the different cases studied the following conclusions can be drawn:

- Compared to the case where all CO_2 leaks immediately, already a leakage time scale of 300 years reduced the peak in CO_2 by 56% and furthermore delays the peak more than 400 years. Longer leakage time scales, typically expected from geological storage, i.e. 30 000 to 100 000, will reduce the peak by 92 to 97%.
- If very large quantities are stored, leakage will also lead very high increase in the atmospheric CO_2 stock, even for very long leakage time scales. Thus, the acceptable leakage rates are strongly dependent on the total amount stored.
- Mixing negative emission technologies with different leakage time scales, is a way of reducing the peak contribution to the carbon stock. Thus, a mixture of three leakage time scales, i.e. 300, 1000 and 10 000 years, gave a reduction of the peak by 75%, compared a 56%, 66% or 83% reduction in peak if all storage had a leakage time scale of 300, 1000 or 10 000 years, respectively. Although the mixed case gives a peak which is quite flat, the major change in CO_2 stock is nevertheless delayed a few hundred years.

The above observations are for the rather pessimistic case where ***all*** of the carbon actually leaks. A more realistic case is that the majority of the CO_2 stored remains permanently stored. Thus, using the same mixture of leakage time scales, but assuming 80% of the CO_2 is permanently stored, results in a 95% reduction as compared to the immediate leakage, or an increase in atmospheric CO_2 of 3 ppm.

The contribution of leakage to the atmospheric CO_2 stock should also be seen in the light of a gradual reduction in atmospheric CO_2 under the assumptions that net CO_2 emission will eventually become zero.

The purpose of the paper was to gain an understanding of whether, or rather under which conditions, negative emission technologies would be compromised by leakage. Leakage, under the assumptions used here, with a mixture of negative emission technologies with different uncertainties and different leakage time scales, would not significantly compromise the climate benefit of negative emission approaches.

5. Acknowledgement

This work was carried out with funding from Swedish Research Council, project “Biomass combustion chemistry with oxygen carriers” 2016-06023, the Nordic

Flagship Project No. 77732 "Negative CO_2 emissions in the Nordic energy system" (2015-2019), funded by the Nordic Energy Research and the project “Premises for bioenergy with carbon capture and storage in the global response to climate change (BECCS)” funded by the Swedish Energy Agency.

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