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An assessment of cumulative CO_2 reductions from carbon capture and storage at coal fuelled plants in a carbon constrained world

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Abstract. This brief study endeavours to estimate the extent of contributions from Carbon Capture and Storage (CCS) to cuts in global CO_2 emissions under certain explicit assumptions as to deployment of the technology, capture efficiency, energy penalty and overall emissions from fossil fuels in the medium and long term perspective. The cumulative emissions captured and the cumulative emissions to the atmosphere in a CCS-scenario are assessed in order to identify the cumulative emissions avoided due to CCS. These estimates are finally put in perspective of the remaining global 2° Celsius budget for CO_2.[1] The study's focus is on coal fuelled mainly power generation plants. The study indicates contrary to most reports and studies that CCS cannot deliver significant reductions in time to play a role in the effort of keeping the global temperature increase below 2° Celsius. The estimated cumulative avoided emissions from CCS on coal 2010-2050 will amount to 11% of the cumulative emissions from all coal fuelled plants. The cumulative emissions to the atmosphere that will take place despite deployment of CCS will make demands on 89% of the remaining 2° Celsius CO_2-budget for fossil fuels or 212% of the proportion of the remaining 2° Celsius CO_2-budget that could be allotted to coal.

1. Introduction

CCS (Carbon Capture and Storage) is a controversial high cost mitigation technology designed to play a major role in future climate policies all over the world. CCS is repeatedly referred to as an important bridging technology. The technology ideally serves a double purpose of allowing fossil fuels, primarily coal, to continue to be a substantial part of the future global energy supply while at the same time abating climate impacts from fossil fuel sources. Yet this immature technology features a number of large problems like cost, funding, additional energy and water consumption and other detrimental environmental effects.[2,3] One extremely important aspect of CCS as a climate tool, however, has been practically neglected in the extensive literature on the subject: its actual aggregate effect on the climate system.

In order to properly assess CCS as mitigation technology over the next decades all the facilities in one sector or in all sectors that reasonably could be equipped with CCS would be included. In this study it is coal fuelled power generation and industries that are considered.

It is important to look not only at a snapshot of "one facility" or of one year in the future (e.g. 2030, 2040 or 2050) but the whole film, i.e. the whole period from now and till 2050. Viewing carbon capture and storage in relation to the available carbon budget will reveal the overall effect of applying the technology.

The budget approach

"Latest research shows that there is only a realistic chance of restricting global warming to 2 °C if a limit is set on the total amount of CO2 emitted globally between now and 2050 (CO2 global budget)."[4]

The overall frame is the available greenhouse gas – GHG – budget, which is an expression of the cumulative amount of GHG that can be emitted to the atmosphere in the future (e.g. the rest of the century or as in this study before 2050) if the CO_2-eq-concentration in the atmosphere is to be kept below a certain level. Setting 2050 as the far end of the perspective is justified in light of the warnings from recent science, e.g. Climate Change, Global Risks, Challenges and Decisions (2009)[5], Meinshausen et. al. (2009)[6] and Copenhagen Diagnosis (2009)[7]

"Specifically, cumulative CO2 emissions to 2050 will largely determine the extent to which global temperature rise can be kept within the 2 °C guard rail. In order to achieve this with a probability of 67 %, CO2 emissions to midcentury must be capped at around 750 Gt, with only a small residual amount being emitted post-2050. At current emissions rates, however, this CO2 budget will be exhausted within around 25 years – and even sooner if emissions continue to rise." [8]

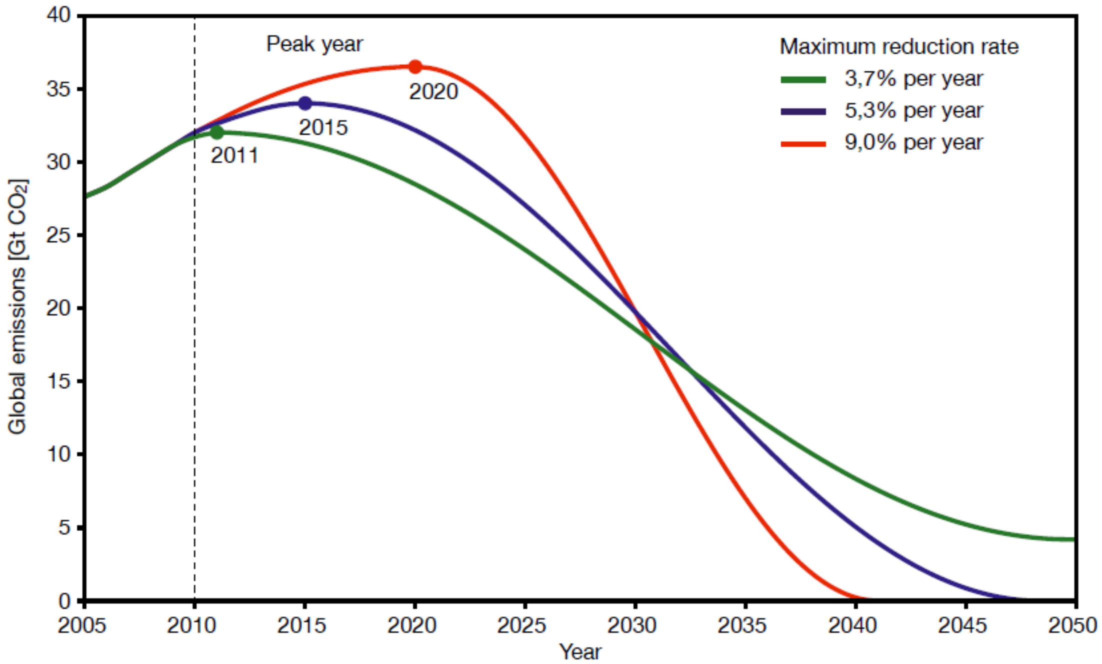

Figure 1. "Examples of global emission pathways for the period 2010–2050 with global CO_2 emissions capped at 750 Gt during this period. At this level, there is a 67 % probability of achieving compliance with the 2 ℃ guard rail (…). The figure shows variants of a global emissions trend with different peak years: 2011 (green), 2015 (blue) and 2020 (red). In order to achieve compliance with these curves, annual reduction rates of 3.7 % (green), 5.3 % (blue) or 9.0 % (red) would be required in the early 2030s (relative to 2008)." Source: WBGU, p. 16, Figure 3.2-1

Figure 1 is a strong illustration of the emergency in the present situation. Climate action has to be now and it must be all-encompassing. Yet the pathways in Figure 1 reflect a 33% probability of exceeding a 2^o Celsius rail. The global budgets in the present paper refer to a 20% probability of exceeding the 2^o Celsius global warming which would make the pathways in Figure 1 even steeper.

"If the acceptable exceedance probability were only 20%, this would require an emission budget of 890 Gt CO2 or lower (illustrative default). Given that around 234 Gt CO2 were emitted between 2000 and 2006 and assuming constant rates of 36.3 GtCO2 yr^{-1}(ref. 3) thereafter, we would exhaust the CO2 emission budget by 2024, 2027 or 2039, depending on the probability accepted for exceeding 2^o C (respectively 20%, 25% or 50%)."[9]

Under these conditions the budget is calculated to be 543 Gt CO2 for all CO2 emissions or 400 Gt CO2 for fossil fuel emissions alone for 2010-2049.

The CCS reports we have studied to date have not given any assessment of the influence of large scale deployment of CCS on the remaining CO_2 budgets. In fact they do not include the perspective of having a restricted budget. The questions for this study are therefore:

A. How much could a large scale deployment of CCS contribute to cut emissions of greenhouse gases to the atmosphere seen in the perspective of a constrained CO2 budget?
B. How large will the emissions to the atmosphere be despite large scale deployment of CCS?
C. Will CCS be able to meet the urgency in a situation where emissions must peak before 2015?

2. Methodology

Definitions and boundaries

This study focuses on coal fuelled plants only and does not include other greenhouse gases than CO2 except emissions of methane pertaining to coal mining that are considered in relation to the assessment of CO2 efficiency. Consequently emissions are calculated as CO2, not CO2-equivalent.

We define avoided emissions due to CCS as the difference between 1) the cumulated emissions from all sources in a system without CCS and 2) the cumulated emissions in a system with CCS. This definition goes beyond the definition used by IEA:

"tCO2 avoided: the level of emissions abatement achieved by CCS-equipped facilities relative to the emissions of an equivalent facility (i.e., with the same output) without CCS."[10]

IEA's definition does not include the emissions outside the capture process of a single facility.[11] It does not take the whole sector in consideration and it does not consider the emissions accumulated over time. [See also our definition of CO_2 efficiency below under point 4.]

In the calculation of cumulated avoided emissions 2010-2049 from CCS the following parameters are taken into consideration:

1. The deployment of CCS as aggregate CCS-capacity on coal fuelled plants 2010-2050.
2. The energy penalty, "the percentage of additional energy that would have to be used to generate the same amount of electricity."[12] i.e. extra energy consumption due to the capture process.
3. The capture efficiency; expresses a single facility's ability to separate and remove CO_2 from the flue gas.[13] It is the amount of CO_2 emissions that is actually captured in the capture part of the plant divided by the amount of CO_2 emissions that enter the capture process with the flue gas. It is often rendered as a theoretical 85%, which is also used here.
4. The CO_2 efficiency; an expression of the whole sector's ability to separate and remove CO_2 given that CCS is deployed on a large scale. We define it as the amount of CO_2 emissions that are actually captured in the sector divided by the amount of CO_2 emissions generated from extraction to underground storage. They include upstream emissions pertaining to extraction and transportation of coal, one-off emissions from building of CCS plants and building of transport infrastructure, emissions under operation from the capture process and compression of CO_2, downstream emissions from transport and injection into the storage and finally emissions connected with monitoring of and leakages from the storage for an extended period.
5. The global emissions from all coal fuelled power plants and industries without CCS.
6. The global emissions from all coal fuelled power plants and industries with CCS.

Calculations

In order to single out the importance of CCS on coal to the global 2^o Celsius CO_2 budget we have chosen a scenario close to the WEO / Blue Map Scenario[14] which is the basis for IEA Technology Roadmap Carbon Capture and Storage (2009)[15]. The BLUE Map has a reduction pathway aiming at

50% reductions by 2050 (down to about to 14 Gt CO_2) compared to 2005 but with an unabated baseline assuming a rise in CO_2 emissions from about 28 Gt in 2005 to 62 Gt in 2050.

We have several reservations concerning assumptions of the primary demand for energy services or the inclusion of nuclear in the mix of mitigation tools in the BLUE Map. We also consider 50% reductions by 2050 compared to 2005 to be insufficient in order to stay below the 2^o Celsius ceiling. Still we have chosen to make our calculations on a basis that resembles the BLUE Map reductions pathway because the IEA's perspective is one of the most authoritative in relation to CCS. Our results can be debated on a level ground by being put into that well-known perspective.

		2010	2020	2030	2040	2050	
I	BLUE Map Baseline	30.0	38.0	40.2	52.1	62.0	Gt CO_2
II	BLUE Map excluding CCS	30.0	27.5	24.9	23.3	21.6	Gt CO_2
III	**This study's standard baseline**	**30.0**	**27.3**	**23.8**	**20.7**	**17.5**	Gt CO_2
IV	BLUE Map Scenario	30.0	27.0	22.8	18.1	13.4	Gt CO_2

Table 1. BLUE Map Baseline; reductions curve in BLUE Map excluding CCS; baseline of this study's standard scenario; BLUE Map reductions' curve including CCS.

The numbers for emissions 2010-2050 from all fossil fuels in our baseline (Table 1, III) are estimates from readings of the emissions curves in the BLUE Map Scenario (Table 1, IV) under the supposition that the reductions from the other mitigations tools are effectuated. Table 1, II shows the values from BLUE Map Scenario excluding the abatement from CCS. Our baseline is set as the mean value between II and IV.

The point of departure of the calculation is therefore a situation where energy development and the whole portfolio of mitigation tools are deployed as envisaged in the BLUE Map. Herein their contributions to reductions of the expected 48 Gt CO_2 in the year of 2050 are: Nuclear 6%; Renewables 21%; Power generation efficiency and fuel switching 7%; End use fuel switching 11%; End use electricity efficiency 12%; End use fuel efficiency 24%. CCS industry and fuels transformation (upstream) is expected to contribute with 9%. CCS power generation is set to contribute with 10%. This does not distinguish between the fuels.

There is a coal part in CCS industry and a gas part in CCS power generation. In order to make calculations on CCS on emissions from coal fuelled plants we estimate that emissions from coal are roughly fifty per cent of emissions from industry and power with CCS. This estimate allows us to deal with emissions from coal fuelled plants in a scenario that reasonably well resembles the reductions pathway in BLUE Map.

	Standard scenario	Calculated as	**2010-2019**	**2020-2029**	**2030-2039**	**2040-2049**		**2010-2049**
A	Emissions from all fossil fuels	Re Table 1	287	256	223	191	Gt CO_2	**957**
B	Emissions from coal fuelled plants (no CCS)	42 % of A	121	108	94	80	Gt CO_2	**402**
C	Deployment of CCS	Estimate	1	8	24	40	%	
D	Emissions from plants with CCS, incl. 25% energy penalty	B*1.25* C/100	1	11	28	40	Gt CO_2	**80**
E	Emissions from plants without CCS	B*(100-C)/100	119	99	71	48	Gt CO_2	**337**
F	Emissions total (with and without CCS)	D+E	121	110	99	88	Gt CO_2	**418**
G	Emissions stored	D*0.77	1	8	22	31	Gt CO_2	**62**
H	Emissions to the atmosphere despite CCS	F-G	120	102	77	57	Gt CO_2	**356**
I	Avoided emissions	B-H	1	6	16	23	Gt CO_2	**46**
J	Avoided emissions as percentage	(I/B)*100						**11%**

Table 2. The numbers for emissions from all fossil fuels (A) are estimates from readings of the emissions curve in IEA's BLUE Map scenario. The ratio for emissions from coal vs. all fossil fuels is from IEA's key World statistics (2009). This ratio is kept unchanged in all four decades. In WEO 2006 Reference Scenario the same ratio between coal, oil and gas is unchanged from 2004 through 2030.[16]

Variables with reference to Table 2

A: Emissions from all fossil fuels. The figure for 2007 was 29 Gt CO_2[17]. We have extrapolated this to be 30 Gt CO_2 in 2010. Emissions in Table 2, row A are calculated from the figures in Table 1, III.

B: Emissions from coal fuelled plants (no CCS). The part of CO_2 emissions from coal has been set at 42%[18] as percentage of all fossil fuels emissions from 2010 through 2050. These emissions represent the 100% potential for deployment of CCS on emissions from coal.

C: Deployment of CCS on coal fuelled plants. The deployment has been estimated as percentages per decade of the full potential of CCS on coal (B): 1 – 8 – 24 – 40 per cent throughout the four decades. In an alternative calculation the deployment is ramped up dramatically to 1 – 11 – 50 – 90 per cent throughout the four decades.

D: Emissions from plants with CCS, incl. 25% energy penalty. The energy penalty has been set in the low end, namely 25%.[19]

E: Emissions from plants without CCS. Calculated as a fraction of the emissions from coal fuelled plants (no CCS) (B). The fractions are 99% – 92% – 76% – 60%. In the alternative calculations with the speedy deployment the fractions are 99% - 89% - 50% - 10%.

F: Emissions total. Sum of emissions from plants with CCS (D) and emissions from plants without CCS (E).

G: Emissions stored. The net CO_2 efficiency is calculated to be 77% based on 85% capture efficiency and on upstream and downstream emissions estimated to be 8% (most likely a low estimate[20]. See Viebahn et.al (2007) op.cit. Hence emissions stored are 77% of emissions from plants with CCS (D)

H: Emissions to the atmosphere. Emissions to the atmosphere are emissions total (F) minus emissions stored (G).

I: Avoided emissions. Avoided emissions are the cumulated emissions from coal fuelled plants in a system without CCS (B) and the cumulated emissions to the atmosphere in a system with CCS. (H).

J: Avoided emissions as percentage. Avoided emissions (I) as percentage of emissions from coal fuelled plants (no CCS) (B)

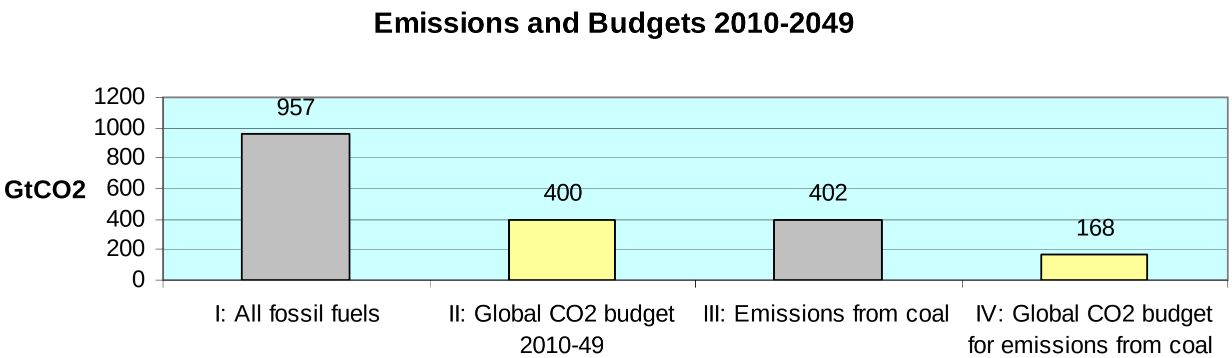

Figure 2. Emissions 2010-2049 from all fossil fuels are calculated to be 957 Gt CO_2 (Table 2, row A), and the emissions from coal fuelled plants are calculated to be 402 Gt CO_2 as 42% of the overall fossil fuels emissions (Table 2, row B). The global CO_2 budget for all fossil fuels is calculated to be 400 Gt CO_2. The budget for emissions from coal is 168 Gt CO_2 provided a constant 42% share of emissions from coal.

The 400 Gt CO2 for all fossil fuels is derived from Meinshausen et al.(2009), which has a budget of 886 Gt CO2 for the period 2000-2049. "Given that around 234 Gt CO2 were emitted between 2000 and 2006 and assuming constant rates of 36.3 GtCO2 per year" in 2007-2009, the remaining budget 2010-2049 is 543 Gt CO2 from all sources with a 20% probability of exceeding 2^{o} Celsius for such a budget. The fossil fuels share of the total CO2-budget is 73.8% of the overall CO2-emissions according to IPCC AR4 Summary for Policy Makers, Figure SPM 3.

It is dramatic that even after abatement from the portfolio of mitigation tools: nuclear, renewables, efficiency etc. there is still 957 Gt CO_2 emitted, which is 239% of the global 2^{o} Celsius CO_2-budget of 400 Gt CO_2 2010-2049.

3. Results

In a scenario with decreasing CO_2-emissions in the period 2010-2049 (Figure 3) CCS will contribute cumulative avoided emissions of 46 Gt CO_2 or 11% compared to CO_2-emissions (402 Gt CO_2) from coal fuelled plants in a scenario without CCS.

The CO_2 emitted to the atmosphere is consequently 89% of the sector's emissions or 356 Gt CO_2 despite aggressive deployment of CCS.

Only 7 Gt CO2 will be avoided 2010-2029 despite deployment of CCS.

CCS influence on 2° Celsius CO_2-budget 2010-2049 for all fossil fuels: The CCS-on-coal related emissions (356 Gt CO_2) account for 89% of the remaining 2° Celsius CO_2-budget for 2010-2049 for all fossil fuels (400 Gt CO_2).

CCS influence on 2° Celsius CO_2-budget 2010-2049 for emissions from coal: The emissions to the atmosphere (356 Gt CO_2) add up to 212% of the total 2° Celsius CO2-budget for 2010-2049 for emissions from coal (168 Gt CO_2) provided that coal's share of the CO2-emissions continues at 42%.

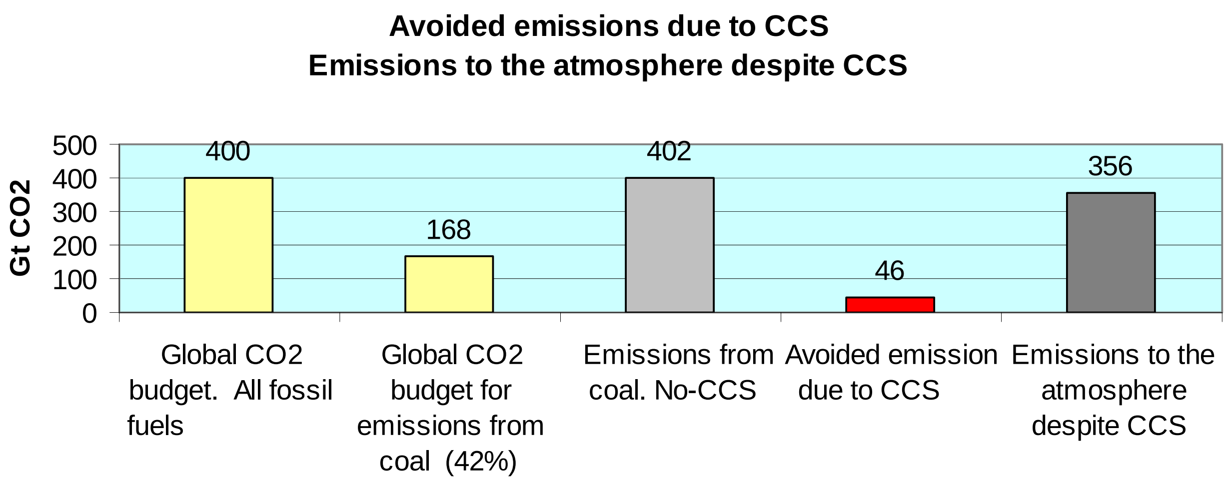

Figure 3. Global CO_2 budgets and emissions from coal without CCS split into avoided emissions and emissions to the atmosphere. The global CO_2-budget for fossil fuels 2010-2049 is calculated as 56.6%[21] of the total global CO_2-budget of 886 Gt CO2 for 2000-2049 (Meinshausen et. al. 2009).

Alternative calculations

<u>90% deployment 2040-2050.</u> In an alternative scenario with unchanged energy penalty and upstream and downstream emissions but a much faster deployment of 1% – 11% – 50% – 90% of the potential capacity for CCS throughout the four decades the results are as follows:

Total emissions (row F) amount to 435 Gt CO_2; emissions stored 127 Gt CO_2; emissions to the atmosphere 308 Gt CO_2; avoided emissions 94 Gt CO_2; and avoided emissions as percentage 23%.

This reflects a deployment where "power plants must rapidly adopt CCS over the next three decades; by 2040, nearly all fossil-based power plants will use CCS", as stated in IEA's Technology Roadmap CCS (p. 18).

<u>40% energy penalty.</u> In an alternative scenario with deployment unchanged at 1% - 8% - 24% - 40% but with a more severe energy penalty of 40% and upstream and downstream emissions of 12% the results are as follows:

Total emissions (row F) amount to 428 Gt CO2; emissions stored 66 Gt CO2; emissions to the atmosphere 362 Gt CO2; avoided emissions 40 Gt CO2; and avoided emissions as percentage 10%.

4. Discussion

In order to evaluate the CCS mitigation potential in a world with a constrained carbon budget we have created a projection for deployment of CCS 2010-2049 based on reports published by IEA, especially the IEA BLUE Map scenario. As coal is going to be the longest lasting fossil resource and because big coal fired power plants and heavy industries using coal are the most obvious targets for CCS, we have focused on CCS on coal in both sectors. Coal also represents the largest reduction potential among the fossil fuels.

Below we discuss our main findings regarding A: The mitigation potential; B: The volume of emissions to the atmosphere and C: The urgency of the climate crisis.

A. The results presented in Table 2 show avoided emissions of 11%; with more aggressive deployment the avoided emissions can increase to a maximum of 23%.

The avoided emissions percentages are in any case far from the most frequent picture of CCS being capable to capture 85%-90% of emissions. This difference is explained by the difference in approach: we have used a sectoral as well as a long term approach: all coal fuelled plants seen over a period of 40 years. The ordinary presentation has a single facility approach and is not concerned with cumulative (avoided) emissions.

It is indeed justified to take the broader view and look for cumulative effects since this is what matters from a climate perspective. The captured emissions are interesting, the avoided emissions are more important but in the end it is the emissions to the atmosphere that matters.

This is an issue of great importance since the fossil fuel industry and the CCS lobby organizations are heavily lobbying policy makers and the general public by giving the impression that CCS can reduce the CO2 emissions in the flue gas with 85-90% and safely store it underground forever. In the light of our findings the message should be that CCS can only avoid a small fraction of the global emissions – optimistically about 11% and unrealistically with a 90% deployment up to 23% and with increased energy penalty to 40% and increased upstream and downstream emissions of 12% the avoided emissions decrease to 10%.

B. The flip side of the avoided emissions is the emissions to the atmosphere. In our standard calculation (Table 2 and Figure 3) the emissions to the atmosphere are 356 Gt CO_2. These emissions are not only very large but more importantly they exceed the narrow 2^o Celsius budget. This is also the case in the alternative with 90% deployment 2040-2049 which let 302 Gt CO_2 go to the atmosphere.

It is important to bear in mind that we have only focused on CCS on coal, representing 42% of the emissions from fossil fuels. When the emissions to the atmosphere in our standard calculation take up 89% of the remaining 2^o Celsius CO_2-budget there is so little left for natural gas and oil for transportation and other purposes that the budget will burst. We might then get 3^o Celsius or even 4^o Celsius with devastating effects on human societies and natural ecosystems.

The BLUE Map Scenario shows unsurprisingly that the mitigation potential of CCS is largest for the two last decades before 2050. But BLUE Map does not specify the emissions that the large point sources will lead into the atmosphere throughout the four decades.

This is the pivotal point of this study and the results we have found do not support the appreciation of CCS as an important mitigation tool. Rapid deployment of CCS on the large coal fuelled point sources is capable of avoiding only a very small volume of emissions.

We have made cautious assumptions with an energy penalty of 25%[22] and upstream and downstream penalties estimated at 8%.[23] Increasing these to respectively 40% and 12 % did not change the outcome much.

The speed of deployment proves to be the most determining factor for CCS capacity to deliver avoidance of emissions. And this is already the biggest challenge for the whole concept: when will the pilot and demonstration plants be developed and tested with sufficient success to bring CCS to the market place?

We consider the speed of deployment of CCS reaching a level of 40% in average for 2040-2049 as very ambitious. The alternative based on the assumption that “nearly all fossil-based power plants will use CCS” by 2040 is in our view unlikely given the state-of-play for CCS-development as of today, the enormity of the capture facilities, the infrastructure that is demanded and the need for storage capacity within reach of each and all of these plants and not least public acceptance to live on top of a CO_2 storage site or the CO_2 infrastructure in general.

C. We set out to investigate if CCS would be able to meet the urgency in a situation where emissions must peak before 2015. Our results show that we can only expect 1 Gt CO2 avoided emissions before 2020 and another 6 Gt CO2 from 2020 to 2030. In the same two decades a CCS pathway will emit 120 Gt CO2 and 101 Gt CO2 respectively to the atmosphere from coal fuelled plants alone.

The BLUE Map Scenario also renders reductions from CCS around 1 Gt CO2 before 2020. BLUE Map aims at 50% reductions in CO2-emissions by 2050 compared to 2005. This relates to a mere 31% reduction compared to 1990, which is far from enough to keep the global average temperature below 2^o Celsius.

The tools that deliver reductions between 2010 and 2030 in BLUE Map are mainly improvements in end use of fuels and electricity, in power generation, fuels switch and renewables. If BLUE Map should be improved to deliver less than 2^o Celsius these tools must be scaled up from the beginning. Very soon however every country must decide what direction of development it wants to follow: either they phase out fossil fuels or they continue investments in fossil fuel infrastructure by way of CCS on new power plants or by retrofitting older ones. The nuclear option is not one we recommend for a number of reasons. But it obviously competes with CCS and renewables.

CCS and nuclear have strong drawbacks in relation to a development of a flexible energy supply system based on renewables. CCS will be so expensive that in power generation there will be a pressure to keep the plants running around the clock delivering a constant base load very much like a nuclear power plant. In other words they cannot play a balancing role in a system with a large part of oscillating renewables like sun and wind[24] and the large base load will limit the room for renewables.

Likewise the social, health and environmental problems that are connected with the use of fossil fuels will not only continue but they will increase due to the extra energy consumption needed for CCS. Another factor that has received little attention with respect to CCS is the severe increase in water consumption and water withdrawal that makes CCS an unsuitable option in inland China, India, Australia, South Africa, USA and Spain where water shortages are already a serious problem.

The environmental, social and health damages due to extraction of coal are most often incurred upon people not benefitting from the energy services that rely on coal as fuel. The same would be the case for the risks related to possible leakages from underground storage and CO2 transport infrastructure.

Several international organisations and industries with vested interests in fossil fuels especially coal seem resolved to pursue CCS. But embarking upon a CCS pathway is going to be very costly and important time risks to be lost by betting on CCS. It does not suffice to say that we should make use of all available tools if some of the tools are counterproductive. The results of this study indicate that labelling CCS as a bridging technology is unfounded.

Regional and national scenarios exist that are indicative of how global scenarios could be performed at the same time phasing out fossil fuels, nuclear, biofuels and without developing CCS. The report "Europe's Share of the Climate Challenge" (2009)[25] published by Stockholm Environment Institute in partnership with Friends of the Earth Europe makes the case for a reduction pathway in EU-27 respecting the 2^o Celsius guard rail including neither CCS, nuclear, biofuels nor offsetting. The report shows it is feasible to reach 40% reductions in greenhouse gas emissions by 2020 in the EU.

Everywhere action plans are needed that are based on a mix of mitigation tools with the main elements: energy savings in the developed countries and energy efficiency combined with renewable energy like e.g. wind power in flexible local or regional energy systems to meet the energy demands. However such action plans must also consider the non-energy emissions. This means they should also include land-use, land-use-change, forest and agriculture.

5. Conclusions

- **The mitigation potential of CCS on coal is insignificant. Only 11% of the cumulative emissions before 2050 will be avoided.**

- **Emissions of 356 Gt CO2 to the atmosphere despite a fast deployment of CCS will burst the 2^o Celsius CO_2-budget.**

- **CCS cannot contribute to bring down the global emissions in time to avoid a 2^o Celsius increase in global temperature. In the next 20 years only 7 Gt CO2 will be avoided despite deployment of CCS.**

- **CCS has no place in a sustainable energy future because it relies on continued use of fossil fuels and has a negative interaction with the elements of a renewable low energy system.**

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[1] Meinshausen, M; Meinshausen, N; Hare, W; Raper, S C B.; Frieler, K; Knutti, R; Frame, D J & Allen, M R; 2009. Nature, Vol 458|30 April 2009. Available at: http://www.nature.com/nature/journal/v458/n7242/full/nature08017.html

[2] Griffiths, M; Cobb, P & Marr-Laing, T; 2005. Carbon Capture and Storage: An arrow in the quiver or a silver bullet to combat climate change? A Canadian Primer, The Pembina Institute, (November 2005). Available at http://www.pembina.org/pub/584

3 von Goerne, G & Lundberg, F; 2008. Last Gasp of the Coal Industry; AIR POLLUTION AND CLIMATE SERIES 21, by the Air Pollution & Climate Secretariat, (October 2008). Available at: http://www.airclim.org

[4] WBGU, 2009. Solving the climate dilemma: The budget approach. Special Report. (Berlin 2009). Available at: www.wbgu.de/wbgu_sn2009_en.html

[5] International Scientific Congress, Copenhagen 2009. Climate Change: Global Risks, Challenges & Decisions - Synthesis Report, (2009). Available at: http://climatecongress.ku.dk/pdf/synthesisreport

[6] Meinshausen et. al., 2009. op.cit.

[7] The Copenhagen Diagnosis, 2009: Updating the World on the Latest Climate Science. UNSW Climate Change Research Centre, Australia. (2009) Available at www.copenhagendiagnosis.com

[8] WBGU, 2009. Op.cit. Figure 1.

[9] Meinshausen et al. , 2009. op.cit.

[10] IEA Technology Roadmap - Carbon capture and storage. (2009) p. 13. Available at http://www.iea.org/Papers/2009/CCS_Roadmap.pdf

[11] IPCC, 2005. Carbon Dioxide Capture and Storage: Summary for Policy Makers. Geneva (2005). Fig. SPM.2. Available at http://www.ipcc.ch/pdf/special-reports/srccs/srccs_summaryforpolicymakers.pdf

[12] http://www.co2captureproject.org/glossary.html

[13] http://ccs-info.org/klima.html; see: Operation of CCS facilities.

[14] http://www.iea.org/papers/2009/CCS_roadmap_targets_%28printing%29.pdf

[15] IEA (2009); op.cit.; fig. 1

[16] http://www.iea.org/speech/2007/ramsay/oxford.pdf

[17] http://www.iea.org/co2highlights/co2highlights.pdf p.44

[18] http://www.iea.org/textbase/nppdf/free/2009/key_stats_2009.pdf p.44

[19] Viebahn P, et al., Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, . . ., Int. J. Greenhouse Gas Control (2007), doi:10.1016/S1750-5836(07)00024-2. Available at: http://www.dlr.de/tt/en/Portaldata/41/Resources/dokumente/institut/system/publications/JGGC_CCS_Paper_Viebahn_etal.pdf

[20] http://ccs-info.org/klima.html develops this perspective more;

[21] IPCC, *Summary for Policymakers of the Synthesis Report of the IPCC Fourth Assessment Report.* Figure SPM.3. Available at http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm

[22] IPCC, 2005. Carbon Dioxide Capture and Storage: Summary for Policy Makers. Geneva (2005); p.4 Available at http://www.ipcc.ch/pdf/special-reports/srccs/srccs_summaryforpolicymakers.pdf

[23] Viebahn P, et al., Comparison of carbon capture and storage with renewable energy technologies regarding structural, economic, . . ., Int. J. Greenhouse Gas Control (2007), doi:10.1016/S1750-5836(07)00024-2. Available at: http://www.pik-potsdam.de/members/edenh/publications-1/Viebahn_etal.pdf

[24] Mathiesen, B.V. (2009); Carbon Capture and Storage (CCS) renewable energy systems and economy. Presentation at Klimaforum09, 16 December 2009, Copenhagen.

[25] Heaps, C.; Erickson, P.; Kartha, S.; Kemp-Benedict, E., 2009. Europe's Share of the Climate Challenge. Domestic Actions and International Obligations to Protect the Planet. Stockholm Environment Institute. (2009) Available at: http://sei-international.org/publications?pid=1318