Bellona Paper:

Energy Infrastructure with CO_2 Capture and Storage (CCS)

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Abstract

CO_2 capture and storage (CCS) has together with solar power and wind power been put forward by industry and politicians worldwide as alternatives for sustainable future energy systems with low CO_2 footprints. Introduction of CCS and renewable power production is however challenging as it will have large implications for the power production infrastructure.

Fossil fuelled power plants are often localised close to the electricity consumers to ensure short distances for electricity transport. CCS raises a new challenge because CO_2 storage locations are often located far away from the electricity consumers. The aim of this study is therefore to perform cost calculations to identify how large transport distances for CO_2 will influence future energy systems. The aim is also to determine if future coal power plants with CCS should be built close to electricity consumers or close to CO_2 storage sites. The latter can results in large distances for electricity transport.

Lack of public support for storing CO_2 in nearby onshore storage sites will most likely result in long transport distances to offshore storage sites. Cost calculations are therefore performed to compare cost effectiveness of coal power plants with short and long distances for transport of electricity and CO_2. Furthermore, the cost effectiveness of coal power plants with CCS is also compared to offshore wind power.

The study is limited to Germany and Norway, because Germany is heavily dependent on coal and will need to invest in CCS and renewable power production, while Norway has a large potential for offshore wind production and large offshore storage capacity for CO_2, which can turn out as alternatives for a future German energy infrastructure.

The cost calculations shows that coal power plants with CCS and nearby CO_2 storage can produce electricity at a lower cost than a coal power plant that purchases emission allowances instead of building CCS. The cost is 0.62 eurocent per kWh lower in the case with CCS.

Transporting CO_2 or electricity for long distances will be more expensive than buying emission allowances. If the CO_2 is transported from Germany to the Utsira Formation on the Norwegian continental shelf, the electricity production cost will be 0.36 eurocent per kWh higher than a coal power plant without CCS. Building coal power plants in Norway and transporting electricity to Germany will be even more expensive, and the cost is in this case is 0.95 eurocent per kWh higher than the reference case where emission allowances are bought instead of implementing CCS.

Building offshore wind parks in Norway and transporting the electricity to Germany will be even more expensive than all the CCS cases.

The study shows the importance of carrying out public information campaigns to gain public support for storing CO_2 locally in onshore storage locations. This will minimize the power production cost and make CCS cheaper than the alternative of buying emission allowances instead of implementing CCS.

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1. Introduction

Global warming is already taking place and has become the biggest challenge of our time. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), global warming is caused by human activities [1] and if business proceeds as usual, anthropogenic greenhouse gas (GHG) emissions will increase the average global temperature from 1.1 to 6.4 ^{o}C during the 21st century. The global temperature is already 0.7 ^{o}C above the pre-industrial level, and a 2 ^{o}C increase is generally considered as the threshold above which dramatic and irreversible impacts will occur. Ecosystems may collapse and 15 to 40 percent of all species may become extinct. More draughts, floods and other extreme weather events will increase pressure on scarce food and water resources as the world population grows towards nine billion humans by 2050 [2,3,4]. As a consequence, hundreds of millions of people may become refugees or starve to death. This would have knock-on effects in term of social upheavals and large-scale conflicts. Other secondary effects may be the release of stored methane from the tundra and from the seabed, creating feedback loops that further exacerbate climate change.

To have a reasonable chance of avoiding such dire consequences of global warming the greenhouse gas (GHG) emissions that causes global warming must be reduced. According to the IPCC, GHG emissions should be reduced by 50 to 85 percent from 2000 to 2050 and a peak in emissions no later than 2015 [1].

There is not one single solution that can lead to such large emission reductions. Several strategies have to be implemented simultaneously to be able to reduce the GHG emissions sufficiently, and a combination of enhanced energy efficiency, more renewable energy and CO_2 capture and storage (CCS) must be part of the solution to combat global warming [5,6].

Power production is the sector with the largest greenhouse gas emissions, because fossil fuels are the dominant energy sources globally [7]. More than two thirds of global power production is based on fossil fuels like coal, oil and natural gas [7]. Replacing fossil fuels with renewable energy sources like solar and wind are challenging, especially because solar and wind are intermittent power sources, which means that we hardly get any solar power when it is cloudy or at night, and we do not get any wind power when it is not windy.

One solution that has been put forward to solve this challenge is to build large supergrids for power production that connects whole continents [8]. For example, if southern Europe needs power because it is cloudy and no wind, the power can be supplied through a supergrid from wind power produced in northern Europe. The next day it can be the other way around; northern Europe can get its power through the supergrid from solar power in Southern Europe.

CCS also raises many challenges, and one of them is to enhance the public awareness of CCS. If we fail to inform the public about CCS, there could be a strong negative public perception for onshore CO_2 storage close to densely populated areas. The final effect of poor public communication could therefore be that the CO_2 must be transported for long distances to offshore storage sites or to a onshore storage site in remote areas.

Introducing CCS and more renewable energy in future power production will alter electricity prices. Production cost of renewable energy, and cost of CCS are known [6,9], but more analysis is needed to determine the cost of transporting electricity and CO_2 for long distances.

The aim of this study is to analyse the cost of the transportation of electricity and CO_2 in a future energy system where renewable power is transported through cables or supergrids and fossil fuelled power plants are built with CCS.

The study is limited to Germany and Norway, because Germany is heavily dependent on coal and will need to invest in CCS and renewable power production, while Norway has a large potential for offshore wind production and large offshore storage capacity for CO_2 that can turn out as good alternatives for the future German energy market.

Several case studies for future energy systems are defined in Section 2, including renewable power and fossil fuelled power production with CCS. The cases have different transport distances for power and CO_2, and cost calculations are performed in Section 3 to define the cost of transporting renewable power and the cost of transporting CO_2. A discussion of the calculations is then given in Section 4 before the conclusions and recommendations are given in Section 5.

2. Defining cases for transport of CO_2 and electricity

The cases studied in this report are limited to Norway and Germany, because there could be future interactions between power production and consumption in Germany and Norway. Germany could end up in a situation where it needs a foreign storage location for CO_2. Furthermore, Germany could also import renewable power from Norway, which has a large potential for large offshore wind parks.

The power supply in Germany is mostly based on coal power. The coal power plants emit large volumes of CO_2, and Germany will in the future have to reduce these emissions to meet its emission reduction targets. The EU has stated that it will reduce its CO_2 emissions by 20 percent by 2020 [10], and as a consequence Germany will have to increase its renewable energy production and use CCS in its coal power plants.

It is unlikely that Germany will be able to meet all its energy demand with domestic renewable energy within the next decades. We therefore aim at calculating the cost of filling the gap between energy demand and domestic renewable energy production. There are several alternatives for filling this gap, and in this study we consider four cases for future energy supply:

- Case A: Coal power plants with CCS in Germany and CO_2 stored onshore in Germany.
- Case B: Coal power plants with CCS in Germany. CO_2 stored in the Utsira formation on the Norwegian continental shelf.
- Case C: Coal power plants with CCS in Norway. Electricity transported from Norway to Germany, and CO_2 stored in the Utsira Formation.
- Case D: Offshore wind power plants in Norway. Electricity transported to Germany.

The different cases are visualized in Figure 1.

The objective is to calculate the electricity production cost for each case and identify the most cost effective future energy system. Each case is compared to a reference scenario where coal power plants are built without CCS.

Case A is obviously the most cost effective case for coal power plants with CCS, because it has the shortest distance for transport of CO_2 and electricity.

CCS is a new concept, and there is a strong concern regarding the safety of CO_2 storage among the public, because they are lacking information on what CCS is and how it works. If CO_2 storage projects are properly operated, the CO_2 storage *is* safe [11,12], and information campaigns to inform the public about CCS and CO_2 storage should therefore be established. The consequence of not giving the public proper information could be lack of public support for storing CO_2 onshore.

If public support for onshore CO_2-storage in Germany should be lacking, Case B could be an alternative, and the CO_2 will then be transported to the Utsira formation outside the Norwegian coast where there is a large CO_2 storage capacity.

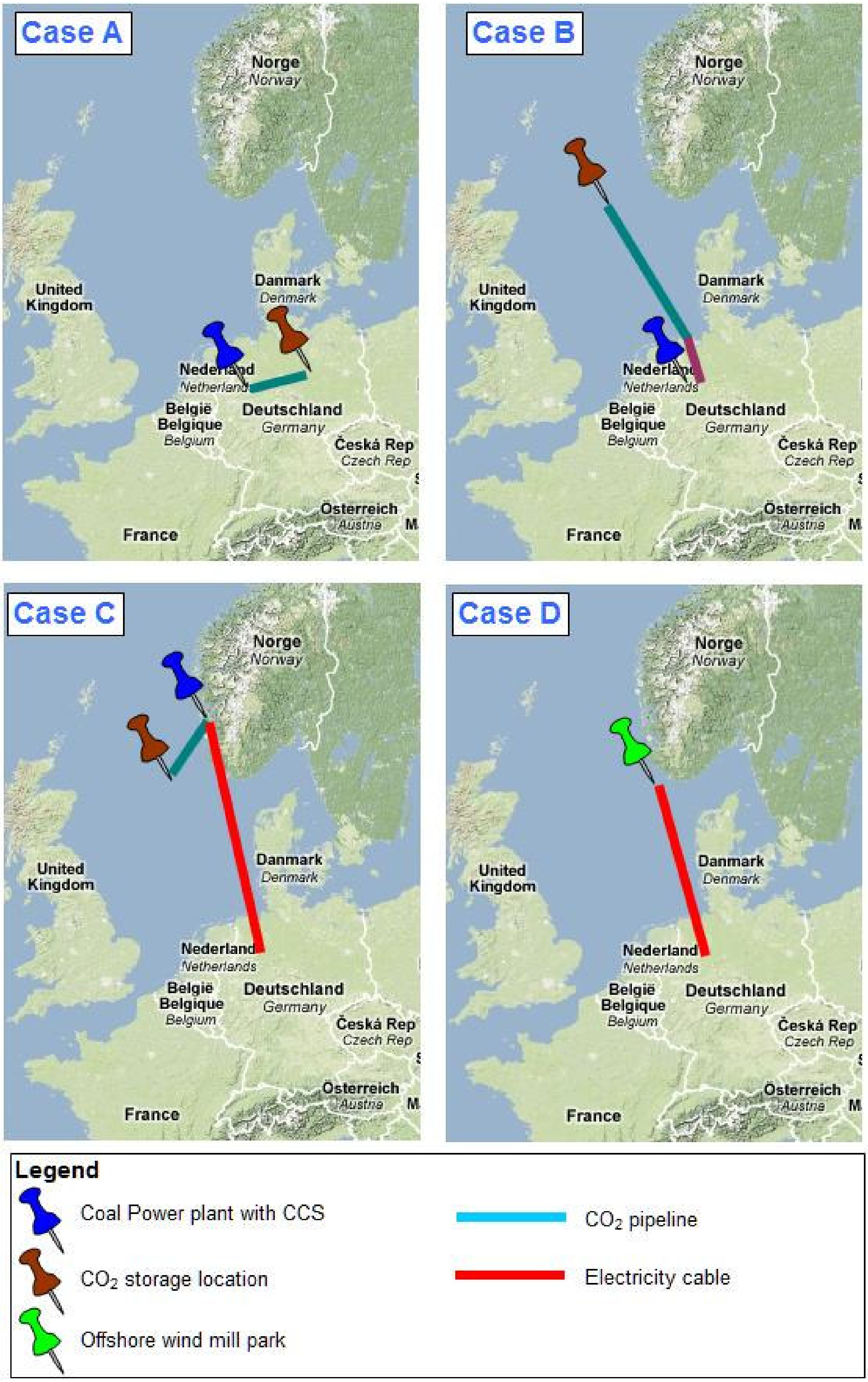

Figure 1. Illustration of the four Cases; Case A: Coal power plant with CCS in Germany and onshore CO_2 storage close by; Case B: CO_2 stored in Utsira; Case C: Coal power plant with CCS in Norway, electricity transported to Germany, and CO_2 storage in Utsira; Case D: Offshore wind power parks in Norway and electricity transported to Germany.

Case B will be more expensive than Case A because of the long distance for CO_2 transport. Alternatively, one could transport the electricity. This is done in Case C where coal power plants with CCS are built in Norway to supply Germany with electricity. Case C has a much shorter distance for CO_2 transport than Case B, but the long distance for electricity transported from Norway to Germany introduces a significant cost element.

More renewable power is, of course, an alternative to coal power plants with CCS. We have therefore included Case D where Norway builds large offshore wind power parks that can supply Germany with electricity. By including Case D it will be possible to compare the cost renewable energy production and coal power plants with CCS.

3. Calculations

3.1. Key assumptions for cost calculations

The reference case is coal power plants without CCS, and because European fossil fuelled power production is part of the EU Emission Trading Scheme (ETS) there will be a CO_2 emission cost related to the reference case. A recent study by McKinsey [9] predicts future CO_2 cost at the ETS in the range 30 to 48 euro per tonne CO_2 from 2015 and onwards. A CO_2 emission cost of 40 euro per tonne CO_2 is for simplicity used in our study.

CCS costs are also based on the study by McKinsey [9], and the key assumptions for CCS cost calculations are summarized in Table 1.

Table 1. Assumptions for CCS cost calculations. All data are based on McKinsey [9]

Parameter	**Value**
Power plant size	900 MW
Efficiency penalty due to CCS	10 % in early commercial phase* 9 % in mature commercial phase*
Utilization	86 %
Power plant life time	40 years
Weighted average cost of capital (WACC)	8 %
CO_2 capture cost	28.5 euro per tonne CO_2 in early commercial phase* 21.5 euro per tonne CO_2 in mature commercial phase*
Onshore CO_2 transport cost, 200 km **	4 euro per tonne CO_2
Offshore $_{CO2}$ transport cost, 300 km **	6 euro per tonne CO_2
Onshore CO_2 storage cost in saline aquifer	5 euro per tonne CO_2
Offshore $_{CO2}$ storage cost in saline aquifer	12 euro per tonne CO_2

* *"Early commercial phase" is the term used for the first commercial CCS plants to be built. "Mature commercial phase" is the phase when several commercial CCS projects have been built and CCS is a standard part of fossil fuelled power production. The mature commercial phase for CCS will be post 2030 according to McKinsey* [9].
** *Transport in 24'' pipelines.*

The cost of transporting large quantities of power through offshore HVDC electrical cables is based on available data for the NorNed cable between Norway and the Netherlands [13]. The NorNed cable has a capacity of 700 MW, and the capex of the cable was 492 million euros (see Appendix 1 for details).

3.2. CCS cost calculations

Production cost for Case A, B and C are compared with the Reference Case in Table 2. This table shows that a coal power plant without CCS (Case A) will have an additional carbon cost of 2.95 eurocent per kWh on top of the traditional production cost. This additional carbon cost reflects the price of emission allowances at the EU ETS.

Table 2. Additional carbon cost for power production in a coal power plant. The additional carbon cost is equal to the CCS costs for plants with CCS and it reflects the EU ETS cost for plants without CCS. (Details are given in Appendix 1.)

Case	**Additional carbon cost [eurocent / kWh]**	
	Early commercial phase*	**Mature commercial phase***
Reference Case	2.95	2.95
Case A	2.79	2.33
Case B	3.77	3.31
Case C	4.36	3.90

* *"Early commercial phase" is the term used for the first commercial CCS plants to be built. "Mature commercial phase" is the phase when several commercial CCS projects have been built and CCS is a standard part of fossil fuelled power production. The mature commercial phase for CCS will be post 2030 according to McKinsey [9].*

Table 2 also shows that the additional carbon cost in Case A is lower than for the Reference Case. Building coal power plants with CCS will therefore be cheaper than buying emission allowances, and in a mature commercial phase a coal power plant with CCS (Case A) will have a total production cost that is 0.62 eurocent per kWh lower than the reference case.

But if CO_2 or electricity has to be transported for long distances, like in Case B and C, respectively, the cost of implementing CCS will be higher than the cost of buying emission allowances. In Case B where the CO_2 is transported to the Utsira Formation, the electricity production cost will be 0.36 eurocent per kWh higher than from a coal power plant without CCS in the mature commercial phase. Case C, where power is produced in Norway and transported to Germany, is even more expensive. The additional carbon cost is in this case is 0.95 eurocent per kWh higher than the Reference Case, as seen from Figure 2.

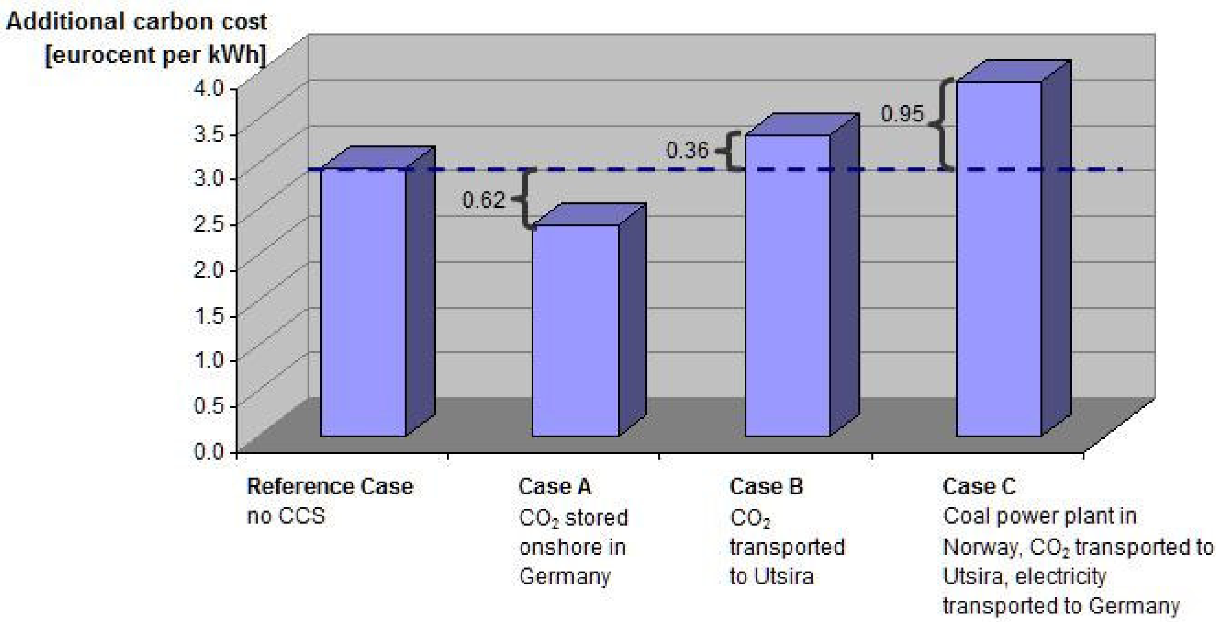

Figure 2. Additional carbon cost in cases with CCS.

3.3. Renewable energy vs CCS

Marked price of electricity 22 January 2009 was 3.75 eurocent per kWh [14]. Case D, where electricity is produced in offshore wind parks has an electricity cost about three times as high. (*c.f.* Appendix 1 for details.)

Future wind power production cost is difficult to estimate. We have based our calculations on power generation cost today and an assumed learning curve onwards to 2020. The World Economic Forum reports power generation cost from offshore wind to be 181.8 US$/MWh [15]. A 20 percent cost reduction onwards to 2020 due to learning effects is assumed, giving a production cost of 11 eurocent per kWh in 2020.

In addition, we have calculated a transportation cost of 1 eurocent per kWh when the electricity is transported from Norway to Germany (*c.f.* Appendix 1). The total cost is then 12 eurocent per kWh which is considerable higher than marked price of electricity.

4. Discussion

Cost data found in literature are often reported in intervals. When such data is used as input parameters in this study we have taken the average of the reported interval. One example is the CO_2 capture cost in the early commercial phase that is reported to be in the range 25 to 32 euro per tonne CO_2 by McKinsey [9]. This interval represents an uncertainty in the cost. Please note that when we use an average CO_2 capture cost of 28.5 euro per tonne CO_2 there will be a significant uncertainty to this number.

This study shows the importance of establishing public communication campaigns. If there should be a lack of acceptance for storing CO_2 onshore in Germany, the CO_2 might have to be transported to the Utsira Formation, like in Case B. This will add 0.98 eurocent per kWh to the power production cost compared to Case A where the CO_2 is stored onshore in Germany. As such, public communication to inform the public about CCS does not only have a social effect in informing the public about CCS as a strategy to combat global warming; it also has an economic dimension.

The study shows that a coal power plant with CCS (Case A) will have a lower carbon cost than a coal power plant without CCS that have to buy CO_2 emissions allowances. This strongly suggests that CCS will be an economic viable alternative for future power production from fossil sources. But CCS represents considerable additional costs to produced electricity. It is therefore recommended to carry out RD&D activities to ensure technology development and cost reduction for CCS.

A roadmap for building large scale CCS demonstration projects has been established by the EU Technology Platform for Zero Emission Fossil Fuelled Power Plants (ZEP) [16]. We recommend that politicians establish the necessary regulations and economic incentives to ensure that this roadmap from ZEP is carried out.

The calculations show that transporting electricity from offshore wind over long distances is an expensive alternative. However, comprehensive research and demonstration programs can reduce the cost considerably, and we therefore strongly recommend that politicians establish regulations and incentives to ensure research and demonstration activities to develop and improve offshore wind power production. Alternatively, wind power can be produced onshore, which is a cheaper alternative than offshore wind. But the onshore wind potential is limited, and onshore wind will therefore probably be consumed close to where it is produced. Onshore wind was therefore beyond the scope of this study where we focused on the effect of transporting electricity or CO_2 for long distances.

5. Conclusions and recommendations

Based on the assumptions established in this study, coal power plants with CCS and CO_2 storage locally have a power production cost that is 0.62 eurocent per kWh lower than a coal power plant that purchases emission allowances instead of building CCS.

Transporting CO_2 or electricity for long distances will be more expensive that buying emission allowances. If the CO_2 is transported from Germany to the Utsira Formation at the Norwegian continental shelf, the electricity production cost will be 0.36 eurocent per kWh higher than a coal power plant without CCS. Building coal power plants in Norway and transporting electricity to Germany will be even more expensive, and the cost is in this case 0.95 eurocent per kWh higher than the reference case where emission allowances are bought instead of implementing CCS.

Building offshore wind parks in Norway and transporting the electricity to Germany will be even more expensive than all the CCS cases.

The study shows the importance of performing public information campaigns to gain public support for storing CO_2 locally in onshore storage locations. This will reduce the power production cost and make CCS cheaper than the alternative of buying emission allowances instead of implementing CCS.

Furthermore, it is also recommended the politicians establish regulatory framework and economic incentives that ensures RD&D activities for CCS and supergrids to ensure technology development and cost reduction.

Acknowledgement

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Appendix 1 – Cost calculations

All cost calculations are carried out in Microsoft Excel, and all calculations are listed below.

Definition of cases

Reference Case
German coal power plant without CCS
Carbon cost: EU ETS cost

Early Commercial Phase:

Case A1 - Early Commercial Phase
German coal power plant with CCS
Onshore Storage
Transport < 200 km
Carbon cost: CCS costs

Case B1 - Early Commercial Phase
German coal power plant with CCS
Offshore Storage
Transport ~650 km
Carbon cost: CCS costs

Case C1 - Early Commercial Phase
Norwegian coal power plant with CCS
Utsira storage
CO2 transport < 300 km
Transport electricity from Norway to Germany
Carbon cost: CCS costs

Case D - Offshore Wind, after 2020
Norwegian offshore wind
Transport electricity from Norway to Germany

Mature Commercial Phase:

Case A2 - Mature Commercial Phase
German coal power plant with CCS
Onshore Storage
Transport < 200 km
Carbon cost: CCS costs

Case B2 - Mature Commercial Phase
German coal power plant with CCS
Offshore Storage
Transport ~650 km
Carbon cost: CCS costs

Case C2 - Mature Commercial Phase
Norwegian coal power plant with CCS
Utsira storage
CO2 transport < 300 km
Transport electricity from Norway to Germany
Carbon cost: CCS costs

Early Commercial CCS

Reference Case: New build 900 MW coal power plant.
Source: McKinsey&Comany, Carbon Capture and Storage: Assesing the Economics

"Cost of CCS": Additional full cost (initial investment and ongoing opex) of a CCS power plant compared to the cost of a state-of-the-art non CCS plant, with the same net electricity output and using the same fuel.

Cost per tonne CO_2 => cost per tonne abated!
- compared with a state-of-the art non-CCs plant with the same electrcity output and using the same fuel

<u>**Early Commercial CCS Projects (2020)**</u>		
Earliest start date	2020	
Size	900	MW
Efficieny penalty	10	%
Capture %	90	%
Utilization (non CCS plant)	86	% (7533 timer)
Electricity production	6.78	TWh/year
WACC	8	%
CO_2 emissions non-CCS plant	5.00	mill. tonne per year
Capacity, CCS plant	1000	MW
CO_2 produced per year	5.56	mill. tonne
CO_2 stored per year	5.00	mill. tonne
CO_2 emitted per year	0.56	mill. tonne
CO_2 abatement per year	4.44	mill. tonne
Abated CO_2 per TWh produced	0.66	mill tonne/TWh
Capex, pipeline, onshore:	1.30	million euros per km
Capex, pipeline, offshore:	1.56	million euros per km

<u>**Sample Project, Onshore Storage**</u>		
Cost per tonne CO_2:		
Capture phase	28.5	
Transport (200 km, no booster station)	4	
Storage (Saline aquifer)	<u>5</u>	
	37.5	**euro/tonne**
CO_2 abatement cost/TWh	24.58	mill. euros/TWh
CO_2 abatement cost/kWh	**2.46**	**eurocent/kWh**

<u>**Sample Project, Offshore Storage, < 300km**</u>		
Cost per tonne CO_2:		
Capture phase	28.5	
Transport, 300 km, no booster station (9 euros/tonne for 400 km with boster)	6	
Storage (Saline aquifer)	<u>12</u>	
	46.5	**euro/tonne**

CO_2 abatement cost/TWh	30.48	mill. euros/TWh
CO_2 abatement cost/kWh	**3.05**	**eurocent/kWh**

<u>Sample Project, Offshore Storage</u>

Transport distance:	650	km
Cost per tonne CO_2:		
Capture phase	28.5	
Transport, Approx. 650 km, two booster station (9 euros/tonne for 400 km with boster)	12	
Storage (Saline aquifer)	<u>12</u>	
	52.5	**euro/tonne**
CO_2 abatement cost/TWh	34.41	mill. euros/TWh
CO_2 abatement cost/kWh	**3.44**	**eurocent/kWh**

<u>Sample Project, Offshore Wind</u>

After 2020, Southern North Sea		
Production cost per kWh	**11.00**	**eurocent/kWh**

Mature Commercial CCS

Reference Case: New build 900 MW coal power plant.
Source: McKinsey&Comany, Carbon Capture and Storage: Assesing the Economics

"Cost of CCS": Additional full cost (initial investment and ongoing opex) of a CCS power plant compared to the cost of a state-of-the-art non CCS plant, with the same net electricity output and using the same fuel.

Cost per tonne CO_2 => cost per tonne abated!
- compared with a state-of-the art non-CCs plant with the same electrcity output and using the same fuel

<u>Mature Commercial CCS Projects (2030)</u>

Earliest start date	2020	
Size	900	MW
Efficieny penalty	9 %	
Capture %	90 %	
Utilization (non CCS plant)	86 %	(7533 timer)
Electricity production	6.78	TWh/year
WACC	8 %	
CO_2 emissions non-CCS plant	5.00	mill. tonne per year
Capacity, CCS plant	989	MW
CO_2 produced per year	5.49	mill. tonne
CO_2 stored per year	4.95	mill. tonne
CO_2 emitted per year	0.55	mill. tonne
CO_2 abatement per year	4.45	mill. tonne
Abated CO_2 per TWh produced	0.66	mill tonne/TWh

Capex, pipeline, onshore:	1.30	million euros per km
Capex, pipeline, offshore:	1.56	million euros per km

Sample Project, Onshore Storage

Cost per tonne CO_2:		
Capture phase, Learning effect (-7 euro)	21.5	
Transport, 200 km, no booster station	4	
Storage, Saline aquifer	5	
	30.5	**euro/tonne**
CO_2 abatement cost/TWh	20.02	mill. euros/TWh
CO_2 abatement cost/kWh	**2.00**	**eurocent/kWh**

Sample Project, Offshore Storage, < 300km

Cost per tonne CO_2:		
Capture phase, Learning effect (-7 euro)	21.5	
Transport, 300 km, no booster station (9 euros/tonne for 400 km with boster)	6	
Storage, Saline aquifer	12	
	39.5	**euro/tonne**
CO_2 abatement cost/TWh	25.93	mill. euros/TWh
CO_2 abatement cost/kWh	**2.59**	**eurocent/kWh**

Sample Project, Offshore Storage

Transport distance:	650	km
Cost per tonne CO_2:		
Capture phase, Learning effect (-7 euro)	21.5	
Transport, Approx. 650 km, two booster station (9 euros/tonne for 400 km with boster)	12	
Storage, Saline aquifer	12	
	45.5	**euro/tonne**
CO_2 abatement cost/TWh	29.87	mill. euros/TWh
CO_2 abatement cost/kWh	**2.99**	**eurocent/kWh**

Case A1

<u>Reference Case</u>

900 MW, German coal power plant without CCS

Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**

<u>Case 1a</u>

Early Commercial Phase

German coal power plant with CCS

Onshore Storage (<200km)

Electricity production	6.78	TWh/year
CO_2 emissions	0.56	mill. tonne per year
CO_2 emissions/TWh	0.08	mill. tonne per TWh
Carbon Price/TWh	3.28	mill. euros per TWh
Additional cost per kWh	**0.33**	**eurocent/kWh**
CO_2 abatement cost	**2.46**	**eurocent/kWh**
Total Carbon Cost	**2.79**	**eurocent/kWh**
Additional Cost (Savings) for CCS	**(0.16)**	**eurocent/kWh**

Case A2

<u>Reference Case</u>		
900 MW, German coal power plant without CCS		
Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**

<u>Case 2a</u>		
Mature Commercial Phase		
German coal power plant with CCS		
Onshore Storage (<200km)		
Electricity production	6.78	TWh/year
CO_2 emissions	0.55	mill. tonne per year
CO_2 emissions/TWh	0.08	mill. tonne per TWh
Carbon Price/TWh	3.24	mill. euros per TWh
Additional cost per kWh	**0.32**	**eurocent/kWh**
CO_2 abatement cost	**2.00**	**eurocent/kWh**
Total Carbon Cost	**2.33**	**eurocent/kWh**
Additional Cost (Savings) for CCS	**(0.62)**	**eurocent/kWh**

Case B1

Reference Case

900 MW, German coal power plant without CCS

Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**

Case 1b

Early Commercial Phase

German coal power plant with CCS

Utsira storage (approx. 650km)

Electricity production	6.78	TWh/year
CO_2 emissions	0.56	mill. tonne per year
CO_2 emissions/TWh	0.08	mill. tonne per TWh
Carbon Price/TWh	3.28	mill. euros per TWh
Additional cost per kWh	**0.33**	**eurocent/kWh**
CO_2 abatement cost	**3.44**	**eurocent/kWh**
Total Carbon Cost	**3.77**	**eurocent/kWh**
Additional Cost for CCS	**0.82**	**eurocent/kWh**

Case B2

<u>Reference Case</u>

900 MW, German coal power plant without CCS

Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**

<u>Case 2b</u>

Mature Commercial Phase

German coal power plant with CCS

Utsira storage (approx. 650km)

Electricity production	6.78	TWh/year
CO_2 emissions	0.55	mill. tonne per year
CO_2 emissions/TWh	0.08	mill. tonne per TWh
Carbon Price/TWh	3.24	mill. euros per TWh
Additional cost per kWh	**0.32**	**eurocent/kWh**
CO_2 abatement cost	**2.99**	**eurocent/kWh**
Total Carbon Cost	**3.31**	**eurocent/kWh**
Additional Cost for CCS	**0.36**	**eurocent/kWh**
Cost increas compared to Case A2	**0.98**	**eurocent/kWh**

Case C1

Reference Case
900 MW, German coal power plant without CCS

Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**

Case 1c
Early Commercial Phase
Norwegian coal power plant with CCS
Utsira storage (approx. 250 km)
Transport electricity to Germany

Electricity production	6.78	TWh/year
CO_2 emissions	0.56	mill. tonne per year
CO_2 emissions/TWh	0.08	mill. tonne per TWh
Carbon Price/TWh	3.28	mill. euros per TWh
Additional cost per kWh	**0.33**	**eurocent/kWh**
CO_2 abatement cost	**3.05**	**eurocent/kWh**
Transportation Cost	**0.99**	**eurocent/kWh**
Total Carbon + Transp. Cost	**4.36**	**eurocent/kWh**
Additional Cost for CCS	**1.41**	**eurocent/kWh**

Case C2

<u>**Reference Case**</u>		
900 MW, German coal power plant without CCS		
Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**
<u>**Case 2c**</u>		
Mature Commercial Phase		
Norwegian coal power plant with CCS		
Utsira storage (approx. 250 km)		
Transport electricity to Germany		
Electricity production	6.78	TWh/year
CO_2 emissions	0.55	mill. tonne per year
CO_2 emissions/TWh	0.08	mill. tonne per TWh
Carbon Price/TWh	3.24	mill. euros per TWh
Additional cost per kWh	**0.32**	**eurocent/kWh**
CO_2 abatement cost	**2.59**	**eurocent/kWh**
Transportation Cost	**0.99**	**eurocent/kWh**
Total Carbon + Transp. Cost	**3.90**	**eurocent/kWh**
Additional Cost for CCS	**0.96**	**eurocent/kWh**
Cost increas compared to Case A2	**1.58**	**eurocent/kWh**

Case D

Reference Case		
900 MW, German coal power plant without CCS		
Electricity production	6.78	TWh/year
CO_2 emissions	5.00	mill. tonne per year
CO_2 emissions/TWh	0.74	mill. tonne per TWh
Carbon price	40.00	euro/tonne
Carbon price/TWh	29.50	mill. euros/TWh
Total Carbon Cost	**2.95**	**eurocent/kWh**
Market Price (without CCS)	**3.75**	**eurocent/kWh** (Nord Pool 22 january)
Total Cost	**6.70**	**eurocent/kWh**
Case 1d		
Offshore wind (Sørlige Nordsjø) after 2020		
Transport electricity to Germany		
Electricity production	6.78	TWh/year
Production cost per kWh	**11.00**	**eurocent/kWh**
Transportation Cost	**0.99**	**eurocent/kWh**
Total Cost	**11.99**	**eurocent/kWh**
Additional Cost for Offshore Wind	**5.29**	**eurocent/kWh**

Electricity transport

NorNed

580 km (Feda, Norway - Eemshaven, Nederland)

Produced by ABB, HVDC

700	MW capacity			
4 600	MNOK	Capex, over three years		
492	mill. euros	Capex, over three years	Exchange rate:	9.35
-	mill. euros	Opex assumed close to zero		
700	MW capacity			
5.60	TWh/Year			
2 %	Losses			
5.49	TWh/Year, Net Electricity			
8 %	WACC			

Transportation Cost 0.99 eurocent/kWh

Cash Flow`, million euro

	1	2	3	4	5	6	7	8 to 23
Capex	(164)	(164)	(164)					
Opex				-	-	-	-	-
Revenue	-	-	-	54	54	54	54	54
	(164)	(164)	(164)	54	54	54	54	54

NPV (0) mill. euro Goalseek to 0, by changing Transportation Cost"!