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A Model for the CO_2 Capture Potential

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Summary

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 30 billion tonnes CO_2 can be captured and stored within the EU by 2050. Globally, 240 billion tonnes CO_2 can be captured by 2050. The calculations indicate that wide implementation of CCS can reduce CO_2 emissions by 56 % in the EU and 37 % globally in 2050 compared to emission levels today.

Such a reduction in emissions is not sufficient to stabilize the climate, however, and 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 raise the average global temperature by 1.4 to 5.8 °C from 1990 to 2100 [1].

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 to 80 % by 2050.

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 raise of up to one meter by 2100, an increased frequency of extreme climate events, permanent flooding of costal cities, disruption of ecosystems, and extinction of species [2]. Recent studies even indicate that the consequences of global warming could be worse than previously believed.

CO_2 is the most important GHG gas, and the largest source of man made CO_2 emissions

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is fossil fuel combustion for power production. Fossil fuels are the most important energy source today, and according to the International Energy Agency (IEA), 80 % of the global energy consumption is based on coal, oil, and natural gas [3]. The IEA further predicts that the global energy demand will increase by 30 to 50 % by 2030. Most of this increased energy demand is expected to be covered by fossil energy.

CO_2 capture and storage (CCS) is a technology with the potential to reduce GHG emissions while allowing fossil fuel use [4]. With CCS, the CO_2 arising from combustion of fossil fuel is captured, transported, and finally safely stored in an underground geological formation.

Increasing energy efficiency and energy production from renewable sources have the potential to reduce the GHG emissions in the long term. However, implementing energy efficiency measures and adapting an energy source switch from fossil fuel to renewable energy at a realistic pace will not be sufficient to meet the required reduction in CO_2 emissions. Emissions must be cut rapidly, and, therefore, CCS is a 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.

The purpose of this paper is to estimate the CO_2 capture potential. Scenarios for future energy demand and CO_2 emissions are presented in Section 2. These scenarios are the basis for modelling the potential for CCS, and calculated CO_2 capture potential are presented in Section 3. The results are discussed in Section 4, and the conclusions are finally given in Section 5.

2. The Energy challenge

Future CO_2 emissions depend on the future energy demand, the share of energy produced from renewable sources, and the policies and incentives implemented to reduce CO_2 emissions.

The IEA has presented several scenarios for future energy demand and CO_2 emissions [3,5]. The IEA Reference Scenario [3] 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. The IEA Alternative Scenario [3], however, 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 Scenario does not account for the potential 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 Scenario is, although a good start, not a sustainable path [5].

The IPCC [6] 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 Figure 1. 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.

In 2005, the IEA were asked by the G8 leaders and Energy Ministers to advice on new scenarios and strategies aiming at a clean, clever and competitive energy future [5]. IEA have therefore established new scenarios called Accelerated Technology (ACT) scenarios [5]. These scenarios account for deployment of new technologies that could put the world on a more sustainable path. The IEA ACT scenarios 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.

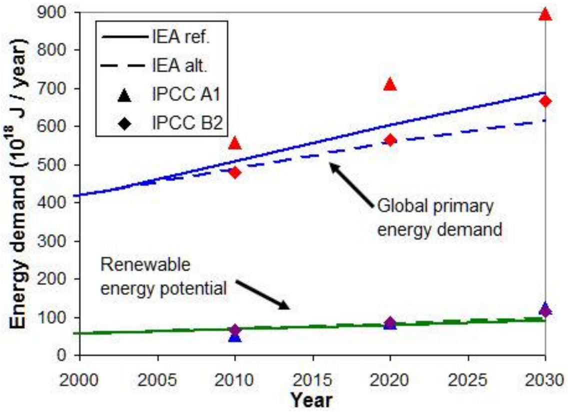

Figure 1 - IPCC and IEA scenarios for global primary energy demand and renewable energy potential. Only the A1 and B2 of the IPCC scenarios are shown. These are the scenarios predicting highest and lowest energy demand of the main IPCC scenarios.

The IEA has also published a scenario called TECH Plus [5] which they characterize as optimistic but speculative. This scenario is more positive regarding wide implementation of CCS and fuel cells than the IEA ACT scenarios.

Predicting energy demand beyond 2050 is difficult due to large uncertainties in how the global energy marked will develop. However, The IEA Act scenarios indicated that primary global energy demand in 2050 could be at the same level as the IEA Alternative Scenario prediction for 2030.

The global energy demand will increase considerable as indicated in Figure 1. Fossil fuel is expected to cover for most of the increase, and a raise in future CO_2 emissions is therefore expected. The IEA Alternative Scenario predicts nearly 30 % increased CO_2 emissions from today to 2030 as indicated in Figure 2. The largest increase in CO_2 emissions comes from the power production and transport section, while industry and other sources show smaller increase.

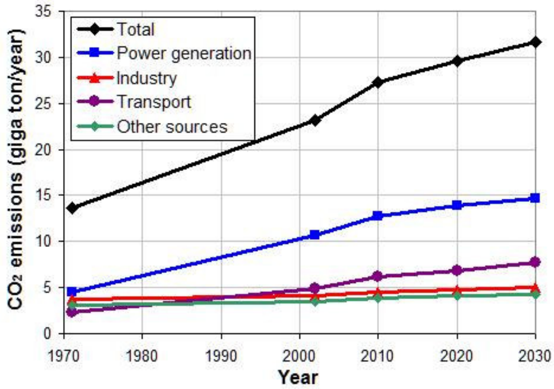

Figure 2 - Predicted global CO_2 emissions based on the IEA Alternative scenario. CO_2 emissions from different sectors are also shown.

The IPCC has also set up several scenarios for future CO_2 emissions [6], and both the IEA and the IPCC scenarios for global CO_2 emissions are compared in Figure 3. This figure indicates that the IEA scenarios fit reasonably with the IPCC scenarios.

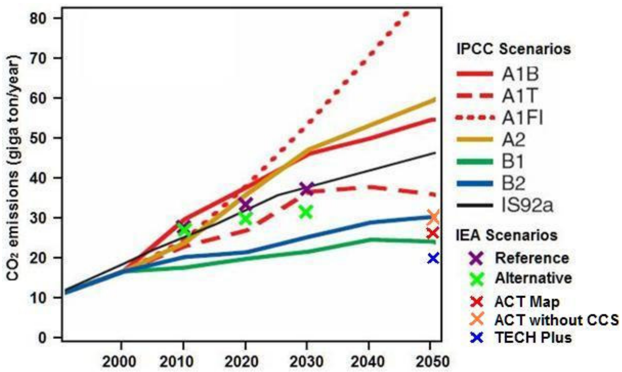

Figure 3 - Predicted global CO_2 emissions based on the IPCC [1] and IEA [3] scenarios.

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 Figure 3 shows that global CO_2 emissions will be higher in 2050 than today. The most optimistic predictions (*i.e.* the IEA TECH Plus scenario) indicate that global CO_2 emissions in 2050 will only be slightly lower than emissions today. It is therefore essential that stronger incentives than accounted for in the IEA and IPCC scenarios are established to reduce the CO_2 emissions.

3. The CCS potential

CCS includes capture of CO_2 from large point-sources, transportation of compressed CO_2 by pipeline or ship, and finally secure storage in underground geological formations as aquifers. A detailed description of CCS is provided by the IPCC [7], and all processes involved in CCS are presented schematically in Figure 5.

Huge storage capacity exists worldwide, and the CO_2 emission reduction potential of CCS is therefore limited by the CO_2 capture potential.

3.1. The CO_2 capture potential

The potential for global CO_2 capture by 2050 is calculated 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 Scenario [3] is therefore the starting point for calculation of the CO_2 capture potential.
- The IEA Alternative Scenario does not provide any data beyond 2030. Total CO_2 production* is therefore assumed to be constant between 2030 and 2050.
- CO_2 capture from CCS projects will start in 2015.
- The European Union (EU) Technology Platform for Zero Emission Fossil Fuel Power Plants is aiming for power plants capable of capturing their CO_2 emissions by 2020 [4]. Most CO_2 capture processes are capable of capturing at least 90% of the CO_2 emitted, and, conservatively, it is assumed that 80 % of CO_2 produced in the power sector will be captured in OECD countries by 2050.
- In the transport sector, 50 % of the CO_2 produced will be captured in OECD countries by 2050, based on the EU Hydrogen and Fuel Cell Technology Platform which aims to make hydrogen a major transport fuel for vehicles with a market share up to 50 % in 2050 [8].
- It is assumed that CO_2 capture from industrial sources amounts to 50 % of the CO_2 produced in OECD by 2050.
- It is also assumed that CO_2 capture from other sources amounts to 20 % of the CO_2 produced in OECD by 2050.
- The rate of CO_2 capture will increase faster in the period 2030 - 2050 than in the period 2005 - 2030 due to increasing implementation of technologies for CO_2 emissions reduction after 2030.
- CCS will develop faster in OECD countries than non-OECD countries. CO_2 capture in non-OECD countries will start in 2020 and is assumed to reach ¾ (or 75 %) of the level in OECD countries by 2050.

The calculated global CO_2 emissions and capture based on the above assumptions are presented in Figure 4. The calculated CO_2 capture potential by 2050 is provided in Table 1. Further details on assumptions and calculations are given in Appendix A.

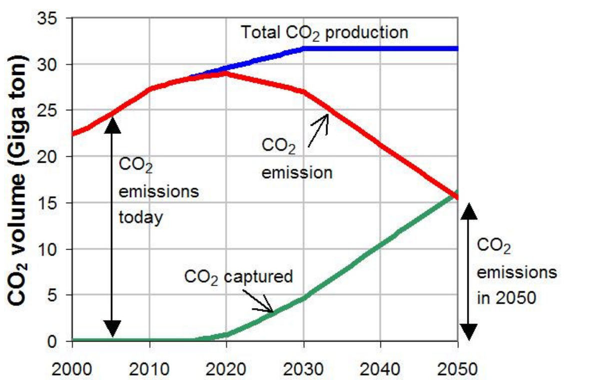

Figure 4 - Global CO_2 production based on IEA [3] and calculated CO_2 emissions and CO_2 captured.

* 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. Please note that the "CO_2 production" is assumed to be constant between 2030 and 2050.

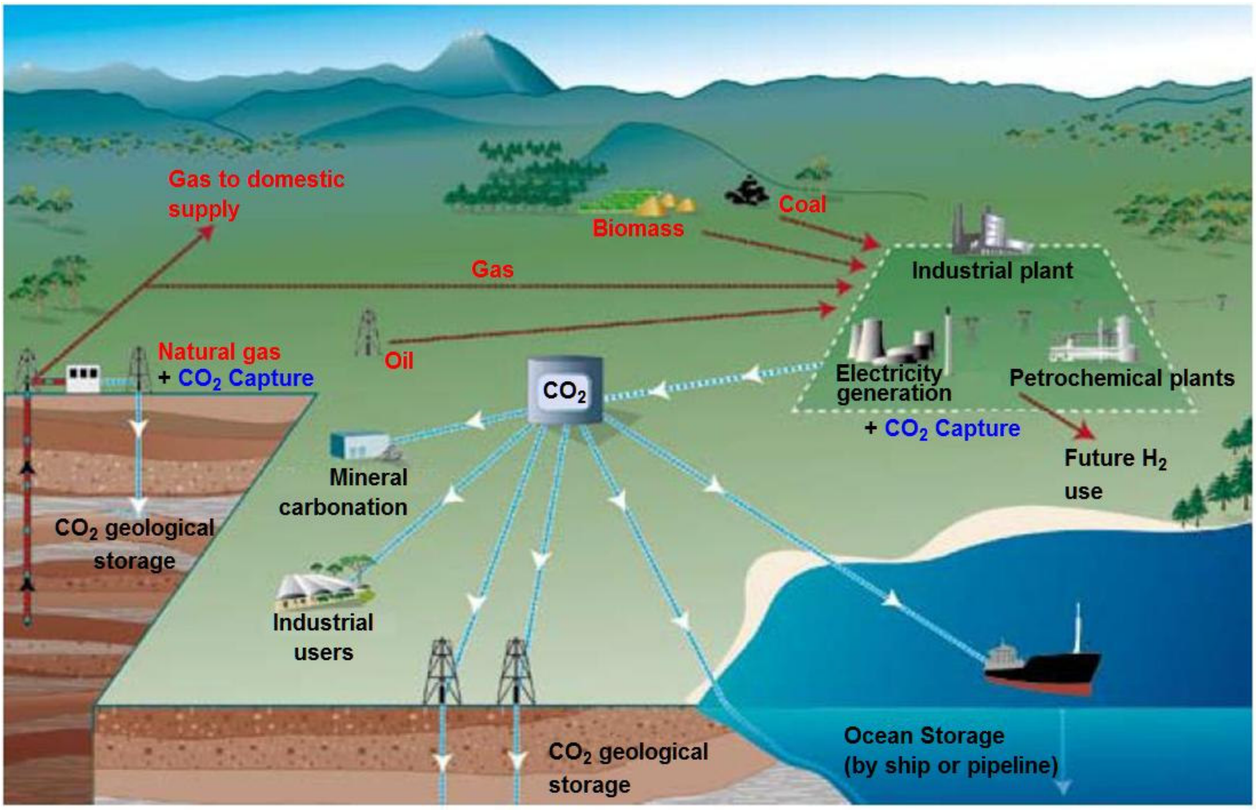

Figure 5 - Schematic presentation of CCS infrastructure, including CO_2 capture from large point sources, transportation of CO_2, and storage options. Source: CO2CRC and IPCC [7].

Table 1. Potential for CO_2 capture and CO_2 emissions reduction.

Area	**Potential for CO_2 capture by 2050**	**Reduction in CO_2 emissions***
EU	30 billion ton	56 %
World	240 billion ton	37 %

* *Reduction in CO_2 emissions in 2050 compared to CO_2 emissions in 2005.*

The results presented in Table 1 indicate that a realistic global potential for CO_2 capture is 240 billion tonnes CO_2 by 2050. In the EU, the potential is 30 billion tonnes by 2050. The CO_2 emission reductions are 37 % globally and 56 % in the EU in 2050 compared to emissions today.

The results in Table 1 show that the IPCC suggestion of more than 50 % reduction in GHG emissions by 2050 can *not* 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 of energy production to renewable energy sources, and *(3)* a wide implementation of CCS.

3.2. New fossil fuelled power plants

The European Commission Joint Research Centre has analyzed the demand for new power plants in the EU onwards to 2030 [9]. 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 calculations are performed as described in Appendix B.

The calculated CO_2 capture potential is presented in Table 2 (indicated as Method B). In this table, the results are compared to similar data obtained from the model presented in Section 3.1 (indicated as Method A in Table 2)

The capture potential from Method B in Table 2 is calculated as an interval due to uncertainties regarding the policies that may be implemented to assure more energy production from renewable sources instead of fossil sources. The uncertainties in Method A are not estimated, but uncertainties is believed to be equal to that in Method B.

Table 2. Potential for CO_2 capture from power production in EU.

Calculation method*	CO_2 capture by 2030
Method A	2.2 billion tonnes
Method B	1.6 – 3.0 billion tonnes

** Method A is based on the IEA Alternative Scenario as presented in Section 3.1. Method B is based on analysis of demand for new power plants in EU, c.f. Appendix B.*

The CO_2 capture potential from power production in the EU calculated by the two different methods presented in Table 2 gives similar results. The fact that both methods provide comparable results strengthens the confidence in the calculated CO_2 capture potential.

4. Discussion

The potential for CO_2 capture strongly depends on which policies that are implemented to set the world on a sustainable energy path. In this study, the IEA Alternative scenario is chosen as the baseline (*i.e.* predicted CO_2 emissions before the potential of CCS is accounted for). This scenario is selected because it, to some degrees, 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 Scenario are required for a sustainable energy path [5]. It can therefore be argued that the IEA ACT scenario without CCS 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 by IEA [5] for the ACT scenarios. Only predictions for 2050 are given, and calculation of CO_2 capture based on IEA ACT would therefore be very inaccurate. The baseline in this study is the IEA Alternative Scenario onwards to 2030 and then constant total CO_2 emissions between 2030 and 2050. As seen from Figure 3 this would give nearly similar global CO_2 emissions in 2050 as the ACT scenario without CCS. It is therefore reasonable to believe that the calculated CO_2 capture potential would not change significantly if the IEA ACT scenario without CCS was the baseline.

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 which corresponds to 16 billion tonnes CO_2 captured annually in 2050 worldwide (*c.f.* Table 6). 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.

The optimistic approach in the current study can give a 37 % reduction in global CO_2 emissions. This is not sufficient to reach the IPCC suggestion of more than 50 % CO_2 emission reduction by 2050. Therefore, even stronger policies favouring energy efficiency, renewable energy and CCS than accounted for in this study are required to avoid dramatic climate changes.

* Please note that the baseline for calculating the CO_2 capture potential must be a scenario that do not account for CCS. The "IEA ACT without CCS" is the only of the IEA ACT scenarios that do not account for CCS.

5. Conclusion

The potential for CO_2 capture has been calculated. In the EU, the CO_2 capture potential is 30 billion tonnes captured and stored by 2050. The global potential is 240 billion tonnes CO_2 captured and stored by 2050. This corresponds to a 37 % 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.

Acknowledgement

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Appendix A – Calculating the CO_2 capture potential (Method A)

The CO_2 capture potential is calculated as described in Section 3.1. CO_2 production is based on the IEA Alternative Scenario [3], and the CO_2 capture is calculated separately for the EU, OECD countries and non-OECD countries. Calculations are performed separately for the following four sectors: *(1)* power production, *(2)* industry, *(3)* transportation, and *(4)* other sources.

The calculations are based on the assumptions given in Section 3.1. In addition, the CO_2 capture from the different sectors is assumed to develop as shown in Figure 6. Resulting data for CO_2 emissions and CO_2 capture are listed in Table 3 to Table 7. Data for CO_2 emissions and capture for the EU, OECD, and non-OECD countries are given in Figure 7 and Figure 8. Global data, which is the sum of OECD and non-OECD countries, is given in Figure 4 in Section 3.1.

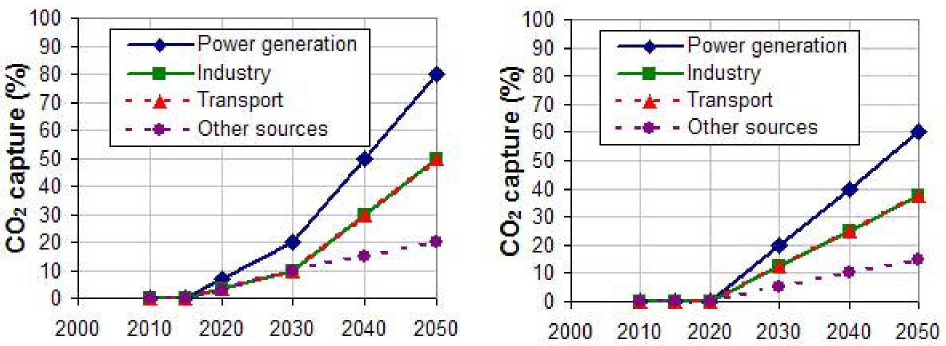

Figure 6 – Assumed percentage CO_2 capture from different sectors in the EU and OECD countries (left), and non-OECD countries (right).

Table 3. Predicted CO_2 production, capture and emissions 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	1 485	1 388	1 014	634	254
	Industry	600	579	540	420	300
	Transportation	1 013	1 036	931	724	517
	Other sources	746	727	664	627	590
	Total	**3 844**	**3 730**	**3 148**	**2 404**	**1 660**
CO_2 capture	Power production	0	99	254	634	1 014
	Industry	0	20	60	180	300
	Transportation	0	36	103	310	517
	Other sources	0	21	74	111	147
	Total	**0**	**176**	**491**	**1 235**	**1 979**
Accumulated	Power production	0	297	2 182	6 811	15 243
CO_2 capture	**Total for all sectors**	**0**	**528**	**4 069**	**13 068**	**29 507**

Table 4. Predicted CO_2 production, capture and emissions 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	5 685	5 435	4 246	2 654	1 061
	Industry	1 792	1 769	1 634	1 271	908
	Transportation	3 864	3 985	3 869	3 009	2 150
	Other sources	1 944	1 906	1 711	1 616	1 521
	Total	**13 286**	**13 094**	**11 459**	**8 549**	**5 639**
CO_2 capture	Power production	0	388	1 061	2 654	4 246
	Industry	0	61	182	545	908
	Transportation	0	137	430	1 290	2 150
	Other sources	0	56	190	285	380
	Total	**0**	**643**	**1 863**	**4 773**	**7 683**
Accumulated CO_2 capture (all sectors)		**0**	**1 920**	**15 153**	**49 787**	**113 520**

Table 5. Predicted CO_2 production, capture and emissions 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	7 041	8 027	7 538	5 654	3 769
	Industry	2 765	2 987	2 773	2 377	1 981
	Transportation	2 310	2 731	3 013	2 582	2 152
	Other sources	1 918	2 102	2 213	2 096	1 980
	Total	**14 034**	**15 846**	**15 536**	**12 709**	**9 881**
CO_2 capture	Power production	0	0	1 885	3 769	5 654
	Industry	0	0	396	792	1 188
	Transportation	0	0	430	861	1 291
	Other sources	0	0	116	233	349
	Total	**0**	**0**	**2 828**	**5 655**	**8 483**
Accumulated CO_2 capture (all sectors)		**0**	**0**	**14 859**	**58 686**	**130 789**

Table 6. Predicted CO_2 production, capture and emissions globally. All data are given in million tonnes CO_2.

Type of data	Sector	2010	2020	2030	2040	2050
CO_2 emission	Power production	12 726	13 463	11 784	8 307	4 831
	Industry	4 557	4 756	4 406	3 647	2 888
	Transportation	6 174	6 715	6 882	5 592	4 301
	Other sources	3 862	4 007	3 923	3 712	3 500
	Total	**27 320**	**28 940**	**26 996**	**21 258**	**15 521**
CO_2 capture	Power production	0	388	2 946	6 423	9 899
	Industry	0	61	578	1 337	2 096
	Transportation	0	137	860	2 150	3 441
	Other sources	0	56	307	518	730
	Total	0	**643**	**4 690**	**10 428**	**16 165**
Accumulated CO_2 capture (all sectors)		**0**	**1 920**	**30 013**	**108 473**	**244 309**

Table 7. Reduction in CO_2 emissions in 2050.

Area	CO_2 emission reduction*
EU	56 %
OECD countries	56 %
non-OECD countries	16 %
Global	37 %

* *Reduction in CO_2 emissions in 2050 compared to CO_2 emissions in 2005.*

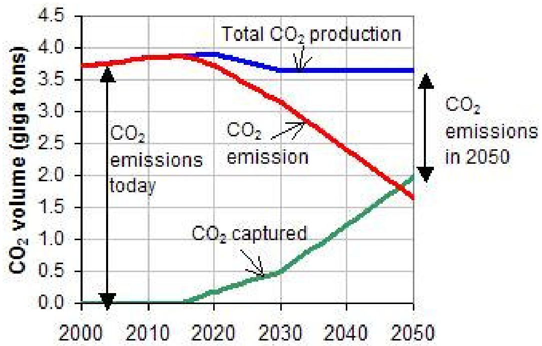

Figure 7 – Predicted CO_2 production, capture and emissions in the EU.

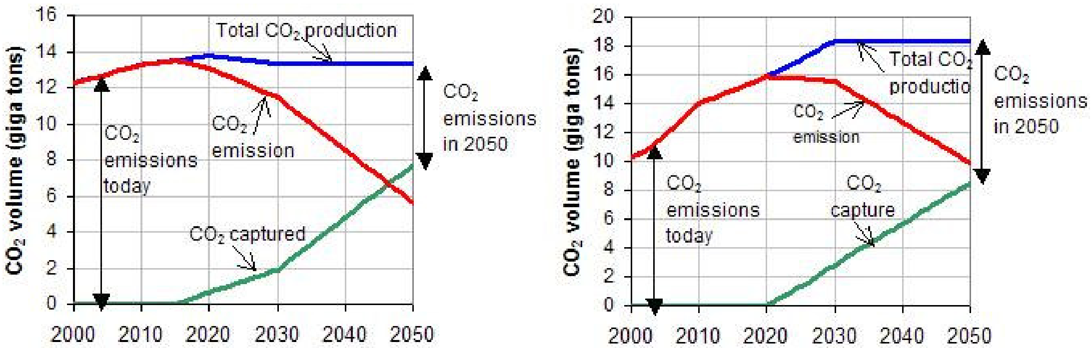

Figure 8 – Predicted CO_2 production, capture and emissions in OECD countries (left), and non-OECD countries (right).

Please note that the results provided above 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 capture projects installed after 2006 are accounted for.

Appendix B – Analysis of CO_2 capture potential from power plants in the EU (Method B)

The CO_2 capture potential in the EU can be verified by analyzing the demand for electrical power in the EU. The European Commission Joint Research Centre has analyzed the electricity demand in the EU onwards to 2030 [9]. They have also estimated to which extent different energy sources will contribute to meet the demand. As seen in Figure 9 fossil fuel will be the most important source for electrical power up to 2030. Figure 9 also indicates how much of today's installed capacity will contribute to the total electricity capacity. Existing power plants will have a limited life-time, and as the plants becomes 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.

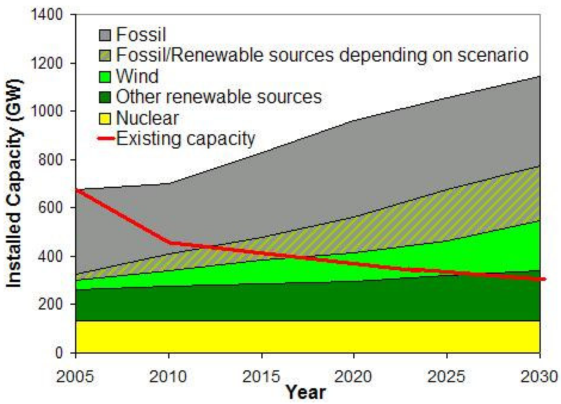

Figure 9 - Estimated electricity capacity in the EU [9] from different sources. Future electricity production from power plants existing in 2005 is indicated by the red line.

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 Figure 9 there is a large uncertainty as to how much electricity will be produced from 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 Figure 10. In this figure the demand for new fossil capacity is given for two scenarios. In Case 1 all capacity marked as "fossil/renewable" in Figure 9 is assumed to be produced from renewable sources. In Case 2, all this capacity is assumed to be produced from fossil fuel.

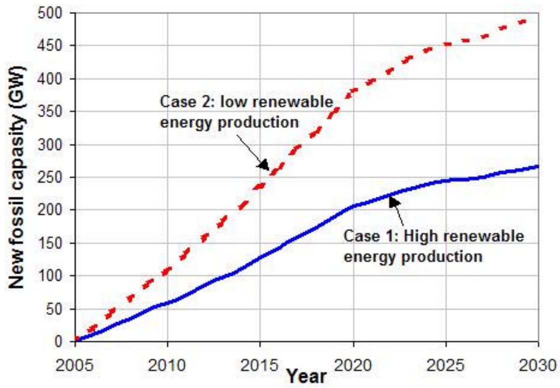

Figure 10 - Estimated new electricity capacity in the EU produced from fossil fuel. The red dotted line represents a scenario where all capacity marked as "Fossil or renewable" in Figure 9 is produced from fossil fuel. The bold blue line is a scenario where all this capacity is produced from renewable sources.

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) [4] is to make new fossil fueled power plants to have near zero CO_2 emissions by 2020. New fossil fueled power plants introduced after 2020 are therefore assumed to have 85 % CO_2 capture.
- One half of the new fossil fueled power plants introduced after 2005 is coal fired. The other half is natural gas fired.
- The plant efficiency of coal and oil fired power plants are assumed to increase from 40 % in 2005 to 50 % in 2030.
- The plant efficiency of natural gas fired power plants is assumed to increase from 55 % in 2005 to 60 % in 2030.
- The power plants run for 7000 hours per year.

- Combustion of coal, oil and natural gas release 86.1, 77.5, and 56.1 g CO_2 per MJ, respectively [10].
- The possibility of retrofitting existing power plants to include CCS is not accounted for.

CO_2 capture from power production in the EU is calculated based on the assumptions above. The results are presented in Figure 11 for both cases, and the accumulated CO_2 capture potential is summarized in Table 8.

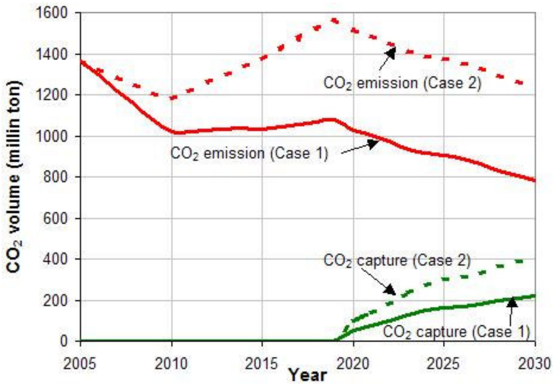

Figure 11 - Estimated CO_2 emissions and CO_2 capture from power production in the EU. Data is given for the same cases as in Figure 10.

Table 8. Potential for CO_2 capture from power production in EU by 2030.

Case	**Renewable vs Fossil fuel***	**CO_2 capture potential in EU by 2030**
Case 1	Renewable	1.6 billion ton
Case 2	Fossil fuel	3.0 billion ton

* *Identifies how the capacity in Figure 9 marked as renewable or fossil fuel is produced.*

The CO_2 capture potential in the EU by 2030 is calculated to be in the range 1.6 to 3.0 billion ton, as shown in Table 8. 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 in the EU by 2030. This model gives a potential of 2.2 billion tonnes CO_2 captured in the EU by 2030. This result is in the range of the CO_2 capture potential presented in Table 8.

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