



## **Negative CO<sub>2</sub> emissions - An analysis of the retention times required with respect to possible carbon leakage**

Downloaded from: <https://research.chalmers.se>, 2026-04-04 18:46 UTC

Citation for the original published paper (version of record):

Lyngfelt, A., Johansson, D., Lindeberg, E. (2019). Negative CO<sub>2</sub> 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>

N.B. When citing this work, cite the original published paper.

# Negative CO<sub>2</sub> Emissions

## - An Analysis of the Retention Times Required with Respect to Possible Carbon Leakage

Anders Lyngfelt<sup>a,\*</sup>, Daniel J.A. Johansson<sup>a</sup>, Erik Lindeberg<sup>b</sup>,

<sup>a</sup>*Chalmers University of Technology, 41496 Göteborg, Sweden*

<sup>b</sup>*SINTEF, Postboks 4761 Torgarden, 7465 Trondheim, Norway*

---

### Abstract

With present emissions the global CO<sub>2</sub> budget associated with a maximum temperature increase of about 1.5 to 2°C 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<sub>2</sub> emissions. The idea is that the cumulative CO<sub>2</sub> emission budget will be exceeded, but that massive negative emissions, especially during the latter part of the century, will remove the surplus of CO<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> stored would leak out at a rate of the order of 1%/year.

---

\* Corresponding author. Tel.: +46-761-257022  
E-mail address: Anders.Lyngfelt@chalmers.se

## 1. Background

With present emissions the global CO<sub>2</sub> budget associated with a maximum temperature increase *well below* 2°C 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<sub>2</sub> emissions.

The concept of CO<sub>2</sub> budgets is used to show the total amount of CO<sub>2</sub> 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<sub>2</sub> and global mean surface temperature change referred to as the Transient Climate Response to cumulative CO<sub>2</sub> Emissions (TCRE), [1], The carbon budgets available for a maximum warming to 1.5 or 2°C 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<sub>2</sub> forcings, 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 2°C correspond to about 420 and 1170 gigatonnes (Gt) of carbon dioxide (CO<sub>2</sub>), 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<sub>2</sub>, whereas the budgets for total greenhouse gas emissions in CO<sub>2</sub> equivalents are larger. Thus, the CO<sub>2</sub> budgets are calculated by subtracting the assumed warming of non-CO<sub>2</sub> greenhouse gases.

As the anthropogenic emissions of CO<sub>2</sub> were 41.4 Gt/a in 2017, [5], the budgets for 1.5- 2°C correspond to around 10-30 years of present emissions. It would be possible to delay the point in time when CO<sub>2</sub> 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 2°C 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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.

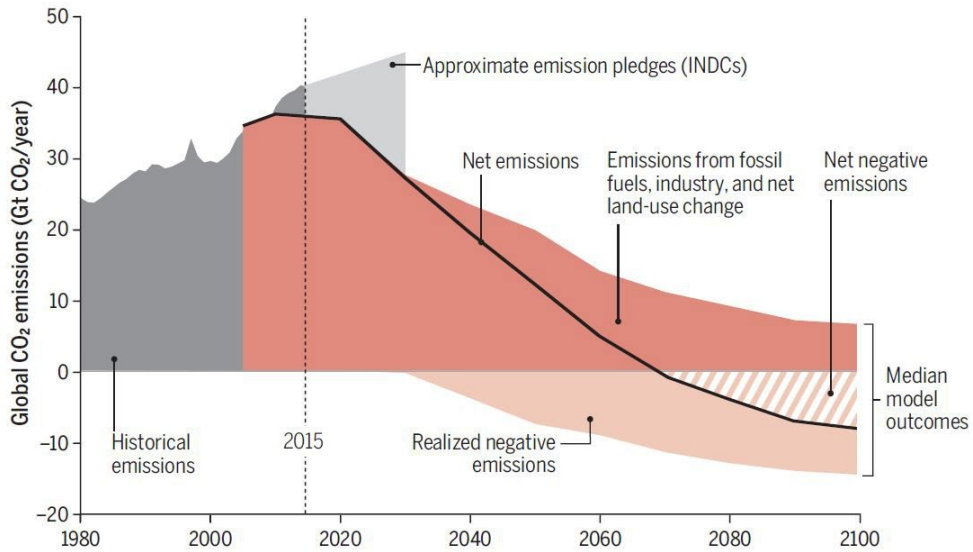


Figure 1. A median IPCC emission scenario for meeting the 2°C target. From [7]

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<sub>2</sub>, i.e. too low atmospheric concentrations of CO<sub>2</sub>. 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<sub>2</sub> 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<sub>2</sub>, 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<sub>2</sub> 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<sub>2</sub> can with the impulse response function be determined by convolution of emissions of CO<sub>2</sub>.

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

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

$i$	$A_i$	$\tau_i$ [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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub>. 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<sub>2</sub> 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<sub>2</sub> 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.  $\tau = 100$  years, delays the peak generated from the contribution of these 800 GtCO<sub>2</sub> by 150 years and reduces the peak by 39%. For  $\tau = 1000$  years, the peak comes after more than 2000 years and is reduced by two thirds, whereas for  $\tau = 100,000$  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.

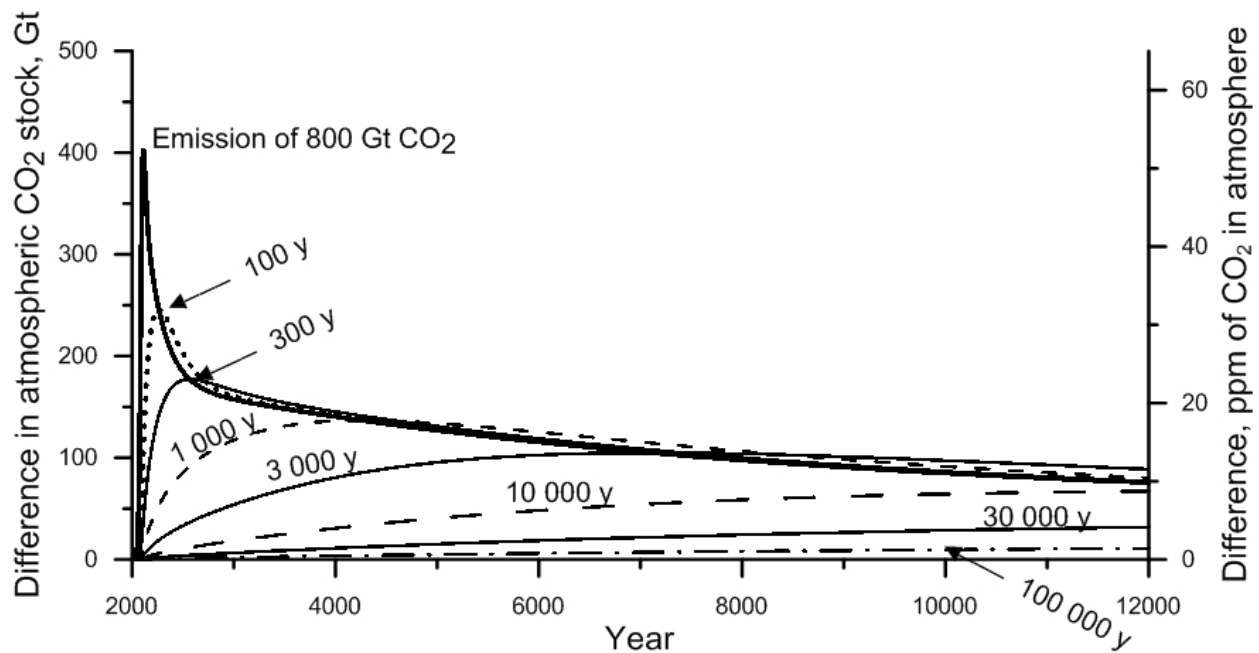


Figure 2. Increased stock of atmospheric CO<sub>2</sub> from 800 Gt of CO<sub>2</sub> for different leakage rates. For comparison emission of 800 Gt is also shown.

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

Leakage case	CO <sub>2</sub> peak, Gt	CO <sub>2</sub> 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<sub>2</sub> stored is trivial, more CO<sub>2</sub> stored means larger amounts will leak, leading to more CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> our model gives an estimate of potential impacts at the lower end of the plausible range.

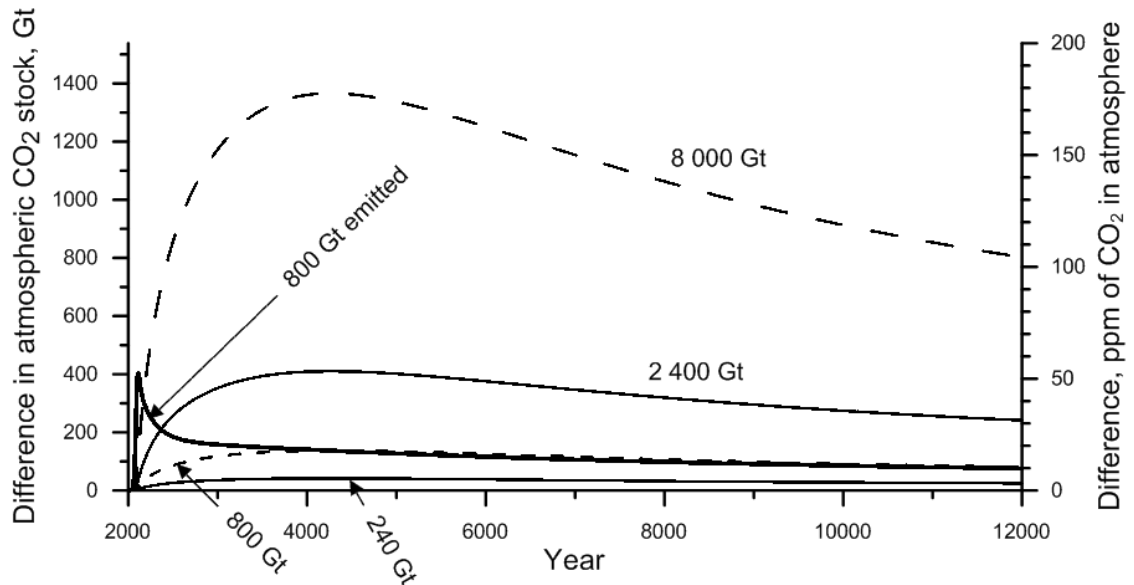


Figure 3. Increased stock of atmospheric CO<sub>2</sub> from 800 Gt of CO<sub>2</sub> for different total amount stored. Leakage time scale is 1000 years

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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> becoming gradually, albeit slowly, permanently trapped. These trapping mechanisms involve residual trapping, where CO<sub>2</sub> is immobilized in fine pores, dissolution trapping, where CO<sub>2</sub> is dissolved in the water of the aquifere, and mineral trapping, where CO<sub>2</sub> reacts with minerals in the porous rock.

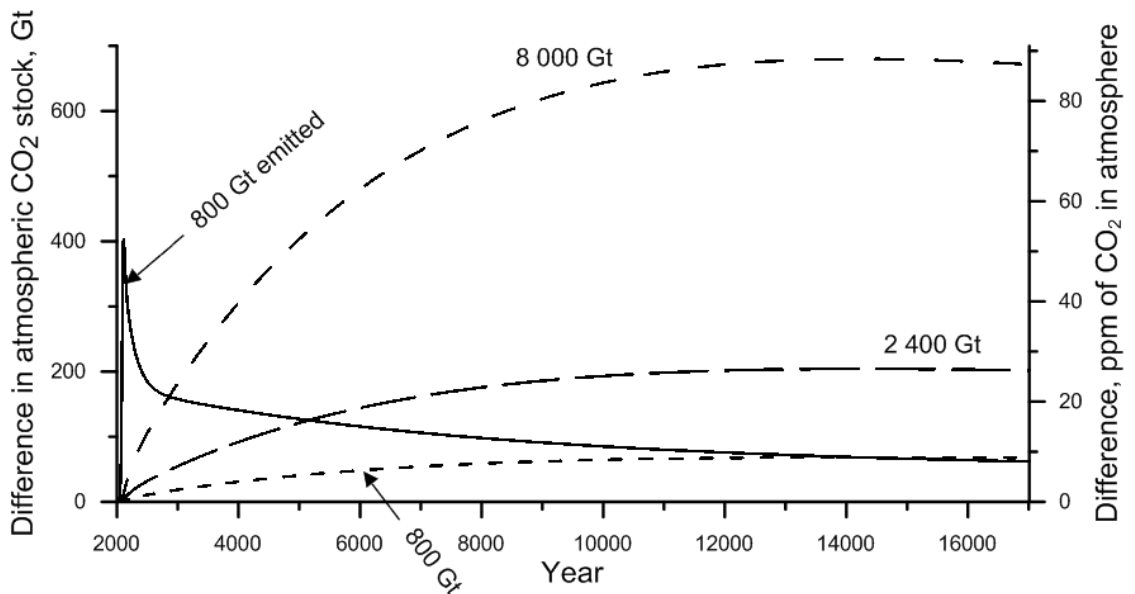


Figure 4. Increased stock of atmospheric CO<sub>2</sub> from 800 Gt of CO<sub>2</sub> for different total amount stored. Leakage time scale is 10 000 years

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

Leakage case	CO <sub>2</sub> peak, Gt	CO <sub>2</sub> peak, ppm	Peak year	Fraction at peak year
No capture, 800 Gt	402	52	2111	100%
Total stored, Gt ( $\tau=1000$ years)				
240	41	5	4265	10%
800	137	18	4265	34%
2400	409	53	4265	102%
8000	1366	178	4265	340%
Total stored, Gt ( $\tau=10,000$ 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<sub>2</sub> 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<sub>2</sub> 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 <sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> atmospheric stock/concentration.

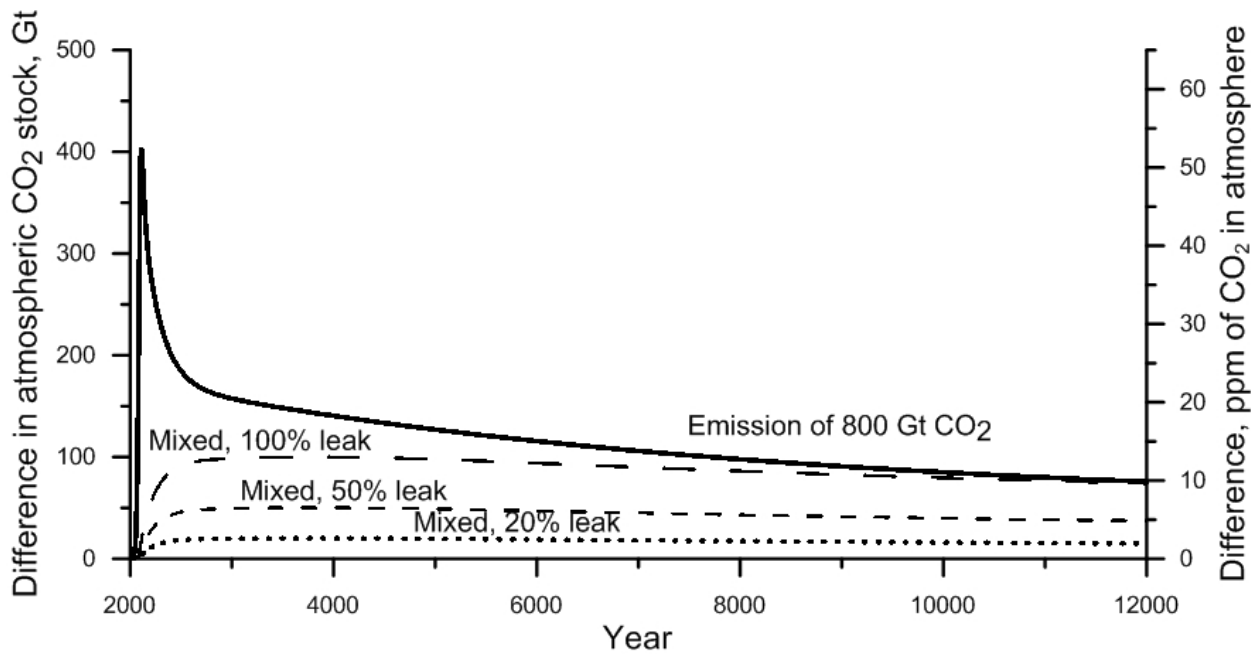


Figure 5. Increased stock of atmospheric CO<sub>2</sub> from 800 Gt of CO<sub>2</sub> for the three mixed cases, cf. Table 5.

Table 6. CO<sub>2</sub> peaks reached for the three different mixed scenarios, as shown in Fig. 5

Leakage case	CO <sub>2</sub> peak, Gt	CO <sub>2</sub> 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<sub>2</sub>

Except for the most extreme cases, like 100% leakage and  $\tau=300$  years, CO<sub>2</sub> storage gives a very significant reduction of the contribution to the atmospheric CO<sub>2</sub> 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<sub>2</sub> stock in the future?

If we assume that a carbon neutral period will eventually follow, i.e. no net CO<sub>2</sub> emissions, this will give a slow fall in the atmospheric CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions scenario virtually identical to the gross positive CO<sub>2</sub> emissions in Figure 1 and where the CO<sub>2</sub> emissions drop towards zero during first decades of the 22<sup>nd</sup> century. We observe a peak in the CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> emissions scenarios and carbon cycle model representation.

Table 7. Atmospheric CO<sub>2</sub> concentration, assuming future net CO<sub>2</sub> emissions to be zero.

Year	Year	CO <sub>2</sub> , ppm	ΔCO <sub>2</sub> , ppm
<u>2°C scenario</u>			
Peak		510	
	3000	420	90
	8000	340	170
	15000	335	175
<u>1.5°C scenario:</u>			
Peak		410	
	3000	350	60
	8000	320	90
<u>Our model</u>			
Peak		460	
	3000	371	89
	8000	336	124
	15000	317	143

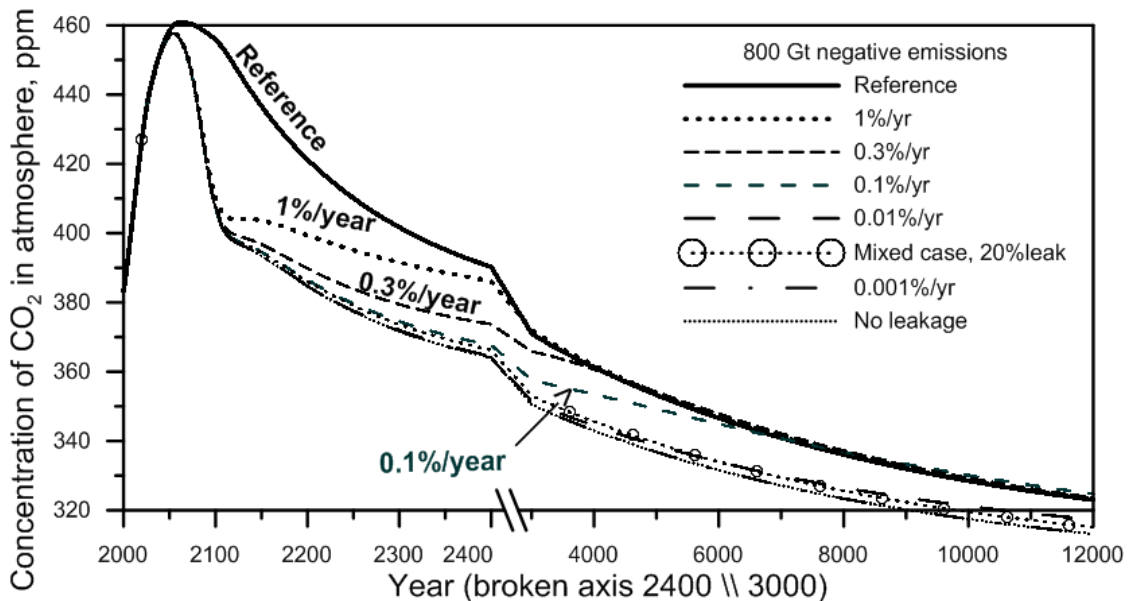


Figure 6. Atmospheric CO<sub>2</sub> concentration with, and without (Reference), negative emissions having various leakage rates.

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<sub>2</sub> stock of less than 10 ppm which is smaller than the expected decrease in the atmospheric CO<sub>2</sub> concentration due to natural CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> leaks immediately, already a leakage time scale of 300 years reduced the peak in CO<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>2</sub> stored remains permanently stored. Thus, using the same mixture of leakage time scales, but assuming 80% of the CO<sub>2</sub> is permanently stored, results in a 95% reduction as compared to the immediate leakage, or an increase in atmospheric CO<sub>2</sub> of 3 ppm.

The contribution of leakage to the atmospheric CO<sub>2</sub> stock should also be seen in the light of a gradual reduction in atmospheric CO<sub>2</sub> under the assumptions that net CO<sub>2</sub> 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<sub>2</sub> 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.

## 6. References

- [1] A. H. MacDougall, N. C. Swart, and R. Knutti. The Uncertainty in the Transient Climate Response to Cumulative CO<sub>2</sub> Emissions Arising from the Uncertainty in Physical Climate Parameters. *Journal of Climate* 2017; **30**.
- [2] J. Rogelj, M. Schaeffer, P. Friedlingstein, et al. Differences between carbon budget estimates unravelled. *Nature Climate Change* 2016; **6**.
- [3] E. Kriegler, G. Luderer, N. Bauer, et al. Pathways limiting warming to 1.5°C: a tale of turning around in no time? *Phil. Trans. R. Soc. A* 376:20160457. <http://dx.doi.org/10.1098/rsta.2016.0457> 2018.
- [4] J. Rogelj, D. Shindell, and K. Jiang. Chapter 2: Mitigation pathways compatible with 1.5°C in the context of sustainable development, in IPCC report "Global Warming of 1.5°C", [http://report.ipcc.ch/sr15/pdf/sr15\\_chapter2.pdf](http://report.ipcc.ch/sr15/pdf/sr15_chapter2.pdf). 2018.
- [5] C. L. Quéré, R. M. Andrew, P. Friedlingstein, et al. Global Carbon Budget 2018. *Earth Syst. Sci. Data* 2018; **10**:2141–2194.
- [6] S. Fuss, J. G. Canadell, G. P. Peters, et al. Betting on negative emissions. *Nature Climate Change* 2014; **4**:850-853.
- [7] K. Anderson and G. Peters. The trouble with negative emissions. Reliance on negative-emission concepts locks in humankind's carbon addiction. *Science* 2016; **354** 182-183.
- [8] G. Myhre, D. Shindell, F.-M. Bréon, et al. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.; 2013.
- [9] F. Joos, R. Roth, J. S. Fuglestedt, et al. Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmospheric Chemistry and Physics* 2013; **13**:2793-2825.
- [10] D. Archer, H. Kheshgi, and E. Maier - Reimer. Multiple timescales for neutralization of fossil fuel CO<sub>2</sub>. *Geophysical Research Letters* 1997; **24**:405-408.
- [11] E. Lindeberg. *The quality of a CO<sub>2</sub> repository: what is the sufficient retention time of CO<sub>2</sub> stored underground.* in *Proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies, Elsevier, Oxford, UK, Vol. 1.* (2003)
- [12] J. Alcalde, S. Flude, M. Wilkinson, et al. Estimating geological CO<sub>2</sub> storage security to deliver on climate mitigation. *Nature Communications* 2018; **9**:Article number: 2201, DOI: 10.1038/s41467-018-04423-1.