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A model for the CO_2 capture potential

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ABSTRACT

Global warming is a result of increasing anthropogenic CO_2 emissions, and the consequences will be dramatic climate changes if no action is taken. One of the main global challenges in the years to come is therefore to reduce the CO_2 emissions.

Increasing energy efficiency and a transition to renewable energy as the major energy source can reduce CO_2 emissions, but such measures can only lead to significant emission reductions in the long-term. Carbon capture and storage (CCS) is a promising technological option for reducing CO_2 emissions on a shorter time scale.

A model to calculate the CO_2 capture potential has been developed, and it is estimated that 25 billion tonnes CO_2 can be captured and stored within the EU by 2050. Globally, 236 billion tonnes CO_2 can be captured and stored by 2050. The calculations indicate that wide implementation of CCS can reduce CO_2 emissions by 54% in the EU and 33% globally in 2050 compared to emission levels today.

Such a reduction in emissions is not sufficient to stabilize the climate. Therefore, the strategy to achieve the necessary CO_2 emissions reductions must be a combination of (1) increasing energy efficiency, (2) switching from fossil fuel to renewable energy sources, and (3) wide implementation of CCS.

1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC) increasing emissions of greenhouse gasses (GHG) will rise the average global temperature by 1.1–6.4 °C by the end of the 21st century (IPCC, 2007a). Climate models established by the IPCC indicate that dramatic climate effects will occur if the global average temperature increases by more than 2 °C. To avoid such a high temperature increase, the IPCC has stated that global GHG emissions should be reduced by 50–80% by 2050 (IPCC, 2001).

If no action is taken, the average global temperature will increase by more than 2 °C. The consequences will be melting polar ice caps, a sea level rise of up to 1 m by 2100, an increased frequency of extreme climate events, permanent flooding of coastal cities, disruption of ecosystems, and extinction of species (IPCC, 2007b; Stern, 2006; Williams, 2002).

CO_2 is the most important greenhouse gas, and anthropogenic CO_2 emissions are mainly a consequence of fossil fuels being the most important global energy sources. Enhanced energy efficiency and increased renewable energy production will reduce CO_2 emissions, but according to the International Energy Agency (IEA), energy efficiency and renewable energy do not have the potential to reduce global CO_2 emissions as much as the IPCC target of 50–80% reduction by 2050 (IEA, 2006a).

CO_2 capture and storage (CCS) is a technology with the potential to reduce GHG emissions while allowing fossil fuel use (IPCC, 2007c; MIT, 2007; Dooley et al., 2006; Edmonds et al., 2007; ZEP, 2006). With CCS, the CO_2 arising from combustion of fossil fuel is captured, transported, and finally safely stored in an underground geological formation (IPCC, 2005). The different processes involved in CCS are presented schematically in Fig. 1.

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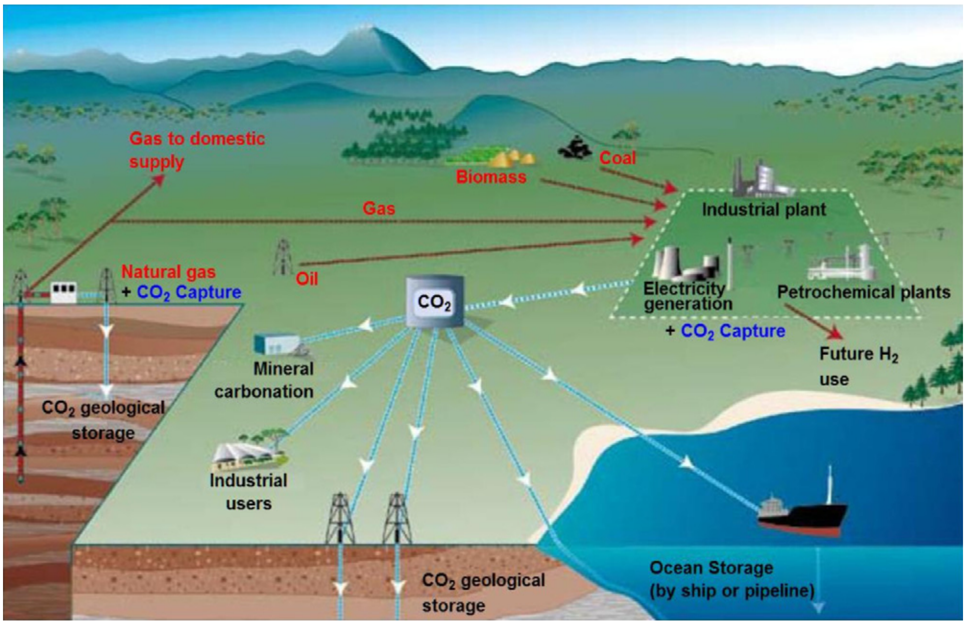


Fig. 1 – Schematic presentation of CCS infrastructure, including CO_2 capture from large point sources, transportation of CO_2, and storage options. *Source*: CO2CRC and IPCC (IPCC, 2005).

Emissions must be cut rapidly (Stern, 2006) and, therefore, CO_2 capture and storage (CCS) can be the bridge to a future society where energy production will be based on renewable energy. As such, CCS has the potential to avoid dramatic climate changes and sustain quality of life while maintaining secure power generation for the next decades.

According to the International Energy Agency (IEA), 81% of the global energy demand is based on coal, oil, and natural gas (IEA, 2006a). The IEA further predicts that the global energy demand could nearly double by 2030. Most of this increased energy demand is expected to be covered by fossil energy. Such an increase in fossil fuels will lead to increased CO_2 emissions if CO_2 capture and storage is not widely implemented.

Many scenarios for future energy demand and CO_2 emissions do not account for the full potential of CCS. The IEA published their Reference Scenario and Alternative Policy Scenario for future energy demand and future CO_2 emissions in 2006 (IEA, 2006a), and these scenarios have been widely cited. However, the IEA Reference Scenario and Alternative Policy Scenario do not account for the potential of CCS. The IPCC has also published scenarios for future CO_2 emissions without accounting for the CCS potential (IPCC, 2000).

In 2006, the IEA published new scenarios for energy demand and CO_2 emissions where CCS was addressed (IEA, 2006b). In these scenarios the CCS potential is determined by the impact of a wide range of policies and measures aimed at overcoming barriers for adoption of new technologies for low GHG emissions, and IEA concludes that up to 7.5 billion tonnes CO_2 could be captured and stored annually on a global level in 2050. This is consistent with a report from the Massachusetts Institute of Technology stating that capture and storage of four to 8 billion tonnes CO_2 annually on a global scale could enable appreciable enhanced coal use and significantly reduce CO_2 emissions (MIT, 2007). Furthermore, a report from the Batelle Memorial Institute (Dooley et al., 2006) suggest that 100 billion tonnes CO_2 should be captured and stored globally by mid-century in a scenario to stabilize the CO_2 concentration in the atmosphere at 550 ppm.

In most scenarios from the literature, the potential for CCS is limited because of significant economical and political barriers that can delay the deployment of new technologies. The aim of the present work is therefore to calculate the full potential of CCS assuming that there are only minor political and economical barriers to wide implementation of CCS. The present work thus assumes much stronger policies and economic incentives favouring implementation of CCS than the latest IEA scenarios. Huge storage capacity exists worldwide (IPCC, 2005), and the CO_2 emission reduction potential of CCS is therefore limited by the CO_2 capture potential. The purpose of this paper is thus to estimate the global CO_2 capture potential. Methods for calculating the CO_2 capture potential are described in Section 2, and calculated results are presented in Section 3. A discussion of the results is given in Section 4, and the conclusions are finally given in Section 5.

2. Methods for calculating the CO_2 capture potential

The CO_2 capture potential is calculated by two different methods. In Method A the calculations are based on scenarios for future energy demand and CO_2 emissions. In Method B the calculations are based on analyses of the demand for new power plants in the EU. Results from Method A are CO_2 emissions and CO_2 capture potential both globally, in the EU, in OECD[1] countries, and in non-OECD countries. In addition,

[1] OECD: Organisation for Economic Co-operation and Development.

the CO_2 emissions and capture potential is also specified for different sectors as power production, industry, transportation, and other sources. Method B gives only data for the power production sector within the EU, and Method B is considered as a verification of the results obtained by Method A.

2.1. *Method A—based on energy demand scenarios*

2.1.1. *Scenarios for future energy demand and CO_2 emissions*

Calculation of the CO_2 capture potential depends on scenarios for future energy demand and CO_2 emissions. The IEA has presented several scenarios for future energy demand and CO_2 emissions (IEA, 2005, 2006a,b), and the IEA Reference Scenario (IEA, 2006a) is a business as usual scenario where only political incentives, laws and regulations currently implemented are accounted for when calculating future energy demand and CO_2 emissions. On the other hand, the IEA Alternative Policy Scenario (IEA, 2006a) accounts for policies and incentives addressing environmental concerns that are currently considered, but not implemented yet. Faster deployment of technologies to reduce energy demand and CO_2 emissions are also accounted for. However, The IEA Alternative Policy Scenario does not account for CO_2 emission reduction through CCS. The IEA state that the energy path in their Reference Scenario is unsustainable. They also state that the improvement in their Alternative Policy Scenario, though a good start, is not a sustainable path (IEA, 2006b).

The IPCC (IPCC, 2000) has developed 40 different scenarios with varying models for demographic, economic, and technological developments throughout the world. The IPCC summarized its results into four main scenarios, which show similar trends as the IEA scenarios. The global energy demand according to the IPCC and IEA scenarios are compared in Fig. 2. This figure shows that the IPCC scenarios overlap with the IEA scenarios, which indicates that both the IEA and the IPCC predicts similar trends in future energy demand.

The global energy demand will increase considerable as indicated in Fig. 2. Fossil fuel is expected to cover for most

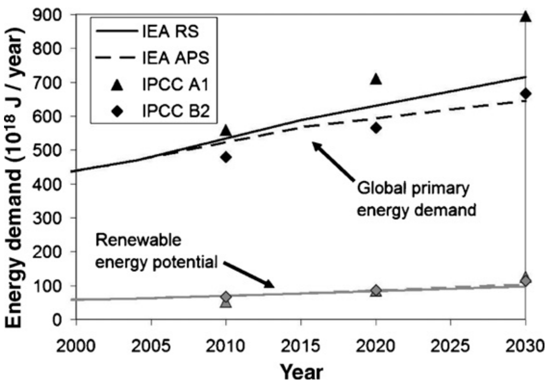


Fig. 2 – IPCC and IEA scenarios for global primary energy demand and renewable energy potential. Only the A1 and B2 of the IPCC scenarios are shown. These are the scenarios predicting highest and lowest energy demand of the main IPCC scenarios. The RS and APS scenarios are the IEA Reference Scenario and the IEA Alternative Policy Scenario, respectively.

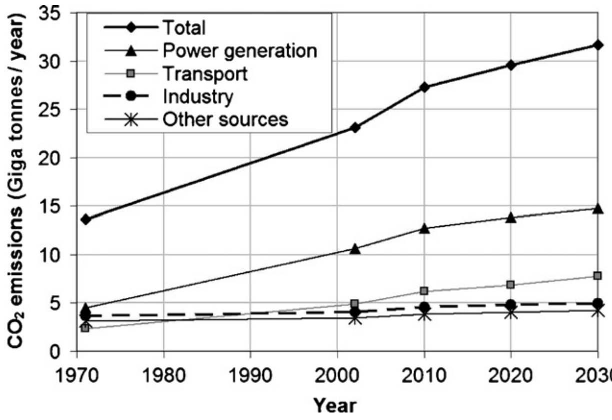


Fig. 3 – Predicted global CO_2 emissions from different sectors based on the IEA Alternative Scenario (IEA, 2005).

of the increase, and a rise in future CO_2 emissions is therefore expected. The IEA Alternative Policy Scenario predicts more than 20% increased CO_2 emissions from today until 2030. The largest increase in CO_2 emissions comes from the power production and transport section, while industry and other sources show smaller increase (*cf.* Fig. 3).

In 2006, the IEA published new scenarios for energy demand and CO_2 emissions which addresses deployment of new technologies that could put the world on a more sustainable path (IEA, 2006b). These scenarios are called Accelerated Technology (ACT) scenarios, and they addresses a portfolio for a sustainable energy future, including energy efficiency, CCS, electricity production from natural gas, nuclear energy, and renewable energy sources. If policies favouring these options are deployed, the IEA ACT scenarios indicate that the global CO_2 emissions in 2050 will be from 6 to 27% higher than emissions in 2003.

The IEA has also published a scenario called TECH Plus (IEA, 2006b) which they characterize as optimistic but speculative. This scenario is more positive regarding implementation of CCS, fuel cells, biofuels, nuclear energy and renewable energy than the IEA ACT scenarios. According to this scenario global CO_2 emissions in 2050 will be 16% lower than in 2003.

The IPCC has also set up several scenarios for future CO_2 emissions (IPCC, 2000), and both the IEA and the IPCC scenarios for global CO_2 emissions are compared in Fig. 4. This figure indicates that the IEA scenarios fit reasonably with the most optimistic IPCC scenarios.

The IPCC has stated that CO_2 emissions should be considerably reduced by 2050 to achieve less than 2 °C rise in the global average temperature. However, most of the scenarios presented in Fig. 4 shows that global CO_2 emissions will be higher in 2050 than today. Even the most optimistic predictions (*i.e.* the IEA TECH Plus scenario) indicate that global CO_2 emissions in 2050 will be higher than the IPCC target of 50–80% reduction in global CO_2 emissions by 2050. It is therefore essential that stronger incentives than accounted for in the IEA and IPCC scenarios are established to reduce the CO_2 emissions.

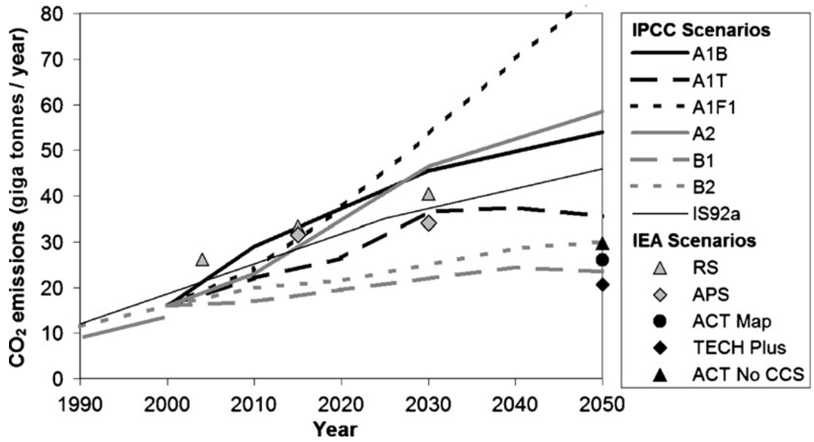


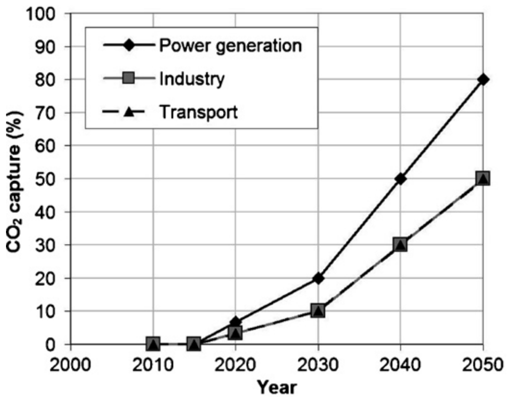
Fig. 4 – Predicted global CO_2 emissions based on the IPCC (IPCC, 2001) and IEA (IEA, 2006a,b) scenarios. The RS and APS scenarios are the IEA Reference Scenario and the IEA Alternative Policy Scenario, respectively.

2.1.2. Assumptions

The potential for global CO_2 capture by 2050 calculated by Method A is based on the following assumptions:

- Incentives and policies favouring increased energy efficiency and more renewable energy production must be part of the strategy to reduce GHG emissions. CO_2 emission data according to the IEA Alternative Policy Scenario (IEA, 2006a) is therefore the starting point for calculation of the CO_2 capture potential.
- The IEA Alternative Policy Scenario does not provide any data beyond 2030. Predicting energy demand beyond 2050 is difficult due to large uncertainties in how the global energy demand will develop. However, The IEA ACT scenarios (IEA, 2006b) indicated that primary global energy demand in 2050 could be at the same level as the IEA Alternative Policy Scenario prediction for 2030. Total CO_2 production[2] is therefore assumed to be constant between 2030 and 2050.
- In the IEA Alternative Policy Scenario (IEA, 2006a) the total CO_2 emissions and the CO_2 emissions from the power production sector is specified, but the CO_2 emissions from industry, transportation and other sources are not specified. The ratios of CO_2 emissions from industry, transport and other sources in the Alternative Policy Scenario is therefore assumed to follow the ratios of these sectors as specified in the Alternative Scenario published in the IEA report World Energy Outlook 2004 (IEA, 2005).
- Only a few large-scale CCS projects have been commissioned so far, and it will take some years until CCS can contribute to large reductions in global CO_2 emissions. The European Union (EU) Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) is aiming for power plants capable of capturing their CO_2 emissions by 2020 (ZEP, 2006). Several CCS projects have been announced with commissioning in the period from 2009 to 2016 (ZEP, 2006). For simplicity, it is therefore assumed in this work that CCS will start to contribute to CO_2 emission reductions in OECD countries in 2015.
- Available technologies can capture 85–95% of the CO_2 processed in a capture plant (IPCC, 2005). However, energy is required to capture, transport and inject CO_2, and CCS can therefore reduce emissions to the atmosphere by approximately 80–90% (IPCC, 2005). As mentioned above, the ZEP is aiming at fossil fuelled power plants capable of capturing their CO_2 emissions by 2020 (ZEP, 2006). If this vision is realised, all fossil fuelled power plants installed in EU, and OECD countries, could be equipped with CCS technology in 2050. As a conservative approach, it is therefore assumed that 80% of CO_2 produced in the power production sector will be captured and stored in OECD countries by 2050.
- The EU Hydrogen and Fuel Cell Technology Platform aims to make hydrogen a major transport fuel for vehicles with a market share up to 50% in 2050 (HFP, 2005). Hydrogen can be produced from fossil fuels, and in such a process CO_2 will be produced. CO_2 can be captured from large Hydrogen production plants, and, therefore, in the transport sector, 50% of the CO_2 produced is assumed to be captured by 2050 in OECD countries.
- CO_2 capture applies mainly to large stationary point sources, including fossil fuelled power plants and large industrial single point emission processes such as refineries, cement plants, chemical plants and steel mills. Implementing CCS for smaller industrial CO_2 sources is impractical and too expensive. According to IEA, global CO_2 emissions from the industry sector were 4.1 billion tonnes annually in 2002 (IEA, 2005). IPCC has identified 2552 industrial CO_2 sources from refineries, cement production, iron and steel industry, and petrochemical plants which emit more than 0.1 million tonnes CO_2 annually each (IPCC, 2005, p. 81). The total CO_2 emissions from these sources are 2.8 billion tonnes CO_2 annually, which are more than half of the global CO_2 emissions from the industry sector in 2002. It is therefore assumed that CCS can reduce CO_2 emissions from the industrial sector in OECD countries by 50% within 2050.
- The main sources for CO_2 emissions are often divided into power production, industry, transport and other sectors (IEA, 2005). The term ''other sectors'' includes agriculture,

[2] The phrase ''CO_2 production'' is in this work used for the CO_2 emissions given by the IEA Alternative Scenario, which does not account for CCS. The CO_2 emissions calculated in this study is the difference between ''CO_2 production'' and CO_2 captured.



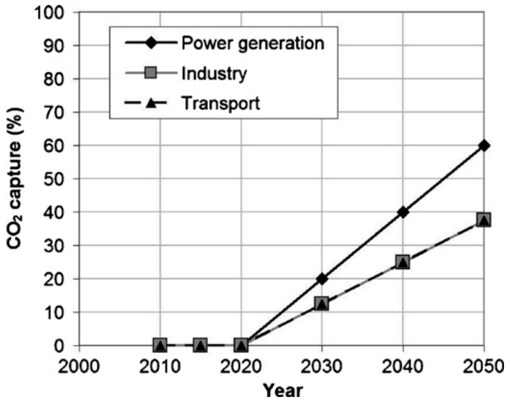


Fig. 5 – Assumed percentage CO_2 capture from different sectors in the EU and OECD countries (left), and non-OECD countries (right).

residential, commercial and public services. Today, CCS is not applicable to these sectors, and it is assumed that CCS will not be introduced in these ‘‘other sectors’’ by 2050.

- The initial CCS projects will be relatively expensive but as technology is further developed and optimized the CO_2 avoidance cost is expected to decrease. Experience gained from the initial projects will also contribute to reduce the cost of CCS. It is therefore expected that the rate of implementing CCS projects will increase after the initial CCS projects have been running for some time. The rate of introduction of CCS projects is therefore assumed to be higher in the period 2030–2050 than in the period from now and up to 2030.
- The rich countries have to take a leading role in deploying strategies for reducing the CO_2 emissions. CCS deployment is therefore assumed to develop faster in OECD countries than non-OECD countries. CO_2 capture in non-OECD countries is thus assumed to start in 2020. It is further assumed that CO_2 capture in non-OECD countries will reach 3/4 (*i.e.* 75%) of the level in OECD countries by 2050. As such, 60% of CO_2 produced from the power generation sector in non-OECD countries is assumed to be captured and stored in 2050. In the industry and transport sectors 37.5% of produced CO_2 will be captured and stored in non-OECD countries in 2050.

The CO_2 capture is calculated separately for OECD countries and non-OECD countries. In addition, data are also calculated separately for the EU region to give a view on how CCS in the EU can contribute to reduce CO_2 emissions. Calculations are performed separately for the following three sectors: (1) power production, (2) industry, and (3) transportation. In addition to the assumptions listed above, the CO_2 capture from the different sectors is assumed to develop as shown in Fig. 5.

A sensitivity study was also carried out in addition to calculations based the assumptions above. In this sensitivity study, several cases were calculated by changing the percentage of produced CO_2 that are captured and stored in 2050 from the power generation, industry and transportation sectors.

2.2. *Method B—demand for new power plants in the EU*

The European Commission Joint Research Centre (EC JRC) has analyzed the demand for new power plants in the EU onwards to 2030 (JRC, 2006). Based on their data, the CO_2 capture potential is calculated by assuming that CCS will be a part of new fossil fuelled power plants from 2020 and onwards.

The EC JRC has also estimated to which extent different energy sources will contribute to meet the energy demand. As shown in Fig. 6 fossil fuel will be the most important source for electrical power up to 2030. Fig. 6 also indicates how much of today’s installed capacity that will contribute to the total electricity demand in the next decades. Existing power plants will have a limited lifetime, and as the plants become too old they will be closed down and replaced by new power plants. By 2030 there has to be built new capacity equal to 875 GW in the EU (JRC, 2006).

CO_2 emissions, and thereby the CO_2 capture potential, depends on how much fossil fuel will contribute to meet the electricity demand. As indicated in Fig. 6 there is a large

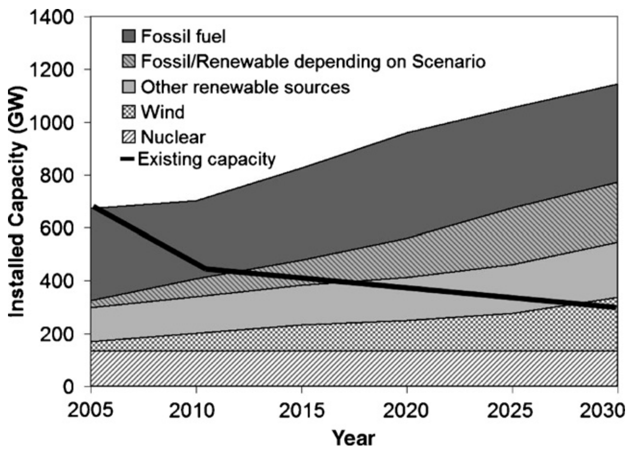


Fig. 6 – Estimated electricity capacity in the EU (JRC, 2006) from different sources. Future electricity production from power plants existing in 2005 is indicated by the bold black line.

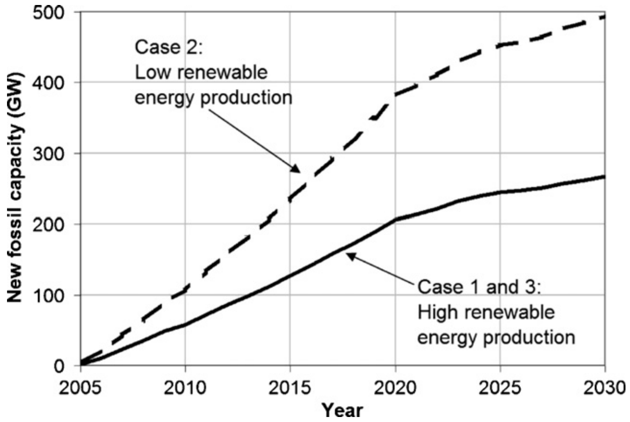


Fig. 7 – Estimated new electricity capacity in the EU produced from fossil fuel. The dotted line represents a scenario where all capacity marked as "fossil or renewable" in Fig. 6 is produced from fossil fuel. The bold line is a scenario where all this capacity is produced from renewable sources.

uncertainty on how much electricity will be produced from fossil fuels and renewable energy sources by 2030. This is due to uncertainties regarding the policies and incentives that may be implemented. The need for new fossil power capacity in the EU is illustrated in Fig. 7. In this figure the demand for new fossil capacity is given for two scenarios. In Case 1 all capacity marked as "fossil/renewable" in Fig. 6 is assumed to be produced from renewable sources. In Case 2, all this capacity is assumed to be produced from fossil fuel.

The CO_2 capture potential from power production in the EU by 2030 is calculated based on the following assumptions:

- The vision of the EU Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP, 2006) is to make new fossil fuelled power plants to have near zero CO_2 emissions by 2020. Available technologies can capture 85–95% of the CO_2 processed in a capture plant (IPCC, 2005). New fossil fuelled power plants introduced after 2020 are therefore conservatively assumed to have 85% CO_2 capture.
- A power plant with CCS will require 10–40% more energy than a plant of equivalent output without CCS (IPCC, 2005). There are strong R&D actions globally to reduce this energy penalty, and it is therefore assumed that new power plants with CCS introduced after 2020 will require 15% more energy than a plant with the same output without CCS.
- One half of the new fossil fuelled power plants introduced after 2005 is assumed coal fired. The other half is natural gas fired.
- Combustion of coal, oil and natural gas release 86.1, 77.5, and 56.1 g CO_2 per MJ, respectively (The Norwegian Directorate for Nature Management, 2006).
- The plant efficiency of coal and oil fired power plants are assumed to increase from 40% in 2005 to 50% in 2030. In addition, the plant efficiency of natural gas fired power plants is assumed to increase from 55% in 2005 to 60% in 2030. These assumptions are in accordance to the EU Technology Platform ZEP which is aiming at achieving efficiencies of 50% from steam power plants and 63% from gas turbines. Please note that all numbers for efficiency mentioned here are for conversion of fossil fuel into electricity. Combined heat and power is not considered here.
- The power plants run for 7000 h per year.
- The calculations are performed both with and without addressing retrofitting of fossil fuelled power plants with CCS. In the case where retrofitting is addressed, the rate of retrofitting existing plants with CCS is assumed equal to the rate of introducing new power plants with CCS.

3. Calculated CO_2 capture potential

3.1. *Method A*

The CO_2 capture potential was calculated based on the assumptions given in Section 2.1.2. In addition to the global

Table 1 – Predicted CO_2 emission and CO_2 capture in the EU. All data are given in million tonnes CO_2

Type of data	Sector	2010	2020	2030	2040	2050
CO_2 emission	Power production	1375	1197	864	540	216
	Industry	643	598	543	422	302
	Transportation	1047	1037	936	728	520
	Other sources	798	768	742	742	742
	Total	3864	3599	3085	2,432	1,779
CO_2 capture	Power production	0	85	216	540	864
	Industry	0	21	60	181	302
	Transportation	0	36	104	312	520
	Other sources	0	0	0	0	0
	Total	0	142	380	1,033	1,686
Accumulated CO_2 capture	Power production	0	262	1875	5,817	12,999
	Total for all sectors	0	431	3207	10,600	24,519

All data are given in million tonnes CO_2.

Table 2 – Predicted CO_2 emission and CO_2 capture in OECD countries. All data are given in million tonnes CO_2

Type of data	Sector	2010	2020	2030	2040	2050
CO_2 emission	Power production	5,138	4,759	3,705	2,316	926
	Industry	1,965	1,902	1,743	1,356	968
	Transportation	4,122	4,296	4,129	3,211	2,294
	Other sources	2,148	2,102	2,029	2,029	2,029
	Total	13,373	13,060	11,605	8,911	6,217
CO_2 capture	Power production	0	340	926	2,316	3,705
	Industry	0	66	194	581	968
	Transportation	0	148	459	1,376	2,294
	Other sources	0	0	0	0	0
	Total	0	554	1,579	4,273	6,967
Accumulated CO_2 capture (all sectors)		0	1,672	12,931	43,535	101,081

All data are given in million tonnes CO_2.

CO_2 capture potential, data is also calculated for OECD countries, non-OECD countries and the EU. The results are listed in Tables 1–4. Please note that the global CO_2 emissions and CO_2 capture is the sum of calculated data for OECD countries and non-OECD countries.

The calculated global CO_2 emissions and CO_2 capture are presented in Fig. 8. Calculated data for the EU, OECD, and non-OECD countries are given in Figs. 9–11, respectively. It is important to note that the CO_2 emissions in Figs. 8–11 are calculated as the CO_2 production minus the CO_2 captured.

The calculated results do not account for existing CCS projects like the Sleipner CO_2 injection in the Utsira formation and CO_2 injection in the Permian Basin in the USA. Only the potential for CCS projects installed after 2007 are accounted for.

The total accumulated CO_2 capture and the reduction in CO_2 emissions that can be achieved by a wide implementation of CCS are presented in Table 5. The potential for accumulated CO_2 capture by 2050 is 236 billion tonnes CO_2 globally. In the EU, the potential is 25 billion tonnes CO_2 by 2050. The CO_2 emission reductions from wide implementation of CCS are 33% globally and 54% in the EU in 2050 compared to emissions today.

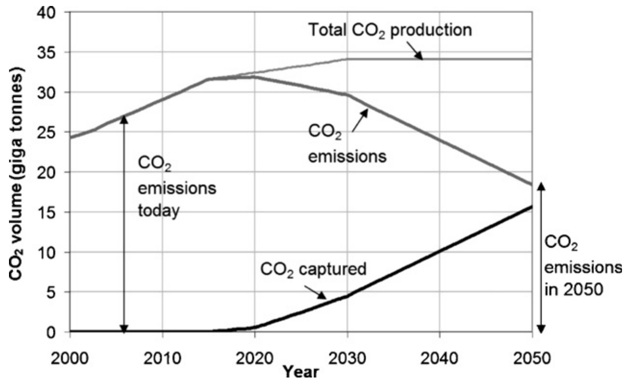


Fig. 8 – Calculated global CO_2 production, CO_2 emissions and CO_2 captured.

The results in Table 5 also show that the IPCC suggestion of more than 50% reduction in GHG emissions by 2050 *cannot* be met by only implementing CCS. Large reductions in CO_2 emissions can therefore best be achieved through a combination of (1) ensuring increased energy efficiency, (2) a transition

Table 3 – Predicted CO_2 emission and CO_2 capture in non-OECD countries. All data are given in million tonnes CO_2

Type of data	Sector	2010	2020	2030	2040	2050
CO_2 emission	Power production	6,875	8,286	7,294	5,471	3,647
	Industry	3,434	3,812	3,534	3,029	2,525
	Transportation	2,959	3,914	4,109	3,522	2,935
	Other sources	2,442	2,792	3,043	3,043	3,043
	Total	15,710	18,804	17,981	15,065	12,150
CO_2 capture	Power production	0	0	1,824	3,647	5,471
	Industry	0	0	505	1,010	1,515
	Transportation	0	0	587	1,174	1,761
	Other sources	0	0	0	0	0
	Total	0	0	2,915	5,831	8,746
Accumulated $_{CO2}$ capture (all sectors)		0	0	15,538	60,727	135,070

All data are given in million tonnes CO_2.

Table 4 – Predicted CO_2 emission and CO_2 capture globally. All data are given in million tonnes CO_2

Type of data	Sector	2010	2020	2030	2040	2050
CO_2 emission	Power production	12,014	13,045	10,999	7,786	4,573
	Industry	5,399	5,715	5,277	4,385	3,493
	Transportation	7,080	8,211	8,237	6,733	5,228
	Other sources	4,589	4,894	5,072	5,072	5,072
	Total	29,083	31,864	29,586	23,976	18,367
CO_2 capture	Power production	0	340	2,750	5,963	9,176
	Industry	0	66	699	1,591	2,483
	Transportation	0	148	1,046	2,550	4,055
	Other sources	0	0	0	0	0
	Total	0	554	4,494	10,104	15,713
Accumulated CO_2 capture (all sectors)		0	1,672	28,468	104,262	236,151

All data are given in million tonnes CO_2.

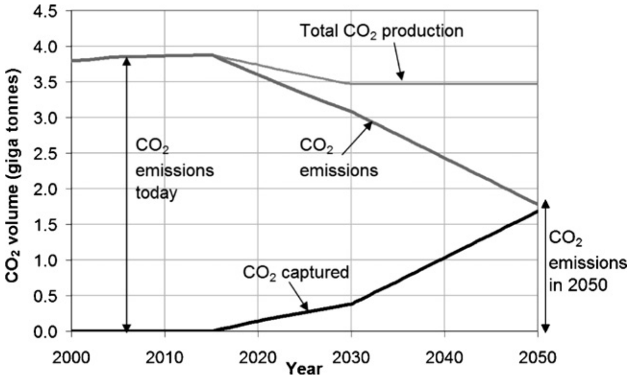


Fig. 9 – Calculated CO_2 production, CO_2 emissions and CO_2 captured in the EU.

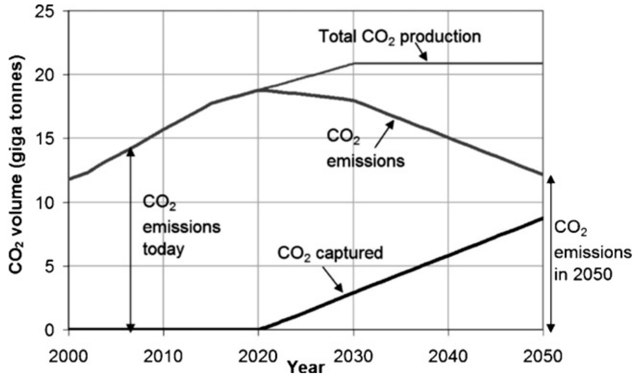


Fig. 11 – Calculated CO_2 production, CO_2 emissions and CO_2 captured in non-OECD countries.

of energy production to renewable energy sources, and (3) a wide implementation of CCS.

A sensitivity analysis has been performed for the reduction in global CO_2 emissions by varying the rate of produced CO_2 that are capture from different regions and sectors. A specification of which parameters that are varied are given in Table 6, and the result are presented in Fig. 12.

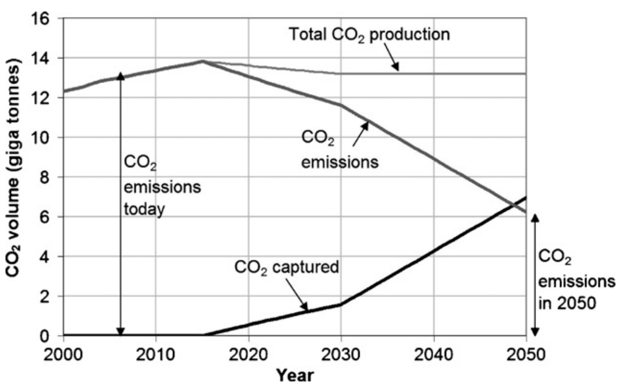


Fig. 10 – Calculated CO_2 production, CO_2 emissions and CO_2 captured in OECD countries.

From Fig. 12 it can be seen that the reduction in global CO_2 emissions is more sensitive to variations in CO_2 capture from the power production sector than the industry and transport sectors. If the rate of CO_2 capture from power production are increased from 80 to 85% in OECD countries and increased from 60 to 65% in non-OECD countries, the reduction in global CO_2 emissions in 2050 compared to emissions in 2007 will increase from 33.3 to 35.8%. Fig. 12 also shows that the reduction in global CO_2 emissions is more sensitive to the capture rate in non-OECD countries than OECD countries.

3.2. *Method B*

The CO_2 capture potential in the EU calculated by Method A in Section 3.1 can be verified by analyzing the demand for electrical power in the EU. The CO_2 capture potential from the power production sector in the EU was calculated based on the EC JRC analysis (JRC, 2006) and the assumptions in Section 2.2.

Three case studies were performed. In Case 1, new capacity defined as fossil energy or renewable energy by the EU JRC (*cf.* Fig. 6) was assumed to be produced only from renewable sources. In Case 2, all this capacity was assumed to be produced from fossil fuel. In Cases 1 and 2 there is not

Table 5 – Potential for CO_2 capture and CO_2 emissions reduction

Area	Annually CO_2 capture in 2050 (billion tonnes)	Potential for accumulated CO_2 capture by 2050 (billion tonnes)	Reduction in CO_2 emissions (%)[a]
EU	1.7	25	54
OECD countries	7.0	101	53
Non-OECD countries	8.7	135	16
World	15.7	236	33

[a] Reduction in CO_2 emissions in 2050 compared to CO_2 emissions in 2007.

addressed any retrofitting of existing power plants with CCS and only new plants with CCS are thus accounted for. Case 3 is based on Case 1, but in Case 3 retrofitting of existing plants is addressed at a rate equal to the rate of introduction of new plants with CCS. Calculated CO_2 emission and CO_2 capture from power production in the EU are presented in Fig. 13. The accumulated CO_2 capture potential in the EU by 2030 is calculated to be in the range 1.9–3.8 billion tonnes, as shown in Table 7. Please note that this is the CO_2 capture potential only from power production. CO_2 capture from transport, industry or other sources is not included.

The model presented in Section 3.1 can also be used to estimate the CO_2 capture potential from the power section in the EU by 2030, and calculated results from Method A (Section 3.1) and Method B are compared in Table 8. The capture potential from Method B is here reported as an interval representing Cases 1–3, and this interval is due to uncertainties in the rate of introducing CCS and uncertainties in the capacity of renewable energy production. From Table 8 is can be seen that Method A resulted in a potential of 1.9 billion tonnes CO_2 captured from power production in the EU by 2030. This result is within the lower range of the CO_2 capture potential from Method B presented in Table 7, indicating that Method A is a conservative approach compared to Method B. The fact that both methods provide comparable results strengthens the confidence in the calculated CO_2 capture potential.

4. Discussion

4.1. *Baseline for energy demand and CO_2 emissions*

The potential for CO_2 capture depends strongly on the demand for fossil energy production. In order to calculate the CO_2

Table 6 – Sensitivity study for reduction in global CO_2 emissions

Case[a]	Input—rate of CO_2 captured and stored from sectors and regions in 2050[b]						Reduction in global CO_2 emissions (%)[c]
	Power sector		Industry sector		Transport sector		
	OECD (%)	Non-OECD (%)	OECD (%)	Non-OECD (%)	OECD (%)	Non-OECD (%)	
Base case	80	60	50	37.5	50	37.5	33.30
$A1_{low}$	75						32.46
$A1_{high}$	85						34.14
$A2_{low}$		55					31.64
$A2_{high}$		65					34.95
$A3_{low}$	75	55					30.80
$A3_{high}$	85	65					35.79
$B1_{low}$			45				32.95
$B1_{high}$			55				33.65
$B2_{low}$				32.5			32.56
$B2_{high}$				42.5			34.03
$B3_{low}$			45	32.5			32.21
$B3_{high}$			55	42.5			34.38
$C1_{low}$					45		32.46
$C1_{high}$					55		34.13
$C2_{low}$						32.5	32.45
$C2_{high}$						42.5	34.15
$C3_{low}$					45	32.5	31.61
$C3_{high}$					55	42.5	34.98

The rate of produced CO_2 that are captured and stored from different sectors and regions are varied in the different cases. Calculated reduction in global CO_2 emissions are reported. Blank cells indicate values identical to the base case (*i.e.* input values identical to the base case are not repeated).

[a] Base case corresponds to the assumptions specified in Section 2.1.2 and the results in Tables 1–5. In the case names, subscripts ''low'' and ''high'' indicate input values lower and higher, respectively, than in the base case.

[b] Only parameters that are changed from the base case are indicated in the table.

[c] Reduction in CO_2 emissions in 2050 compared to CO_2 emissions in 2007.

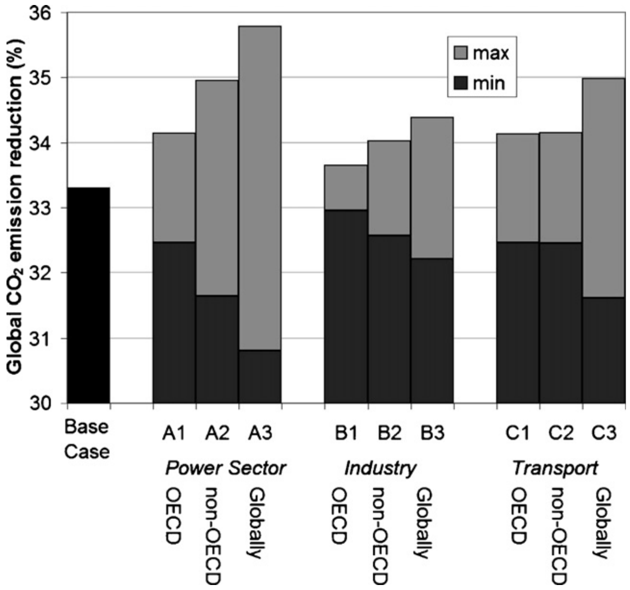


Fig. 12 – Sensitivity analysis. The rates of produced CO_2 from different sectors and regions that are captured and stored are varied in the different cases. The emission reduction is given as reduction in global CO_2 emissions in 2050 compared to global CO_2 emissions in 2007. Input parameters to all cases are specified in Table 6, and the parameter that is changed in each case is indicated in the figure.

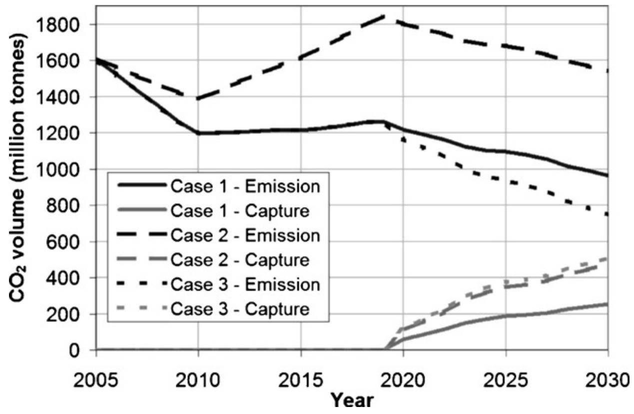


Fig. 13 – Estimated CO_2 emissions and CO_2 capture from power production in the EU. Data are given for the same cases as in Fig. 7.

capture potential a baseline for fossil energy demand and resulting CO_2 production must be defined. This baseline must be a scenario for CO_2 emissions where the potential for CCS is not accounted for. In this study, the IEA Alternative Policy Scenario is chosen as the baseline. This scenario is selected because, to some degree, it accounts for policies favouring energy efficiency and renewables, which is essential for sustainable future energy production.

Stronger incentives favouring energy efficiency and renewable energy than accounted for by the IEA Alternative Policy Scenario are required for a sustainable energy path (IEA, 2006b). It can therefore be argued that the IEA ACT scenario without CCS (ACT no CCS in Fig. 4) could be a more suitable baseline for calculation of the CCS potential. However, the development of CO_2 emissions from different sectors and regions onwards to 2050 is not reported for the ACT scenarios (IEA, 2006b). Only predictions for 2050 are given, and calculation of the CO_2 capture potential based on IEA ACT would therefore be very inaccurate. The baseline in this study is the IEA Alternative Policy Scenario onwards to 2030 and then constant CO_2 emissions between 2030 and 2050. As shown in Fig. 4 this gives only slightly higher global CO_2 emissions in 2050 than the ACT scenario without CCS. It is therefore reasonable to assume that the calculated CO_2 capture potential would only be slightly lower if the IEA ACT scenario without CCS was the baseline.

4.2. CCS as a strategy to reduce CO_2 emissions

The most optimistic IEA scenario, *i.e.* the TECH Plus scenario, estimates that CCS can contribute to global CO_2 emission reduction in 2050 equal to 7.5 billion tonnes CO_2 annually. This is far less than the CO_2 capture potential calculated in this study (15.7 billion tonnes CO_2 captured annually in 2050 worldwide, *cf.* Table 4). The current study, therefore, presumes much stronger policies, economic incentives and technology development to reduce CO_2 emissions than accounted for by the IEA TECH Plus scenario.

According to a study from the Batelle Memorial Institute (Edmonds et al., 2007) there are 8100 large CO_2 point sources globally that could adopt CCS technology. The CO_2 emissions from these sources are more than 15 billion tonnes annually, and if CCS is introduced to all these sources with 85% CO_2 capture, close to 13 billion tonnes CO_2 could be captured and

Table 7 – Potential for CO_2 capture from power production in EU by 2030

Case	Renewable vs. fossil fuel[a]	Retrofitting of CCS[b]	CO_2 capture potential in EU by 2030
1	Renewable	No	1.9 billion tonnes
2	Fossil fuel	No	3.5 billion tonnes
3	Renewable	Yes	3.8 billion tonnes

[a] Identifies how the capacity in Fig. 6 marked as renewable or fossil fuel is produced.
[b] Identifies if retrofitting of existing power plants with CCS is included in the calculations.

Table 8 – Potential for CO_2 capture from power production in EU

Calculation method[a]	CO_2 capture by 2030
Method A	1.9 billion tonnes
Method B	1.9–3.5 billion tonnes

[a] Method A is based on the IEA Alternative Policy Scenario as presented in Section 3.1. Method B is based on analysis of demand for new power plants in EU as described in Section 3.2.

stored annually. This is a rough estimate of the CO_2 capture potential from the power production and industry sectors which is higher than the calculated global CO_2 capture potential from the power production and industry sectors in 2050 (Table 4). This is an indication that the calculated CO_2 potential can be realised if economic and political barriers are overcome.

The optimistic approach in the current study can give a 33% reduction in global CO_2 emissions by 2050. This is not sufficient to reach the IPCC suggestion of more than 50% CO_2 emission reduction by 2050. Therefore, stronger policies favouring energy efficiency, renewable energy and CCS are required than accounted in this study to avoid dramatic climate changes.

4.3. *Parameters influencing the CCS potential*

The potential for CO_2 capture strongly depends on policies implemented to set the world on a sustainable energy path. Introducing policies to enhance energy efficiency will reduce the predicted growth in energy demand. Increasing energy efficiency can therefore result in a lower global energy demand than estimated by the IEA scenarios. The need for fossil fuel could then be lowered, leading to a lower CO_2 capture potential than predicted in this study.

A CO_2 capture plant requires energy, and a fossil fuelled power plant with CO_2 capture will require 10–40% more fuel than a similar power plant without CO_2 capture (IPCC, 2005). As technology development advances the energy required for the CO_2 capture will most likely decrease significantly. However, the extra energy required by a CO_2 capture plant is not accounted for in Method A. In order to achieve significant global CO_2 emission reduction, stronger incentives favouring energy efficiency than accounted for in the baseline in this study are required. The reduced energy demand from such increased energy efficiency is assumed to compensate for the extra energy needed for CO_2 capture plants.

Establishing renewable energy production at a higher rate than addressed in this work will reduce the demand for fossil fuel, which again will reduce the CO_2 capture potential. From Table 8 it can be seen that the CO_2 capture potential from Method A is at the lower end of the range calculated by Method B. Table 7 shows that the CO_2 capture potential in Method B will increase strongly if new power production is based on fossil fuels instead of renewable sources. In addition, retrofitting existing power plants with CCS in addition to new power plants with CCS will significantly increase the CO_2 capture potential compared to a case where retrofitting is not addressed. It can therefore be concluded that the CO_2 capture potential strongly depends on the rate of introducing new renewable energy production and the rate of introducing CCS.

A delay in introducing measures for mitigation of climate change will make it more costly and more difficult to achieve sufficient reduction in global CO_2 emissions (Stern, 2006; IPCC, 2007c). CCS should therefore be deployed as fast and wide as possible. New power plants should be built with CCS as soon as possible, and existing fossil fuelled power plants should be retrofitted with CCS as soon as possible. Therefore, incentives should be introduced to ensure that the rate of CCS implementation assumed is this study can be realised.

The success of introducing CCS as a strategy to reduce global CO_2 emissions depends on achieving wide implementation of CCS in non-OECD countries. The large growth in the Chinese economy will place China as the country with the highest CO_2 emissions by 2010. Achieving large global CO_2 emission reductions through CCS will therefore depend on a fast and wide implementation of CCS in China and other developing countries. If CCS is deployed faster in non-OECD countries than assumed in this work, the CO_2 capture potential will increase.

5. Conclusion

The potential for CO_2 capture has been calculated. In the EU, the accumulated CO_2 capture potential is 25 billion tonnes captured and stored by 2050. The global potential is 236 billion tonnes CO_2 captured and stored by 2050. This corresponds to 33% reduction in global CO_2 emissions in 2050 compared to emissions today. CO_2 capture and storage as the only strategy for combating climate change is therefore not sufficient to reach the IPCC suggestion of 50–80% reduction in CO_2 emissions by mid-century.

The best strategy to reduce CO_2 emissions is therefore a combination of policies and technological development favouring: (1) increased energy efficiency, (2) a transition from fossil fuel to renewable energy as the major energy source, and (3) wide implementation of CO_2 capture and storage.

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