Analysis of potentials and costs of CO_2 storage in the Utsira aquifer in the North Sea

Final Report for the FENCO ERA-NET project

A joint research project:

Institute for Energy Technology (IFE)

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Executive Summary

The FENCO ERA-NET project "Analysis of potentials and costs of storage of CO_2 in the Utsira aquifer in the North Sea" has studied the national and regional cost-effectiveness of CCS in five countries of North West Europe. The focus was on the feasibility of storing CO_2 into the Utsira formation as part of national or regional CO_2 mitigation strategies.

The following partners have been involved in the project:

- University College London, UK
- Utrecht University, NL
- University of Stuttgart, DE
- Risø DTU, DK
- Institute for Energy Technology, NO (coordinator)

The project have used the Pan European TIMES (PET) model and national MARKAL/TIMES models for the United Kingdom, the Netherlands, Germany, Denmark and Norway. To be able to carry out comparable analyses, data which is not country specific (e.g., developments on cost and performance of fossil fuel based power plants) has been harmonized. Analyses were carried out on both national level and regional (North European) level and the model results were compared to study the advantages of a common European CO_2 infrastructure in contrast with national infrastructures.

The future role of the Norwegian Utsira formation as a storage location for CO_2 from North European countries depends on the actual properties of the formation, mitigation strategies, future energy costs, development of Carbon Capture and Storage (CCS) technologies, public acceptance and political barriers. A main limitation for the use of the Utsira formation is the maximum annual injection rate for CO_2. This appears as a stronger limiting factor than the total storage capacity. The maximum simulated injection rate that was found in the literature is 150 Mt CO_2 per year. Under stringent mitigation targets the requirement of annual CO_2 capture can exceed 150 Mt per year in the North European countries. To obtain a better understanding of the limitation of the Utsira formation as a possible storage location for North European CO_2, further research on the injection rate capacity will be required.

The European CO_2 mitigation strategies are vital for the implementation of CCS technologies towards 2050 and the importance of CO_2 storage in the Utsira formation. All the national energy system models give considerable differences in the CCS implementation dependent on the emission reduction targets. The national models have been analysed with both 20 % and 80 % emission reduction targets towards 2050. In

Germany, e.g. the amount of CO_2 captured in 2050 is 22 Mt/y with a 20 % emission reduction compared to 238 Mt/y with an 80 % emission reduction.

The comparison of the modelling results at the national and regional level highlights the impact that geographic scale can have on the design of strategies since analysis made at the regional level tend to have a larger and different spectrum for combining cost-effective measures. In any case, analyses at the national and regional level indicate that, under a stringent climate policy, the storage of CO_2 in the Utsira formation can be a cost effective option for North Europe. With an 80 % emission reduction target in 2050 the regional analysis results in approximately 575 Mt CO_2 captured annually, while the sum of the five national models give approximately 475 Mt CO_2 captured. Up to 1.4 Gt CO_2 will be captured annually in 2050 in Europe according to the regional analysis. This will increase the need for storages, and also long transport distances will be of interest.

According to the PET model results, CO_2 transport to Utsira from outside Norway would mainly originated in the UK (60 to 75 Mt/a in and 2050) and in the Netherlands (20 to 50 Mt/a in 2040 and 2050). The United Kingdom profit from the comparably short transport distance to Utsira and the Netherlands utilise the Utsira formation due to limited domestic low cost storage possibilities over time and the fact that the country appears to become a CO_2 hub for the region. In Germany and Denmark the availability of domestic onshore saline aquifers determines the competitiveness of CO_2 storage in Utsira. If these aquifers are not usable, Utsira will be a competitive storage option.

The price development of oil, natural gas and coal influences the role of CCS in the energy system. CCS technologies compete with renewable and nuclear power production. Higher fossil fuel prices favour the deployment of renewable technologies while lower energy prices tend to favour CCS technologies or natural gas technologies. CCS and nuclear appear in the same cost range so, without further limitations impose by policy, these two technologies appear to compete with each other. Further, the deployment of CCS technologies is also influenced by the national electricity supply options and the opportunity for cross-boundary CO_2 transport.

For the CO_2 transport to Utsira, three different network layouts have been analysed. The analysis showed that electricity generation structure of the neighbouring countries of the North Sea is not influenced by the type of network but rather by climate policies. Different CO_2 infrastructure layouts for the North Sea region primary affect the transported quantities of CO_2 from the Netherlands (acting as a regional hub) to Utsira. However, the different infrastructures options have little impact on the CO_2 storage from the other North Sea countries.

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Table of Content

Abbreviations

CCS	Carbon Capture and Storage
DE	Germany
DK	Denmark
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EOR	Enhanced Oil Recovery
GHG	Greenhouse Gas
GW	Gigawatt
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
IFE	Institute for Energy Technology
kW	Kilowatt
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MARKAL	Market Allocation (optimisation model developed by the IEA)
MILP	Mixed integer linear programming
NGCC	Natural Gas Combined Cycle
NL	The Netherlands
NO	Norway
NOK	Norwegian Kroner
NVE	Norwegian Water Resources and Energy Directorate
PC	Pulverised Coal
PET	Pan European Times Model
PJ	Petajoule
PV	Photo Voltaic
SMR	Steam Methane Reforming
TCM	Test Center Mongstad
TIMES	The Integrated Markal EFOM System
TJ	Terajoule (10^{12} Joule)
TWh	Terawatt hours 10^{12} Wh
UK	United Kingdom
WEO	World Energy Outlook published by the International Energy Agency
WP	Work Package

1 Introduction

The role that mega-structure such as Utsira could play for the large scale deployment of CCS in the North Sea region has gained increased attention since it could increase the cost-effectiveness of CCS in the region while minimizing opposition from the public to CO_2 storage. The potential capacity to store CO_2 in the Utsira formation is large. Recent reservoir simulations indicate a cost effective utilisation of the reservoir in the range between 20 to 60 Gt (see chapter 2). The use of Utsira as a European reservoir will not only depend on its available capacity to store CO_2 flows but also on the cost effectiveness of this option within national portfolios of mitigation measures.

Up to now, although providing useful insights into the scale and role that CCS could play in the medium and longer term, most European system studies dealing with the development of CCS as a part of the portfolio of mitigation measures either take a regional or a national perspective. In the first case most studies fail to include specific local technical, economic, political or physical constrains, making it difficult for local stakeholders and policy makers to interpret the significance of the results. In the latter case, the development of the energy systems (including CCS) are only optimized for local conditions disregarding the influence of developments taking place outside the national frontiers. This report summarizes the findings of the FENCO ERA-NET project "*Analysis of potentials and costs of storage of CO_2 in the Utsira aquifer in the North Sea*". In this project, country specific characteristics have been included in the analyses while parameters and assumptions that are not country dependent have been homogenized. Furthermore, the costs and benefits of constructing a CO_2 offshore network as part of an international cooperation project have been analysed. Quantitative analyses of specific scenarios for the North European Region and for the individual countries of Denmark, Germany, Norway, the Netherlands and the United Kingdom have been carried out. The project has generated insights into the role that an aquifer, such as Utsira, could play for CCS deployment in each country and in the North Sea region as a whole. Capture technologies and infrastructure for CO_2 with their possible levels and timing for each of the countries around the North Sea were assessed. Finally, non-technical barriers and synergies for the construction of a common pipeline network in the North Sea have been identified.

1.1 Objectives

This project aimed to generate insights into the national and regional costs, benefits and bottlenecks of capturing and transporting and storing CO_2 from countries in the North Sea region into the Utsira formation. The project had 5 key sub-goals:

1. Improve knowledge on uncertainties and limitations to use the Utsira Formation as a CO_2 reservoir (capacity, user conflicts, leakage problems etc).

2. Improve knowledge on transportation alternatives and barriers (both technical and political/economical) including possible synergies and conflicts for constructing an international CO_2 pipeline network in the North Sea region.
3. Coordinate analysis of CCS for the countries around the North Sea (Norway, Denmark, Germany, the Netherland and the United Kingdom) for the time period 2015-2050, with a focus on the national and regional implications of offshore CO_2 transport to the Utsira formation.
4. Analyse techno-economic parameters of future carbon capture technologies and their impact on CCS market penetration, considering alternative carbon reduction measures in the context of the countries' energy systems.
5. Develop experience using the TIMES model for infrastructure development leading to an identification of a set of possible stepwise developments.

1.2 Structure of the project

This project was co-ordinated by the Institute for Energy Technology (IFE), Norway with partners from Utrecht University, the Netherlands, University College London, UK, University of Stuttgart, Germany and Risø DTU, Denmark.

This project was organised into three main parts (Figure 1-1): analysis and harmonization of the assumptions (WP 1 and 2); analysis of the CCS pathways at the national (WP 3) and regional (WP 4) level and overview of non-technical issues that are relevant for the deployment of an international pipeline network (WP 5). In WP 6 the outcome of WP 1-5 is summarised into a final report and conclusions. In this report, a summary of the goals, methodology and results of each WP are presented. An integration and comparison of the main findings is provided at the end of this report.

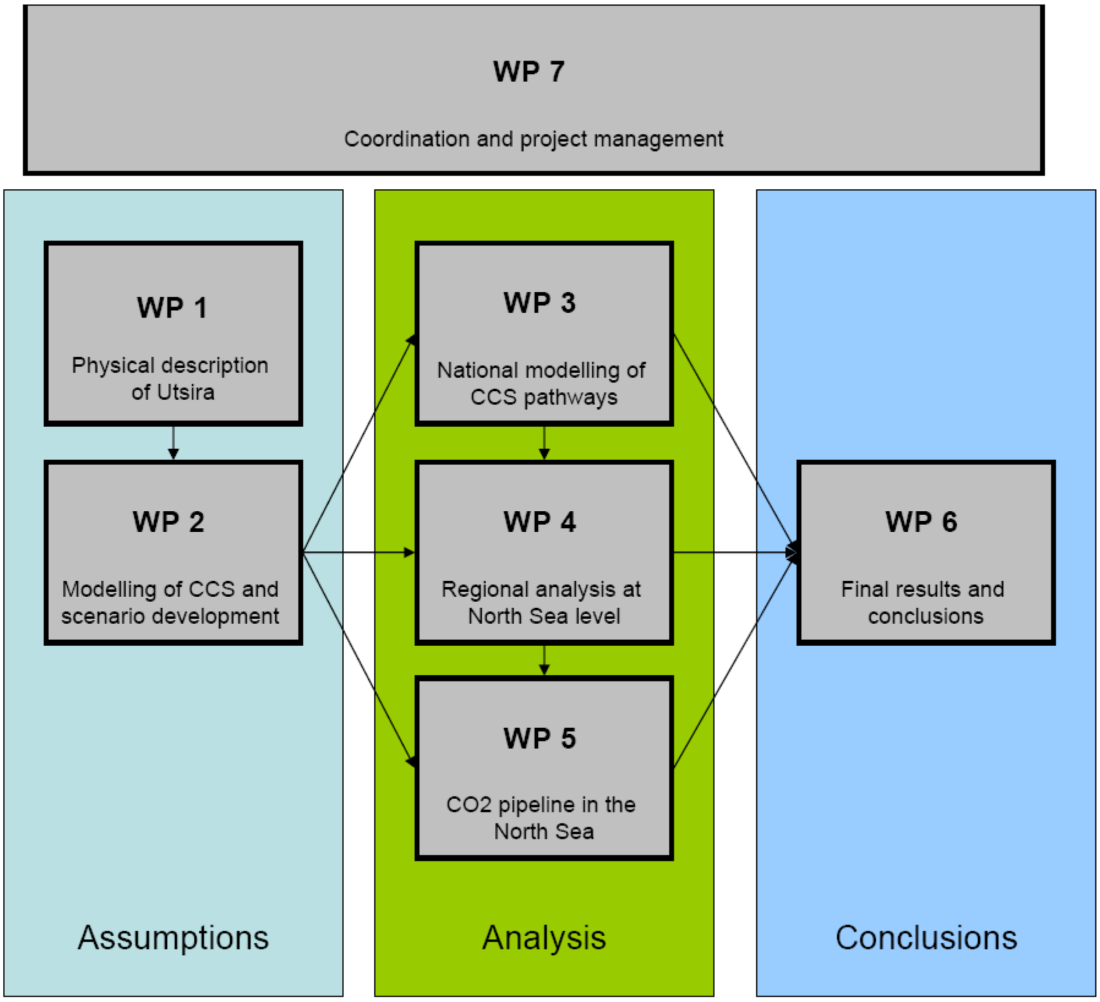


Figure 1-1: Project structure

2 WP 1 – Physical description of Utsira

Deliverable:
- *Physical possibilities and constrains for CO_2 storage in the Utsira Formation [1]*

Estimates in past studies of the potential capacity to store CO_2 in the Utsira formation range from 2 billions tonnes CO_2 annually to a total cumulative storage capacity of 600 billions tonnes of CO_2 (e.g. ACCSEPT, 2007 [2], while recent reservoir simulations (e.g. Lindeberg et al., 2009 [6]) have indicated that 20 to 60 Gt of CO_2 could be stored cost effectively in the Utsira formation. However, if several hundred millions tones of CO_2 are to be stored annually, a large number of CO_2 injection wells may be needed (of order 100) as well as a similar number of water production wells (to make space for the CO_2 and to limit the pressure build-up). In this context, *WP1 aimed to establish possible constrains for the use of the Utsira Formation in the Norwegian North Sea* as a CO_2 storage site for the North West European region. Such constrain can then be taking into account by the modelling work to be performed in WP 3 and 4.

2.1 The Utsira formation

Storage of CO_2 at the Utsira formation at Sleipner has taken place since 1996 and to date more than 13 Mt of CO_2 have been captured and injected (about 1 Mt of CO_2 annually). The Utsira formation consists of marine sandstones and claystones of middle to late miocene age. The formation extends more than 400 km from north to south and between 50 km to 100 km from east to west. The top of the formation varies in depth from 550 m to 1500 m but mostly from 700 m to 1000 m [3]. Isopachs[1] of the reservoir sand show two main depocenters[2], with estimated thickness between 200 and more than 300 m (See Figure 2-1).

Analysis of core and cuttings samples shows uncemented fined-grained sand, with medium and occasionally coarse grains. The fraction of sand varies between 0.7 and 1 and the porosity is estimated to be in the range from 31 % to 42 %. From the size of the formation and the porosity, the total pore volume of Utsira can be estimated to 6.05×10^{11} m^3 [3].

[1] Isopachs are contours that show the thickness of a rock unit

[2] Depocenter - The area of thickest deposition in a sedimentary basin.

Using a typical solubility of 1 mole/kg and the total pore volume, around 26 Gt CO_2 can be stored in the formation water of Utsira. This is in range with the estimate of 22 Gt by Portier and Rochelle [4].

A dominating uncertainty to calculate a realistic storage potential is the volume of accessible pore space and the aquifer permeability. The total pore volume of Utsira is estimated to be 6.05 x 10^{11} m^3 [3] and simulation studies by Lindeberg et al [6] indicate that Utsira has a storage capacity for CO_2 in the range from 20 Gt to 60 Gt. The previous storage estimates by the Geological Survey of Norway for the Utsira formation was 42 Gt [5].

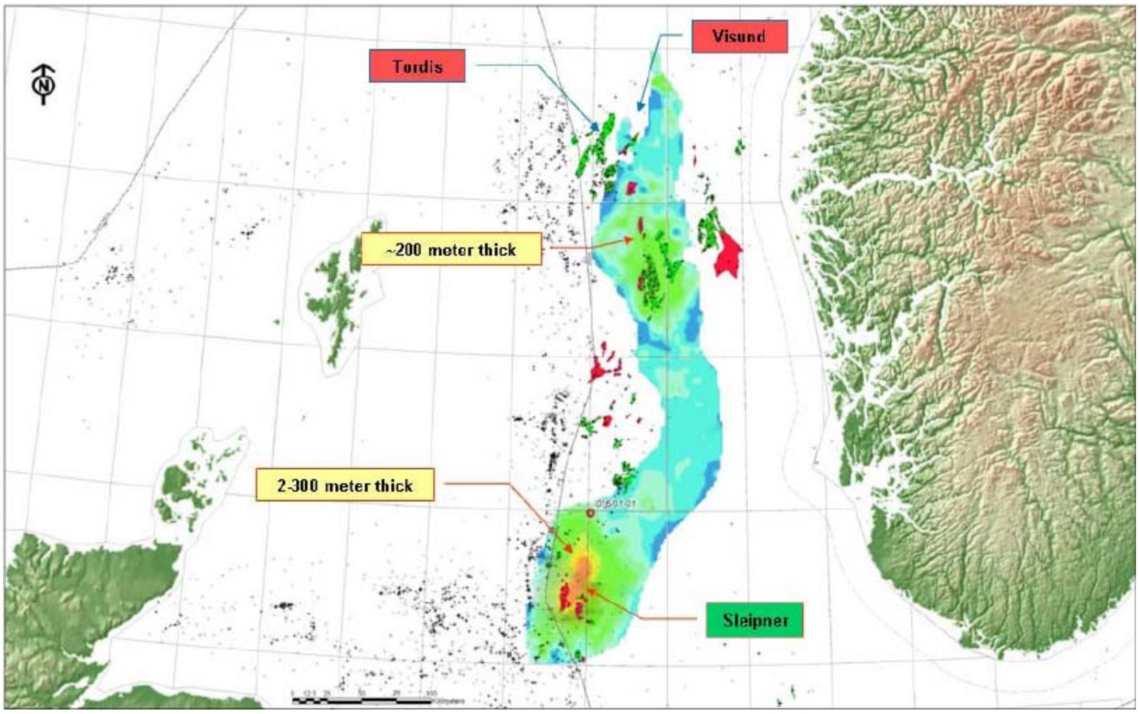


Figure 2-1. The Utsira formation (source: Statoil).

2.2 Injection rate to Utsira

The injection well at the Sleipner field gives an example of how much CO_2 can be injected with one well. The entire pore space of the Utsira Formation sandstone is not accessible from one injection well and in general it is not possible to utilize the entire pore volume. Injection of a fluid into a formation gives a pressure increase at the injection point and in the near well area. An increased injection rate leads to an increased injection pressure. The injection pressure is normally proportional to the injection rate and inverse proportional to the permeability. Water production makes place for the CO_2 and reduces pressure build up. In order to store several hundred millions tons of CO_2 annually, a large number of wells evenly distributed over the formation have to be used. Lindeberg et al [6] studied a total injection rate of 0.15

Gt/year, which was distributed on 70 wells in one scenario and 210 wells in another. The injection rates per well become 2.3 Mt/year and 0.75 Mt/year, respectively.

2.3 Assumptions made for the modelling work.

Based on costs and experiences with one injection well at Sleipner and the work of Lindeberg et.al [6] were a large number of injection wells are assessed, the following parameters are used as input to WP3 and WP4:

The investment cost of the existing injection well at Sleipner in Utsira was 120 MNOK (1996) ~22 M€ (2005) [7] and the annual injection rate at Sleipner is currently 1 Mt CO_2. A conservative model assumption for storage costs is 22 M€ per 1 Mt CO_2 injected per year. The lifetime of the existing injection well is assumed to be 25 years. The maximum storage capacity is assumed to be 42 Gt CO_2 with a maximum annual injection rate of 150 Mt CO_2.

3 WP 2 – Inventory and harmonization of data and assumptions for CCS modelling and scenario development

Deliverable:

- *Assessment and harmonization of CCS related economic and physical performance parameters of the MARKAL and TIMES models [9]*

In order to make a fair comparison of the results obtained in national and regional modeling work, it is necessary to assure that parameters, assumptions and data used are consistent. *This WP aimed to identify and standardized the data and parameters that will be used in the linear optimization models*. Table 3-1 shows an overview of key modeling parameters and whether they have been harmonized. The focus was on harmonize data/parameters that are not country specific. Each model's energy service demands (ESDs) are derived on a national basis. Similarly, national policy and fiscal circumstances are kept model specific. Note that all models have used a 5 % discount rate and no technology specific discount rate.

Table 3-1. Key parameters considered for harmonization

Parameter	**Harmonized**	**Country/model Specific**
Energy prices	✓	
Final electricity demand		✓
Trade of electricity[1]	✓	
Load curve of electricity		✓
Final heat demand		✓
Vintage structure of the electricity park[2]		✓
Policy scenarios	✓	✓
CO_2 sources considered		✓
CO_2 capture technologies and reference plants		
Type	✓	
Fixed capital cots	✓	
Variable capital costs	✓	
Efficiency	✓	
CO_2 Capture rate	✓	
Other CO_2 mitigation options		✓
Life time	✓	
Discount rate	✓	
Availability factor	✓	
CO_2 transport costs	✓	
CO_2 Storage[2]		✓

1: in order to keep consistency, the PAN EU model was run and results on the trade of electricity were taken as exogenous variables by the national models. The only exception is the UK Markal which took the PAN EU results and applied as a maximum bound. 2: though this data was not formally harmonized, the input taken in the national models was cross-checked with the data of the Pan EU model to be certain that they were in range.

A detailed comparison of the data used by the different models and reported in the literature can be found in the final report of WP2 (see ref. 9). In the rest of this section, an overview of the parameters that have been harmonized is presented. It is important to note that the German and Danish national models are derived by using a version of the PET-model. These models are therefore fully harmonised with the regional PET-model. For the other countries (United Kingdom, The Netherlands and Norway), additional efforts have been made to assure coherence between the models.

3.1 Energy Prices

The basic assumption is that energy prices follow the forecast to 2030 provided by the International Energy Agency (IEA) World Energy Outlook (WEO) 2008. Lower energy prices according to WEO 2007 are included as sensitivity. Fossil fuel prices are extrapolated to from 2030 to 2050. The coal, oil and natural gas price trends used for both cases are shown in Table 3-2.

Table 3-2. Fossil fuel price assumptions (€$_{2007}$/GJ)

		2000	**2005**	**2010**	**2015**	**2020**	**2025**	**2030**	**2040**	**2050**
WEO 2008 (high fossil fuel price scenario)-BASE CASE										
Oil	€/GJ	4.5	7.5	13.4	13.4	14.7	15.5	16.4	18.1	20.0
Natural gas	€/GJ	2.4	4.1	8.1	8.4	9.3	9.8	10.3	11.7	13.2
Coal	€/GJ	1.3	2.0	3.9	3.9	3.8	3.6	3.5	3.4	3.2
WEO 2007 (low fossil fuel price scenario)										
Oil	€/GJ	4.5	7.6	8.1	7.9	8.1	8.3	8.5	8.7	8.9
Natural gas	€/GJ	2.4	4.8	4.9	4.9	5.1	5.3	5.5	5.8	6.1
Coal	€/GJ	1.3	1.9	1.8	1.9	1.9	2.0	2.0	2.1	2.2

3.2 Electricity trade

International exchange of electricity is not determined (only) by national conditions but mostly by regional ones. When two or more electricity systems are interconnected, such as in the EU, energy will, in theory, be transmitted from the low price zone to the high price zone. To allow consistency in the model work, the PAN EU regional model (See chapter 5) has been used to generate exogenous inputs into the national models with regard to the import and export of electricity over time. Table 3-3 shows an overview of the data used for the three countries where the PAN EU model was not used directly..

Table 3-3: Harmonised net electricity imports, TWh

Country	Scenario	2005	2010	2015	2020	2025	2030	2040	2050
UK	C-20	9	6	26	32	32	32	29	26
UK	C-80	9	6	26	32	32	32	30	22
NL	C-20	18	18	-5	-6	-13	-13	-6	-3
NL	C-80	18	18	-5	-11	-30	-44	-5	-64
NO	C-20	-12	-11	-25	-42	-42	-42	-42	-42
NO	C-80	-12	-11	-25	-42	-42	-42	-42	-42

3.3 Policy scenarios

In this project two core policy scenarios have been assumed. This entails a 20% reduction (from 1990 levels) in 2020, which follows the EU mitigation target. This target is either maintained, or a linear reduction of 80% by 2050 is imposed (Table 3.4) based on the estimated CO_2 reduction required for developed countries to keep global temperature rise below 2 ºC.

Table 3-4. CO_2 reduction targets

Scenario	Abbreviation	Maximum limit of CO_2 emissions relative to 1990 (%)		
		2010	2020	2050
High CO_2 reduction	C-80	-	-20	-80
Limited CO_2 reduction	C-20	-	-20	-20

Sensitivity scenarios include the following:

- No CCS scenario. Only for the national models.
- High Utsira capacity, with a maximum injection rate at 500 Mt CO_2 per year and a total storage capacity at 100 Gt CO_2
- No storage onshore. For the Danish, German and Dutch models.

The two core scenarios are based on reduction in CO_2 at the EU27+[3] level, which implies that a cost-optimal solution will result in a distribution of mitigation costs across countries in the region. As with the electricity trade parameter, CO_2 reduction targets are applied to the national models by using outcomes of the PET model. The national upper limit for CO_2 emissions for the two scenarios is given in Table 3-5.

[3] EU27+ : EU countries + Switzerland, Iceland and Norway

Table 3-5. Upper limits for the CO_2 emissions for the core scenarios.

Country/ Year	2010	2015	2020	2025	2030	2040	2050
C-20: Upper limit CO_2 emissions							
United Kingdom	518	528	489	472	458	424	370
The Netherlands	164	180	182	184	185	179	196
Germany	752	727	682	616	597	571	528
Denmark	51	47	43	42	43	48	51
Norway	44	47	50	50	47	46	45
C-80: Upper limit CO_2 emissions							
United Kingdom	517	527	485	443	399	284	155
The Netherlands	165	179	171	165	142	114	60
Germany	752	709	639	534	424	235	87
Denmark	51	47	42	36	28	19	5
Norway	45	47	49	45	39	23	15

3.4 Cost and performance of fossil fuel based power plants and CO_2 capture technologies

Table 3.6 shows the basic cost and performance data used for the following types of power plants:

- Natural Gas Combined Cycle (NGCC)
- Pulverized Coal plant (PC)
- Integrated coal gasification combined cycle (IGCC)
- Oxfyfuel

In deliverable [9] a comparison of the ranges found in the literature and in the original models (before harmonization) can be found. Note that the values reported in the table for post-combustion capture (i.e., NGCC-CCS and PC-CCS) are for capture technologies in 2010 based on chemical absorption with MEA. As reference plant, it has been selected a similar state-of-the art plant, with same net output and same kind of fuel. Future solvents are not specified explicitly.

Table 3-6: Costs and efficiencies of electricity production with and without CCS [9]

		2010	2020	2030	2040
NGCC					
Capital	€/kW	676	608	608	608
Fixed O&M	€/kW-yr	19	17	16	16
Variable O&M	€/GJ	0.02	0.02	0.02	0.02
Efficiency	% LHV	58	60	63	64
PC					
Capital	€/kW	1598	1487	1448	1352
Fixed O&M	€/kW-yr	77	72	66	61
Variable O&M	€/GJ	0.36	0.35	0.33	0.33
Efficiency	% LHV	46	50	52	52
IGCC					
Capital	€/kW	2005	1798	1691	1521
Fixed O&M	€/kW-yr	71	66	60	53
Variable O&M	€/GJ	0.29	0.25	0.20	0.19
Efficiency	% LHV	46	50	54	56
NGCC CCS					
Capital	€/kW	1146	1014	938	838
Fixed O&M	€/kW-yr	71	66	60	63
Variable O&M	€/GJ	1.29	1.25	1.08	0.95
Efficiency	% LHV	49	52	56	58
Capture rate	%				
PC CCS					
Capital	€/kW	2546	2328	2110	1892
Fixed O&M	€/kW-yr	95	81	75	68
Variable O&M	€/GJ	1.29	1.25	1.08	0.95
Efficiency	% LHV	36	42.5	45	46
Capture rate	%				
IGCC CCS					
Capital	€/kW	2769	2374	2130	1956
Fixed O&M	€/kW-yr	92	76	70	63
Variable O&M	€/GJ	0.51	0.41	0.27	0.27
Efficiency	% LHV	38	44	48	50
Capture rate	%				
Oxyfuel CCS					
Capital	€/kW	1841	1761	1633	1484
Fixed O&M	€/kW-yr	93	93	93	93
Variable O&M	€/GJ	1.68	1.68	1.68	1.68
Efficiency	% LHV	48.1	50.1	51.6	52.1
Capture rate	%	94	94	94	94

3.5 CO_2 transport

CO_2 transport costs are harmonised between the models. The cost of CO_2 transport varies with capacities, distances and terrain. There are several costs equations available in the literature. Investment costs have been estimated using equation 1 and 2.

$$I = Ft_{Land\,use} * C * D * L \qquad \text{Eq. 1}$$

$$D = \left(\frac{8 * \lambda * M^2}{\Pi^2 * \rho * \frac{\Delta P}{L}} \right)^{1/5} \qquad \text{Eq. 2}$$

Where, I = investment cost (€), $Ft_{Land\ use}$ = terrain factors for different land use types; C = Constant factor (1600 €/m^2) ; D = diameter pipeline (m); L = length pipeline (m); λ = friction factor (0.015); M = mass flow of CO_2 (kg/s); ρ = CO_2 density (800 kg/M^3)
ΔP = pressure drop ($3*10^6$ Pa).

For pipelines longer than 150 to 200 km, a booster station is required to overcome the pressure drop of CO_2 transport. In this study, a booster station is installed for transport distances >150 km to reduce the pressure drop ΔP to 3 MPa (30 bar). The investment costs of the booster station are assumed to be 11 M€, O&M costs are 5% of investment cost and energy cost are 0.11 €/tonne CO_2. Finally, it is important to note that the terrain factor in equation 1 can vary from country to country. For instance, for the Netherlands offshore transport is cheaper than onshore, mainly as a result of limited land available. Figure 3-1 illustrates CO_2 transport costs by capacity and distance for alternate terrain factors.

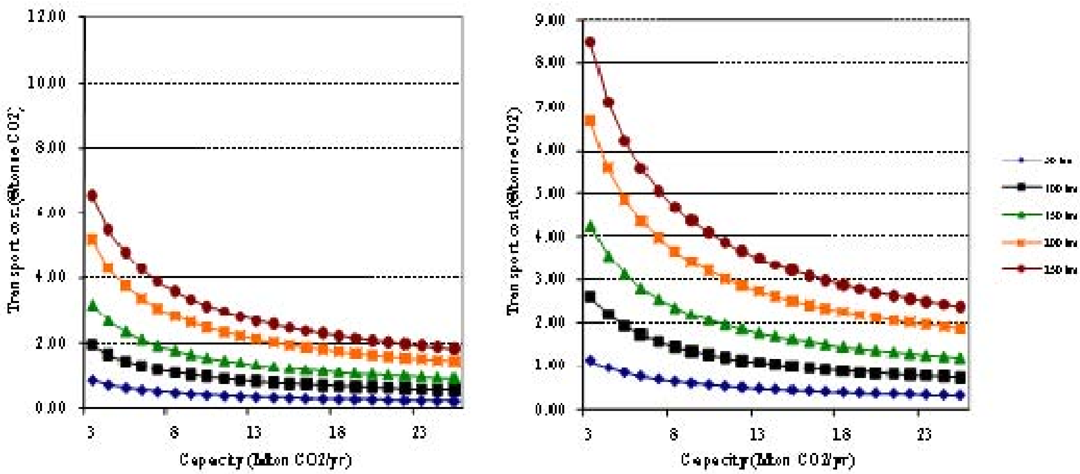


Figure 3-1: CO_2 transportation cost for different capacities and distances for Ft = 0.9 (left) and Ft = 1.2 (right) [9].

3.6 Harmonisation with the regional model (Pan European Times)

To harmonize the country specific CO_2 mitigation targets and electricity trade, scenario runs for the C-20 and C-80 scenarios were made by the PanEU model. The country specific results of these projections were integrated in the national models. Figure 3-2 depicts the projected development of electricity trade and CO_2 emissions to 2050 as projected by the PanEU model. Note that a) CO_2 emission reductions differ per country as the model optimizes the reduction of CO_2 for the EU-27 as a whole and b) the PanEU model has been modified and extended for trans-boundary CO_2 transport during the project. The final projections of the PanEU model are therefore different from the projections used in the national models.

Until 2020, there is little difference between the C-20 and C-80 scenarios as the reduction targets are similar. From 2020 onwards, electricity exports in Germany and the Netherlands increase significantly due to the higher electricity demand for decarbonisation of, amongst others, the transport sector in the C-80 scenario.

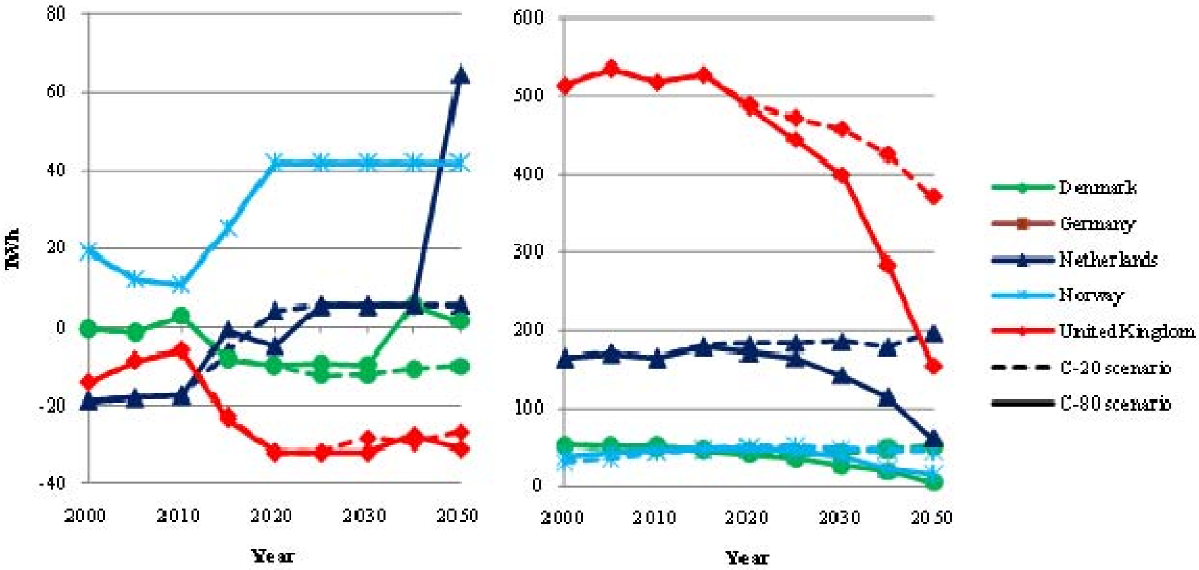


Figure 3-2 Electricity trade (negative means import) (left) and CO_2 emissions (right) as projected by the PET-model for the countries in the North Sea region.

4 WP3 – National modelling of CCS pathways

Deliverables:
- *Country report – United Kingdom [12]*
- *Country report – The Netherlands [13]*
- *Country report – Germany [14]*
- *Country report – Denmark [15]*
- *Country report – Norway [16]*

The development of CCS in the North Sea region will depend on CO_2 reduction targets, mitigation technologies, costs, CO_2 capture potentials and the capacity and availability of geological reservoirs in each of the countries as well as the storage capacity of the Utsira Formation and the development of the infrastructure for CO_2 transport. *This WP aimed to gain insights into cost-effective pathways for CCS in the countries of the North Sea region for the time period 2010-2050*.

The national CCS pathways are described in detail in the deliverables [12, 13, 14, 15 and 16]. The starting point of the analysis are the national MARKAL and TIMES models developed by each of the partners involved. The models are used with the harmonised modelling assumptions and scenarios (WP1 and WP2) to analyse pathways for CCS for all five countries. The country reports give an overview of the potential of CCS with CO_2 storage in competition with other low emission technologies. A brief outline of the models is shown in section 4.1. Section 4.2 and 4.3 show main results and highlights of the modelling work for each country. Finally, the model generators used by the national models are able to handle mixed integer programming, but little common experience is available. This feature has been tested at an early stage using a simple version. Results are summarized in Section 4.4.

4.1 Linear Optimization Models: MARKAL AND TIMES

MARKAL and TIMES are integrated energy systems modeling platform that can be tailored to analyze energy, economic and environmental issues at the global, national and municipal level over several decades. MARKAL is the acronym for MARKet Allocation while TIMES — which is the next generation version of MARKAL — stands for The Integrated MARKAL/EFOM System.

MARKAL and TIMES generate economic equilibrium models formulated as linear (or non linear) mathematical programming problems. MARKAL computes energy balances at all levels of an energy system: primary resources, secondary fuels, final energy, and energy services. The model aims to supply energy services at minimum global cost by simultaneously making equipment investment and operating decisions and primary energy supply decisions, by region [17]. They calculate the technological configuration of an energy system by minimising the net present value of all energy system costs. Linear programming bases its decisions on 'perfect foresight', which means that the model can 'look ahead' to the end of the model period to find the least-cost energy configuration over the whole period. The MARKAL energy economy consists of [17]:

- Demands, that represent the energy services (e.g., space heating, vehicle-kilometers travelled, tonnes of steel production) that must be satisfied by the system;
- Energy sources (mining or imports), that represent methods of acquiring various energy carriers;
- Sinks, that represent exports;
- Technologies (also called processes), that either transform an energy carrier to another form or into a useful energy service; and
- Commodities consisting of energy carriers, energy services, materials, and emissions that are either produced or consumed by the energy sources, sinks, technologies and demands.

In this project, national MARKAL models have been used to analyse the energy system development of Norway, the Netherlands and the United Kingdom.

The TIMES models generator shares the basic modelling paradigm with MARKAL The main difference is that TIMES is more flexible in the management of time periods and technology data. The Pan European TIMES (PET) model is the largest model development using the model generator. PET has been developed within the FP 6 European research project NEEDS and contains all countries of the EU-27 plus Switzerland, Norway, and Iceland. The model covers, at the country level, all sectors connected to energy supply and demand (i.e., the supply of resources, the public and industrial generation of electricity and heat, and the industry, commercial, households and transportation sectors). In this project the PET-model has been used to assess the development of CCS in the North Sea Region and, at the national level, for the developments in Germany and Denmark.

4.2 Key results of the national models

Results from the national models highlight large differences on the role that CCS and Utsira can play in the national portfolios of CO_2 mitigation. A brief overview of the results by country for 2050 for the C-20 and C-80 scenario follows. Unless otherwise specified, the results presented are low mitigation targets (C-20 Scenario) and energy prices from WEO 2008. The results presented here focus on the development of the power generation sector. For results on the other sectors or detail data on the power sector we refer to the individual national reports.

4.2.1 Core scenario. Low mitigation targets (C-20)

United Kingdom: Electricity generation in 2050 is estimated at 1585 PJ, 21% of which is generated by renewables. Coal (without CCS) power generation has a share of 58 %. With WEO 2008 prices, CCS technologies are not selected by the model. CO_2 emissions of the power sector are estimated at 196 Mt. When the C-20 scenario is combined with WEO 2007 energy prices, CCS technologies are selected as part of the portfolio if mitigation measures (19 % of the generation capacity). In this case, about 61 Mt CO_2/year is stored in 2050. Regarding the sensitivity scenarios, for the no-CCS scenario, this makes no difference to C-20 as this scenario did not choose CCS in the first place. Only modest changes are seen in the C-20 scenario with WEO 2007 prices as this scenario's modest decarbonisation vectors remain increased efficiency, new technologies and demand changes.

Netherlands: Total electricity generation reaches 592 PJ in 2050. The Netherlands switches from being a net importing country in 2020 (19 PJ) to a net exporting country of electricity (21 PJ) in 2050. CO_2 emissions in 2050 from the power and industrial sector are about 193 Mt. CCS technologies for electricity generation are limited to IGCC-CCS plants. The capacity of coal power plants with CCS is projected to be 8 GW in 2050 producing about 36 % of the electricity (coal plants without CCS have a share of 22%). Wind appears with a share of about 20% whereas other mitigation options (mainly PV) becomes significant from 2050 (9%). The amount of CO_2 stored in 2050 is estimated at 43 Mt per year. If lower fossil fuel prices are assumed (WEO 2007 projections), NGCC plants will become more cost effective than coal fired plants with CCS due to lower variable costs from fuel. In this case the share of gas fired power generation increases significantly (235% higher compared to the C-20 scenario) whereas coal based CCS power generation is 39% lower in 2050. If no CCS technologies are available, the target is reached by an increase in wind power and gas. The share of coal (without CCS) remains constant.

Germany: In 2050 primary energy consumption reaches 10.2 EJ. The consumption of fossil fuels reduces from 7.0 EJ in 2000 to 3.5 EJ in 2050. The electricity supply increases to a level of 2.2 EJ, with 50% being produced from renewable energy sources of which 60% are generated from wind energy, 22% from biomass, 10% from hydro and 8% from solar energy. The share of electricity from fossil fuels of total electricity supply declines over time, reaching a level of 0.9EJ in 2050 (1.2 EJ in 2000). Coal technologies profit from the increase of fuel prices, whereas CCS technologies only play a subordinated role.

Denmark: In 2050 electricity demand will increase by 18 % (compared to 2000) reaching a level of 137 PJ. The results show a significant increase in the use of biomass (126 PJ), mainly for electricity and heat, which is broadly in line with national targets. The very dominant feature is the variation of wind power and electricity export. Coal (without CCS) generates 43 PJ electricity in 2050 (30 PJ if 2007 WEO prices are applied). In this scenario CCS technologies do not play a role. The total amount of CO_2 emissions in the electricity and heat sector are estimated at 12 Mt in 2050 (9 Mt under 2007 WEO prices).

Norway: Primary energy demand in 2050 is estimated at 1033 PJ. Electricity generation is dominated by renewables (mainly hydropower). The model assumes exogenous CO_2 capture to the existing NGCC power plant at Kårstø from 2015. In this scenario this investment is the only source for CO_2 captured. CO_2 is stored at Utsira, which is assumed to be the most mature Norwegian storage formation.

4.2.2 Core scenario. Stringent mitigation targets (C-80)

The results for this scenario and energy prices as in WEO 2008 (unless otherwise is specified) show an increasing renewable electricity production:

United Kingdom: In this scenario, about 2372 PJ of electricity is generated in 2050. Electricity is mainly produced by nuclear (45%) renewables (39%) and coal with CCS (12%). About 53 Mt CO_2 are captured via CCS in 2050. If lower prices are assumed (WEO 2007), the share of CCS in the energy system increases to 51% of the electricity generation. The amount of CO_2 stored in this case is about 213 Mt. In both cases, a major trade-off is between coal with CCS, nuclear, and large scale wind generation. The marginal cost effectiveness of these electricity technologies within the UK electricity system is close and the model can substitute to any of them. However without CCS, coal electricity is not a viable generation technology in a decarbonised energy system. The key role of CCS in the C-80 scenario is highlighted when a sensitivity scenario with no CCS is run. In this case, the loss of a major low carbon vector such as CCS has major impacts. The use of coal as a fuel effectively ends, with a reduction from 2169 PJ to a mere 4 PJ. In the energy sector, the loss of CCS is compensated via expanded nuclear and offshore wind capacity which requires (expensive) back-up capacity. This increased cost reduces the output of electricity and decarbonisation efforts switch to demand reductions and increased (to a lesser extent) bio-fuels in transport.

Netherlands: Electricity generation is projected to increase to 1031 PJ in 2050, with about 232 PJ being exported. CO_2 emissions in 2050 from the power and industrial sector are about 60 Mt. The share of electricity generation from power plants with CCS is 80% in 2050 (70% coal/biomass and 10% gas). The total capacity of power generation with CCS is estimated at 34 GW. Under low fuel prices (WEO 2007), the total amount of CCS is 7% larger compared to the C-80 scenario in 2050 due to additional capacities of NGCC-CCS plants. If no CCS technologies are assumed to be available, the C-80 CO_2 reduction target will not be reached with the available mitigation options in the MARKAL-NL-UU model in combination with the large demand for electricity generation as projected with the PET-model for the Netherlands. In this scenario, wind becomes the most important mitigation option with 28 GWe installed capacity in 2050 compared to 12 GWe in the C-20 scenario. With lower fossil energy prices (WEO 2007), the share of wind would be lower (15 GWe) whereas NGCC plants would replace all coal fired power plants.

Germany: In 2050, the electricity supply increases to about 2808 PJ. The electricity production from renewables energies increases to 1490 PJ. Electricity generation from fossil fuels develops to 1224 PJ in 2050 while electricity from renewables is estimated in the order of 1500 PJ, with the share of electricity generated in wind turbines amounting to about one third of the total electricity supply in 2050. Electricity from CCS power plants contributes to 40-50% to total electricity supply in 2050. Depending on the fossil fuel prices, coal CCS power plants have a share of CCS based electricity generation of 85%. In the case of this scenario under WEO 2007 prices, electricity generation changes from coal based CCS technologies to natural gas technologies. The amount of CO_2 captured amounts to 237 Mt. At lower energy prices (WEO 2007) 159 Mt CO_2 are captured. If not CCS technologies are available in this scenario, total electricity supplies decreased by 600 PJ. The electricity generation structure in this case is characterised by a very high penetration of renewable energy, and a substitutions of coal with natural gas.

Denmark: The very dominant feature is the variation of wind power and electricity export. As the offshore potential for wind power from the North Sea and the Baltic Sea is huge, and practically unlimited compared to any forecast of electricity demand in Denmark (European Environment Agency, 2009 [19]), model results will be determined of model assumptions outside Denmark. The very large wind capacity may be considered as wind capacity located in the Danish part of the North Sea, but serving the German market. Coal appears with a minor role, in fact, coal without CCS does not appear at all in this scenario while coal with CCS only account for 1 PJ of electricity produced (and it does not appear if WEO 2007 prices are applied). Gas technologies with CCS have in contrast a modest share (28 PJ in the base case and 31 PJ in the 2007 WEO). The amount of CO_2 stored in this scenario amounts to 9.4 Mt (10.2 if WEO 2007 energy prices are used). Most of the CO_2 is stored in national aquifers. However, the most interesting result is that a small amount (about 2Mt/yr) is exported to be stored in the Utsira formation, which indicates that transport to Utsira may be an interesting option for Denmark, if the international infrastructure becomes available. The key feature of thermal electricity generation is combined heat and power for district heating, which can be used for increasing the efficiency of carbon capture as well as a more flexible response to wind power. This feature will have a very high priority in the national version of the PET model, which is under development. Unfortunately, it has not been implemented and tested in the version of the model that was used for this project.

Norway: Primary energy demand in this scenario is estimated at 1040 PJ in 2050. In addition to the CO_2 capture unit to the existing NGCC power plant (see C-20 scenario), 2.9 Mt CO_2 are captured from the industrial sector in 2050 (0.82 Mt from cement production and 2.1 Mt from the refineries).

4.3 CO_2 Storage and the potential role of Utsira

In this section we focus on the results shown by the national models regarding the transport and storage of CO_2. Of particular interest is the share of the CO_2 that is stored at the Utsira location. Since in the C-80 scenario CCS (and Utsira) appear to play a significant role the focus is on this scenario. For details on the C-20 scenario we refer to the national reports.

4.3.1 United Kingdom

Figure 4-1 shows the distribution of the storage of CO_2 for different scenarios. In the base case (C-80 2008 WEO), about 53 Mt of CO_2 are stored in 2050. All of the CO_2 is stored in national fields (offshore aquifers). Lowering fuel prices (C-80-2007 WEO) results in a significant increase in the amount of CO_2 stored (225 Mt). In this case, Utsira appears as a cost-effective option from 2030 onwards (20 Mt). By 2050 about 54 Mt are stored in this reservoir. The general ordering of costs of CO_2 transport and storage is: Enhanced Oil Recovery (EOR), the lower portion of the supply curve for UK aquifers, the lower portion of the supply curve for the UK oil and gas reservoirs, Utsira, higher costs UK aquifers and higher costs oil/gas fields. The share of CO_2 stored at Utsira increases (109Mt in 2050) when a higher capacity for Utsira is considered (36 Gt compared to the base case which has an exogenous limit of 15Gt, corrsponding to 35% of the potential storage capacity in Utsira). The increase in the share of Utsira in this scenario (C-80-2007-HU; see Fig 4-1) is a consequence of removing the need to use higher costs reservoirs in the UK (gas/oil fields and some aquifers).

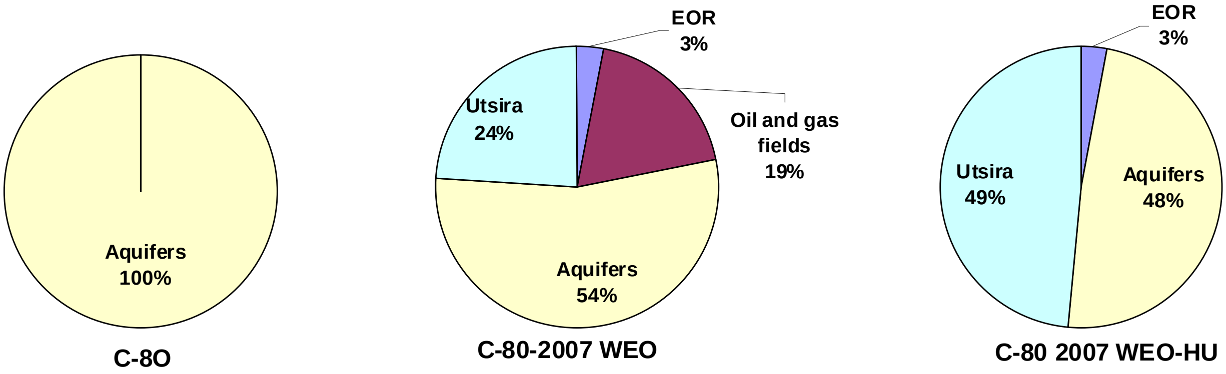


Figure 4-1. Distribution of CO_2 storage in the UK model according to different scenarios for 2050.

4.3.2 The Netherlands

Figure 4-2 shows the distribution of the storage of CO_2 for different scenarios. In the base case (C-80 2008 WEO), about 145 Mt of CO_2 are stored in 2050. In this case, CO_2 is initially stored in onshore gas fields, increasing from 7 Mt in 2020 to 48 Mt in 2030. Due to the rapid increase in deployment of CCS, offshore storage of CO_2 both in the Utsira formation and in the Netherlands starts already in 2030. The use of the Utsira formation however has a marginal role in the period 2030-2040 (2.4 Mt CO_2/yr corresponding to about 3% of the total amount being stored). In the period 2040-2050, the results show a rapid increase of Utsira reaching 105 Mt in 2050 (72% of CO_2 stored). The specific costs for transport and storage of CO_2 are about 7.4 Euro/tonne in 2050 which are dominated by the transport and storage costs in the Utsira formation. Lowering fuel prices (WEO 2007) results in a slightly larger share for Utsira (78%) as well as an earlier deployment (5 years). The impact of excluding Utsira while trying to achieve stringent emissions targets results in a decrease of 46% in the share of CCS (and therefore in lower amounts of CO_2 that need to be stored) and in earlier use of offshore gas fields.

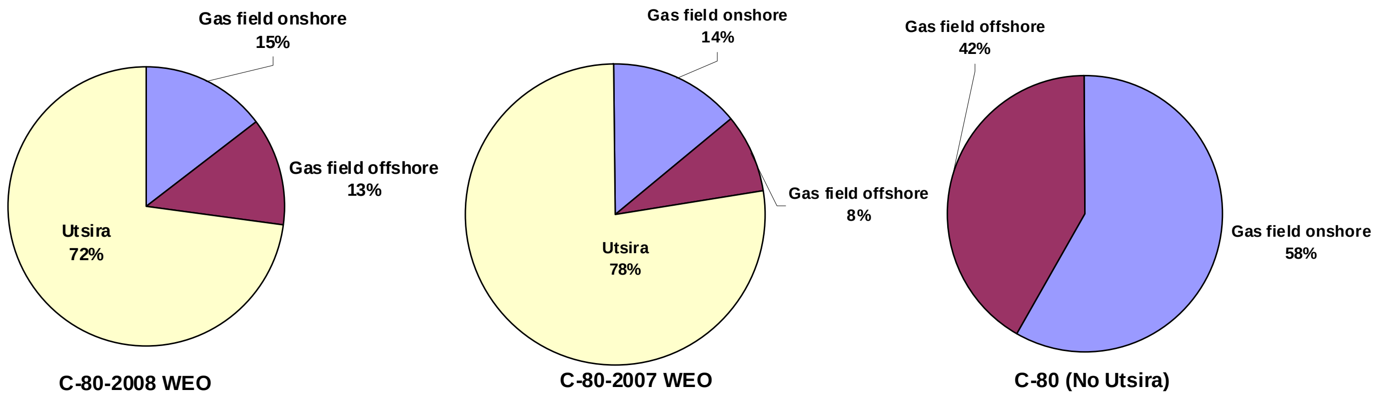


Figure 4-2. Distribution of CO_2 storage in the Dutch model according to different scenarios for 2050.

4.3.3 Germany

In 2050, domestic saline aquifers and hydrocarbon fields are primary used (Figure 4-2). The storage quantities for aquifers increase to a maximum of 243 Mt in 2050 in the base case scenario. Additionally 25 Mt of CO_2 are stored in hydrocarbon fields in 2050. Over the whole model horizon a quantity of 5700 Mt of CO_2 is stored in aquifers and 300 Mt. in hydrocarbon fields. Only minor quantities of CO_2 are transported and stored abroad (to fields in the Netherlands and Denmark). In this scenario as well as in the scenario with lower fuel prices the direct transfer of CO_2 to Utsira via a pipeline with a hub at the German North Sea coast does not appear to be as cost effective. If the Utsira formation can be used at lower costs (-2 €/t CO_2 compared to the standard costs) an increased use of Utsira for carbon storage beginning in 2040 can be observed. In 2040 and 2050 about 40 Mt per year are transported to Utsira. Moreover, the exports to the Netherland increased leading to an increased use of Utsira via the Dutch pipeline system.

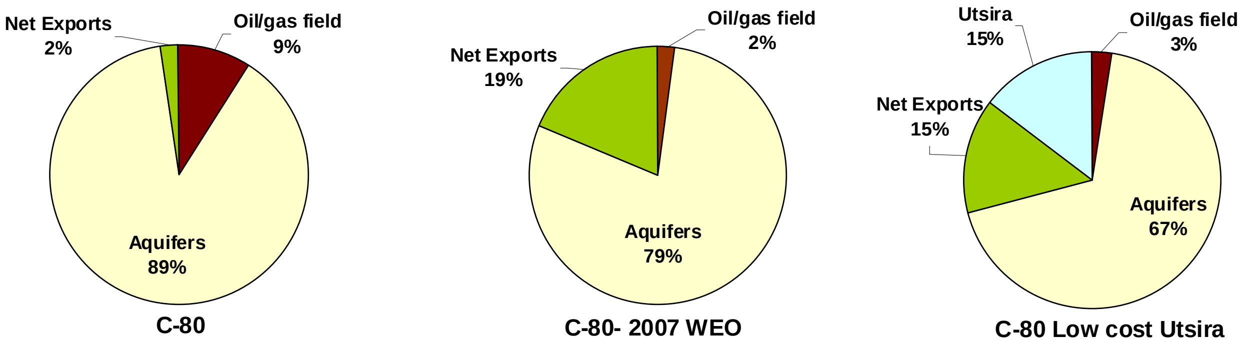
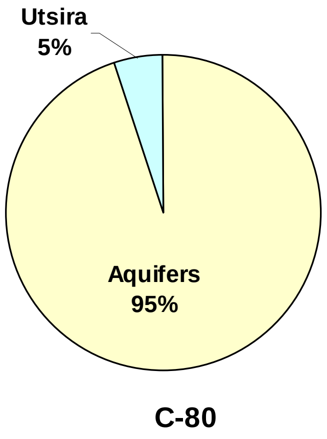
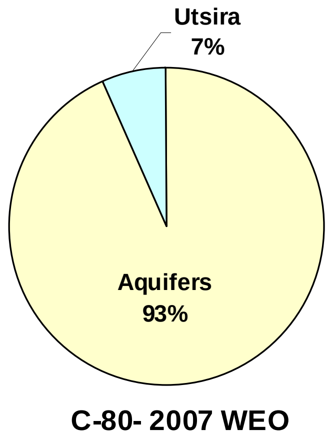


Figure 4-2. Distribution of CO_2 storage in the PanEU model for Germany according to different scenarios for 2050.

4.3.4 Denmark

The amount of CO_2 stored in the base case corresponds to 29.4 Mt (30.2 if lower energy prices are taken into account). Remarkably, only 32% of this amounts are originated in the Danish electricity sector (9.4 Mt in the base case). The rest of the CO_2 stored is imported from Germany. Utsira plays in both cases just a minor role.





4.3.5 Norway

The amount of CO_2 stored in Norway (without imports of CO_2 flows from other countries) is 2.9 Mt for both the base case and the case in which lower fuel prices are applied. All CO_2 is stored at the Utsira location. It is important to note however that this location was the only one included in the national model.

4.3.6 Some final remarks

In the C-80 scenario all countries have CO_2 capture. The Netherlands, Norway and Denmark also have CO_2 storage in the Utsira formation. Germany is the country with largest amount of CO_2 captured with 268 Mt/y in 2050 followed by the Netherlands and The United Kingdom. The Netherlands is the country with the largest share of CO_2 storage in the Utsira formation with 105.2 Mt/y.

With lower energy prices (C-80-07), more CO_2 is captured in the United Kingdom, in the Netherlands and Denmark and less CO_2 is captured in Germany. In the United Kingdom, nuclear power is decreased to benefit of increased coal CCS and in the Netherlands and in Germany, the coal CCS power is decreased and gas CCS increases. Lower energy prices increase the total amount of CO_2 injected to the Utsira formation.

4.4 Test of Mixed Integer Linear Programming (MILP)

The benefits and the properties of mixed integer linear programming (MILP) have been discussed in [12]. MILP offers a tool to specify a discrete investment in a particular technology or infrastructure. This approach is valid if investments are indeed sufficiently ‘lumpy’ in nature as to require explicit characterisation as such within the optimisation.

The implementation of integer programming is computationally intensive, and hence can only apply to limited number of model variables. A critical drawback is that marginal values (e.g., CO_2 emission prices) have a different meaning; now calculated assuming integer investments are already made.

In a series of exploratory integer runs on nuclear plant (chosen over CCS due to the complexity of CCS vintages and the CCS chain), a step size of investments of 5 GW per 5 year period (1GW/annum) is chosen with the current UK system at 84 GW.

Table 4-1: Integer runs and investments in nuclear and CCS plant [12]

Bound	Blocks	Period		2020	2025	2030	2035	2040	2045	2050	Cumulative
None			Nuclear	-	3.4	11.0	6.3	15.3	5.0	-	40.9
			CCS	-	4.7	3.2	-	-	5.0	-	12.9
1GW/ annum	Build constraint		Nuclear	-	5.0	5.0	5.0	5.0	5.0	5.0	30.0
			CCS	-	4.1	10.4	-	3.4	0.9	0.1	18.8
1GW/ annum	multiple	any	Nuclear	-	5.0	10.0	5.0	15.0	5.0	-	40.0
			CCS	-	4.0	4.0	0.2	-	5.5	-	13.6
1GW/ annum	one	any	Nuclear	-	5.0	5.0	5.0	5.0	5.0	5.0	30.0
			CCS	-	4.1	10.4	-	3.4	0.9	0.1	18.8
1GW /annum	one	one	Nuclear	-	5.0	-	-	-	-	-	5.0
			CCS	-	3.1	15.5	4.8	6.3	-	8.6	38.2
4GW/ annum	one	one	Nuclear	-	20.0	-	-	-	-	-	20.0
			CCS	-	-	5.2	5.1	7.1	2.4	4.3	24.0
8GW/ annum	one	one	Nuclear	-	-	-	-	40.0	-	-	40.0
			CCS	-	7.1	13.9	-	-	-	-	21.0

A range of runs, all with CO_2 emission reduction of 80% are conducted and investments in nuclear and CCS are compared in table 4.1. These results illustrates that the integer investment characterisation does hold. For example, if the model is only allowed to build multiple blocks of 1GW/annum (Row 3), this mirrors the unconstrained investment (Row 1). If the model is only allowed to build single blocks of 1GW/annum (Row 4) this mirrors the build constraint investment (Row 2). More restrictive integer bonds (Rows 5-7) show a logical placement of discrete blocks of capacity according to the size of the integer investment and the timing of the electric system to absorb such investments (in cost optimal terms). However for power plant investments, these more radical integer investments appear impractical in terms of inclusion in the electricity network. Given the downsides in computational time and in the reinterpretation of marginal values, for power-plant investments at least it is recommended that build constraints are used instead of integer investments. In terms of the transport infrastructure, mixed integer functions may improve the quality of the results. In the national report of the Netherlands for instance, Utsira appears as a cost-effective option under the C-80 scenario in 2040 with an amount of 2.4 Mt/yr. This amount increases to 105 Mt/year by 2050. It is however highly unlikely that a small pipeline will be built before 2040 just to have to build large pipelines 5 year later. Mix integer functions would most likely result, for the Dutch case, on a delay of 5 years in the use of Utsira and in therefore a more realistic result.

5 WP4 – Analysis for the North Sea region

Deliverable:
- *Regional analysis at North Sea level [18]*

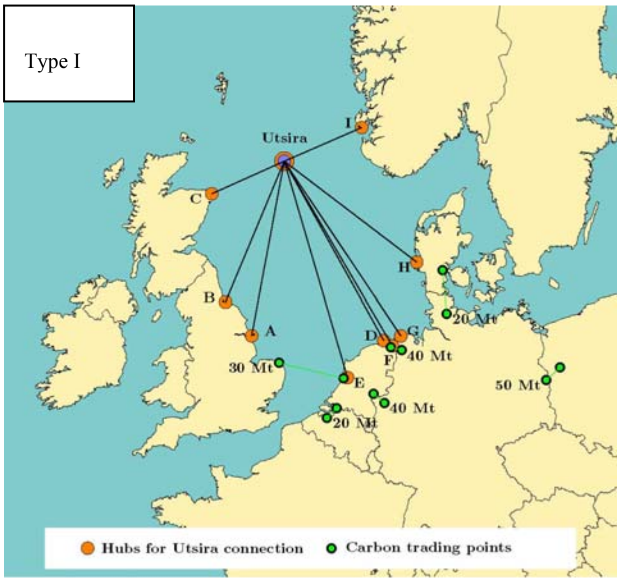
This WP aims to analyse CCS for the countries around the North Sea (Norway, Denmark, Germany, the Netherlands and the United Kingdom) for the time period 2015-2050, with a focus on the national and regional implications of offshore CO_2 transport to the Utsira formation.

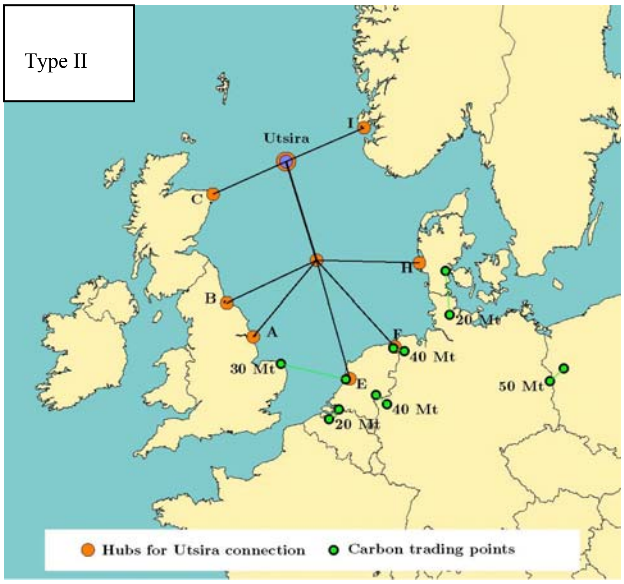
The analysis at this level is done with the pan-European energy system model TIMES, which has been developed in the European FP 6 research project NEEDS and enlarged and updated by IER, University of Stuttgart. Considering the data and results elaborated in WP 3, this work package additionally takes interregional CO_2 infrastructure options into account and shows the opportunities and limitations of trans-boundary CO_2 transport within the region as well as common infrastructure usage of the Utsira connection. Several sources have been used to estimate national potential for storage of CO_2 in European countries, most notably results from the GeoCapacity-project and the GESTCO-project [20] and [21].

5.1 Infrastructure options

For the connection of the Utsira formation different infrastructure designs could be applied for the North Sea region. Three possible layout of a pipeline network are analysed by the PanEU model (based on analysis done in WP5).

The first layout (network I) represents the construction and operation of pipelines to Utsira individually by each country. This type of pipeline network need high capital investment under the condition that transport quantities are comparably low and pipelines are not operated at full load. The second pipeline layout (network II) represents the case, that countries (e.g. the UK) build up one own trunk pipeline to Utsira, whereas countries which do not reach the significant quantities for an own trunk pipeline collaborate with other countries, like the connection of Denmark to the trunk pipeline from the Netherlands to Utsira. The third infrastructure layout (network III) is characterised by a trunk pipeline from Utsira to the Southern border of the Norwegian exclusive economic zone. From this collecting hub countries are connected via individually constructed sub pipelines. The transport costs are calculated for this pipelines under two scenarios: high capacity and low capacity. Table 5-1 shows the values that have been used in the model by type of network.





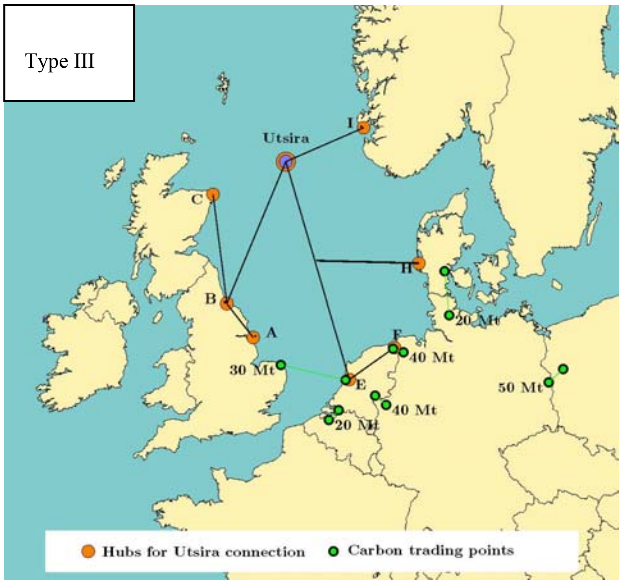


Figure 5-1: Types of network infrastructures to Utsira analysed in this report [18]

Table 5-1 Transport cost data for different types of network

	Network type I		Network type II		Network type II	
Hub (see fig 5-1)	High capacity (Euro/t)	Low Capacity (Euro/t)	High capacity (Euro/t)	Low Capacity (Euro/t)	High capacity (Euro/t)	Low Capacity (Euro/t)
A	2.5	2.9	2.4	2.9	2.6	2.8
B	2.2	2.5	1.9	2.3	2.5	2.8
C	1.2	1.4	3.7	4.3	1.2	1.4
D	2.8	3.8				
E	3.3	4.3	3.3	4.3	2.9	3.5
F	3.0	4.0	4.2	5.3	3.2	3.2
G	2.9	3.9				
H	4.2	5.3	4.3	5.0	3.4	3.9
I	2.2	2.2	2.2	2.2	2.2	2.2

5.2 Results

Under tight climate targets for Europe (C-80), CCS technologies are a cost efficient GHG reduction measure in future and widely applied in the European energy system. Under this condition the use of costly storages and long transport distances is necessary and the Utsira storage formation gains competitive and represents a valuable CO_2 storage option. The results presented here focus therefore on this scenario.

5.2.1 Results for network I

The total electricity generation in the countries of the North Sea region (Germany, Denmark, the Netherlands, Norway and the UK) reaches almost 2000 TWh in 2050 (Figure 5-2). This development is characterised by the switch of the demand sectors from fossil fuel based technologies to electricity applications under a strong climate policy. The electricity generation changes towards a low carbon intensive structure with a high share of renewable technologies (56 % of total generation in 2050) and a widespread use of CCS technologies (38 % in 2050). Especially coal and lignite can be further used in power plants with CCS in large countries like Germany and the UK which implies a high remaining share of solid fossil fuels in the electricity generation sector.

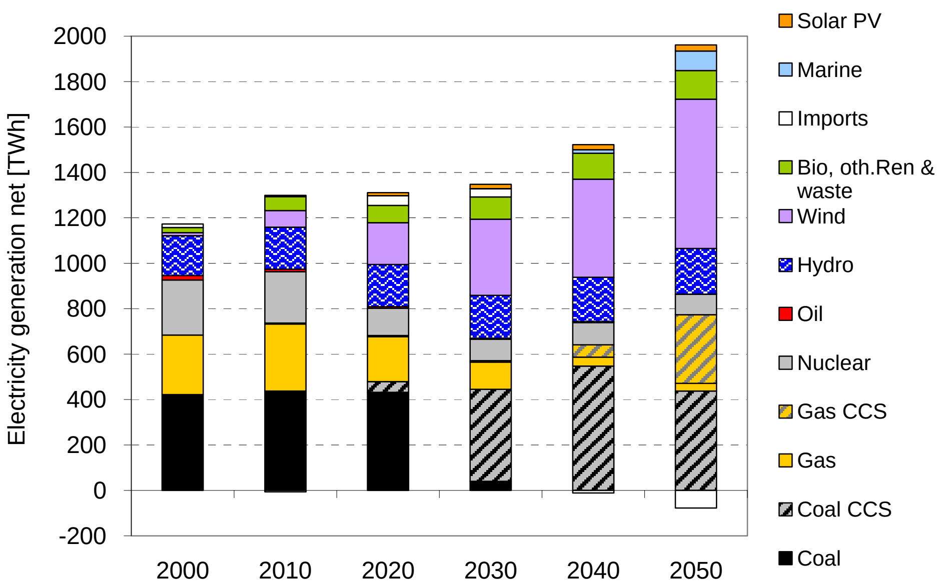


Figure 5-2: Electricity generation in the neighbouring countries of the North Sea [18]

The CO_2 quantities captured increase from 50 Mt in 2020 to 570 Mt in 2050 (Figure 5-3). CO_2 is primary captured from CCS technologies of public electricity and heat generation (90 % in 2050).

Large CO_2 quantities are captured in Germany, reaching a level of 300 Mt in 2050. Capture in the UK amounts to 170 Mt in the same year while 100 Mt are capture in the Netherlands. Denmark reaches a maximum annual level of 15 Mt and Norway 10 Mt (Figure 5-3).

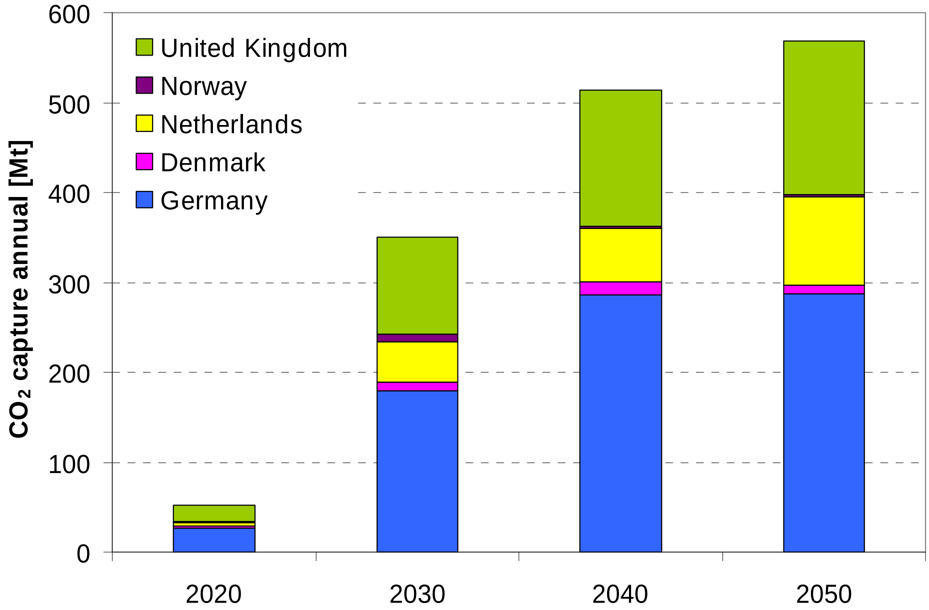


Figure 5-3 CO_2 capture in the neighbouring countries of the North Sea by country [18]

CO_2 storage and the role of Utsira

CO_2 storage quantities exceed the quantities of carbon captured due to additional CO_2 amounts coming from Belgium and Poland to be stored in the Netherlands and Germany. In total almost 640 Mt CO_2 are stored in 2050 (Figure 5-4). The CO_2 is primary stored in saline aquifers with 40 Mt in 2020 increasing drastically to 240 Mt in 2030, and 400 Mt in 2050. Storage in onshore aquifers had a share of 45 % of total aquifer storage in 2050. CO_2 storage in hydrocarbon fields reaches a level of 100 Mt to 140 Mt for the period 2030 to 2050. The reason behind is cross-border carbon exchanges from Germany to the Netherlands. For installations in Germany located nearby the Dutch border (e.g. western Rhine area) CO_2 transport abroad and storage in Dutch hydrocarbon fields represents an economic valuable option compared to domestic storage. From the perspective of the transport to some Dutch hydrocarbon fields such an option has the advantage, that a large pipeline with high mass flow from Germany leads to lower transport costs than the connection of single emission sources with lower mass flow per pipeline connection in the Netherlands.

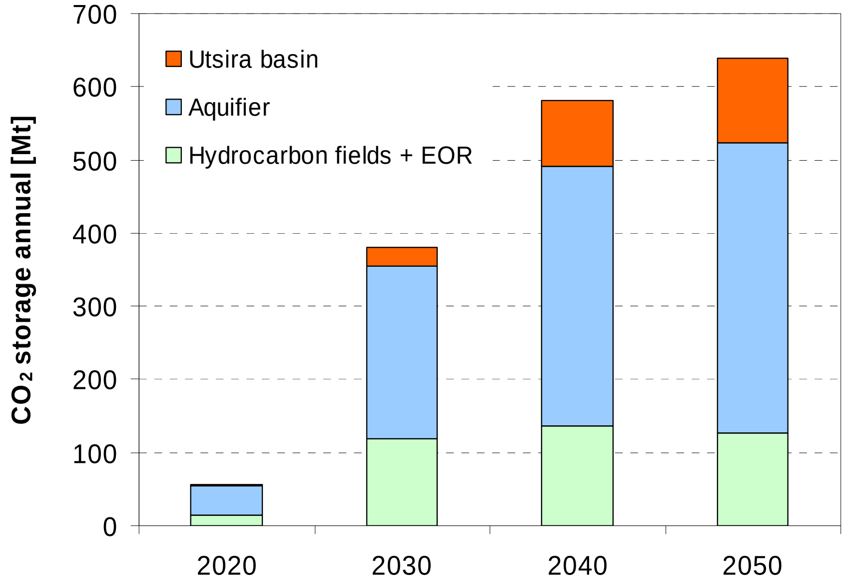


Figure 5-4: CO_2 storage in the neighbouring countries of the North Sea by storage type [18]

The use of the Utsira formation for CO_2 storage from outside Norway begins in 2030 with 17 Mt (12 Mt from the UK and 5 Mt from the Netherlands) and increases to 90 Mt in 2040 and 115 Mt in 2050. This increase is mainly driven by enhanced quantities coming from the UK (55 Mt in 2040 and 75 Mt in 2050) and the Netherlands with 30 Mt in 2040 and 40 Mt in 2050. Neither from Denmark nor Germany, CO_2 is transported to Utsira. In both countries Utsira storage competes against domestic aquifer storages, which are more cost effective.

Trans-boundary CO_2 transport can contribute in the future to an economic use of CO_2 storages due to economy of scale. The total trans-boundary transport extends from about 40 Mt in 2030 to 110 Mt in 2050 (Figure 5-5). On the one hand, countries with limited CO_2 storage potential, like Belgium rely on carbon storage abroad for the application of CCS technologies. Belgian exports to the Netherlands amount to 20 Mt, which is assumed to be the maximum export capacity. On the other hand, countries in which the distance from emission source to domestic storage is longer than to storage sites abroad can profit from trans-boundary CO_2 transport. Related to this issue, CO_2 flows from Poland to German aquifer storages can be economical valuable for Polish power plants (e.g. Dolna Odra and Turow). The cross-border exchanges from Germany to the Netherlands has its maximum in 2040 with almost 40 Mt. From 2040 to 2050 net CO_2 export quantities from Germany to the Netherlands decrease drastically since low cost hydrocarbon storages are almost completely used and further CO_2 quantities from Germany cannot be stored in the Netherlands. In 2050, the Netherlands export CO_2 to the UK due to the lack of domestic storages.

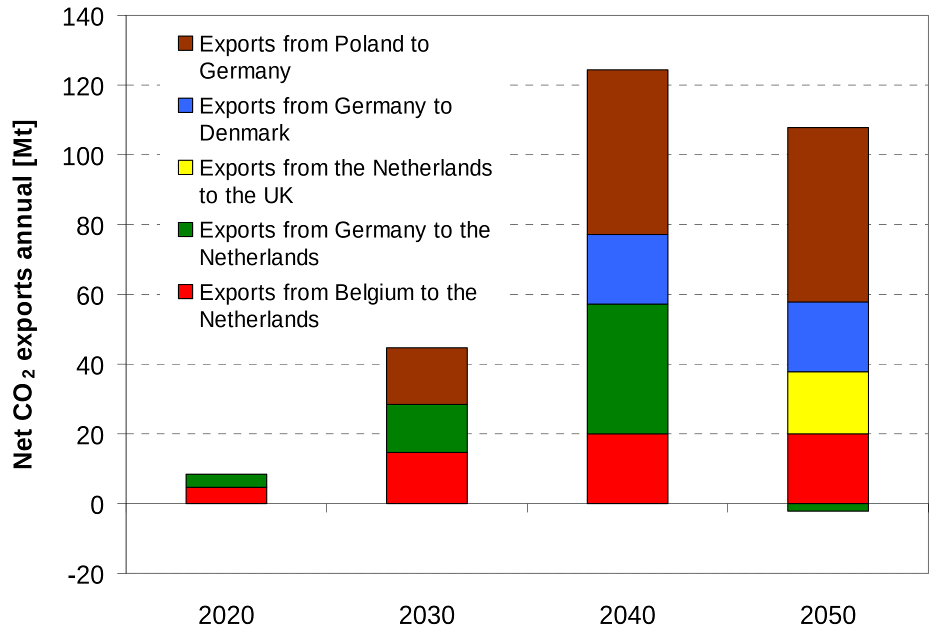


Figure 5-5 : Cross boundary CO_2 exchange [18]

5.2.2 Results for alternative infrastructure options (network II and network III)

Alternative infrastructure schemes for the Utsira connection in the North Sea have almost no influence on the energy system of the neighbouring countries of the North Sea. The total amount of CO_2 stored in the North Sea countries appears not to be influenced by differences in the pipeline network layouts. The total quantities remain on a level of 590 Mt in 2040 and 640 Mt in 2050 independent from the network. However, the CO_2 quantities transported to Utsira differ slightly (Figure 5-6). In 2040 and 2050 the transport via network III results in additional 8 Mt of CO_2 compared to network I. Under network II, the same quantities like under network I are transported and stored in Utsira in 2040, whereas in 2050, 4 Mt less are transported via network II.

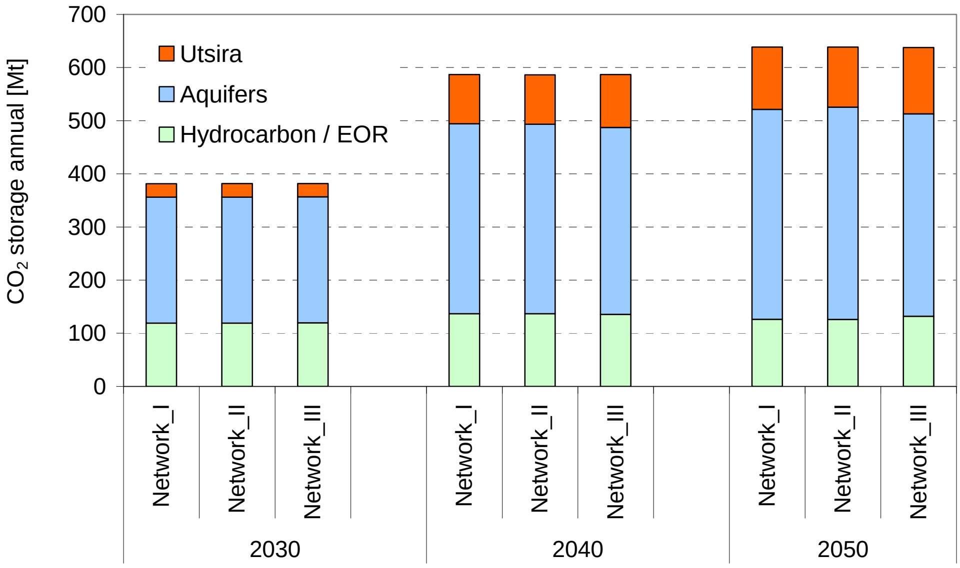


Figure 5-6 CO_2 storage in the neighbouring countries of the North Sea in the different infrastructure scenarios in the high capacity case [18]

5.3 Comparison results of WP3 and WP4

Although the results at the national and regional level differ in level of detail and in the coverage of sectors included, a comparison of the results can provide insights into the implications of national versus regional strategies[4]. Tables 5-2 and 5-3 show a comparison of the results for the scenario with most stringent emission targets (C-80).

Table 5-2: Comparison of national and regional results – Total CO_2 captured (C-80)

Regional (Infra I)	Regional model (infrastructure type I)	National model
United Kingdom	171.8	*53.0*
The Netherlands	97.5	144.7
Germany	287.6	*264.0*
Norway	2.2	2.9
Denmark	9.8	9.4
Total	**568.9**	**474.0**

[4] This does not apply for the national model for Germany and Denmark. As these models are both derived from the PET model, they have the same structure and technology assumptions in both models.

Table 5-3: Comparison of national and regional results –CO_2 storage in Utsira (C-80)

Country	2030	2040	2050
Regional (Infra I)			
United Kingdom	12.3	56.4	73.5
The Netherlands	4.6	34.4	41.4
Germany	0.0	0.0	0.0
Norway	8.7	1.7	2.2
Denmark	0.0	0.2	0.0
Total	**25.7**	**90.0**	**116.2**
National			
United Kingdom	0.0	0.0	0.0
The Netherlands	0.0	2.4	105.2
Germany	0.0	0.0	0.0
Norway	0.7	0.0	2.9
Denmark	0.0	2.0	1.4
Total	**0.7**	**4.4**	**109.5**

The results show significant differences not only in the amounts of CO_2 capture and stored but also in the year at which CO_2 storage at Utsira appears as a cost effective option for the different countries. An advantage of using a regional model is that trade issues (e.g. electricity or CO_2) can be deal with in a more complete way. Trade of CO_2 in an early stage would imply that amounts of CO_2 which appear as cost-effective for transport to e.g., Utsira can be reached earlier, making the option more competitive.

It is important to note that analysis of the scenarios where onshore storage in aquifers is not allowed (e.g. due to lack of public acceptance), increases the cost-effectiveness of Utsira. However, this type of scenarios also decreases the cost-effectiveness of CCS as such and tends to result on lower rates of deployment. Another important aspect to be taken into account is that model work at the national level tends to assume that the whole capacity of Utsira will be available (no competition with flows coming from other countries). Thus, when the results of all separate models are put together, the maximum injection rate established in WP1 (150 Mt/yr) is exceeded.

A way to deal with this is to assume that only a part of the potential storage of Utsira is available for the country (as it was done in the UK model). However, the distribution of such share is not the result of an optimization and therefore remains subjective. This indicates the need to consider Utsira in the context of the region and not just of a given country.

In the rest of this section, insights are provided into the differences between the results of each country if compared to the regional model.

5.3.1 United Kingdom

There are some clear similarities between the UK MARKAL and PET model results for the C-80 CO_2 emissions case under WEO 08 fossil prices:

- Under a stringent CO_2 constraint, both models choose expanded low-carbon electricity as a primary decarbonisation energy pathway.
- CCS is considered a key technology, and although focuses primarily on the power sector, also has a secondary role in abating industrial CO_2 emissions and in producing hydrogen (through natural gas steam methane reforming).
- The ordering of CCS storage options remains consistent with cheapest option being the most favourable saline aquifers together with oil and gas fields (including enhanced oil recovery). The large Utsira formation sit in the middle of this CCS cost curve with less favourable aquifers and oil and gas fields being more expensive.
- The ordering of CCS reservoirs can switch – this is seen in the UK MARKAL sensitivity under large Utsira capacity, or in the PET model's sensitivity on Denmark and Germany's lack of access to domestic aquifers.

The two models have however a range of differences. There are four main drivers of this:

- The PET model includes UK aviation to and from the entire EU-27 nations, whereas the UK only has aviation on a domestic basis, which is much smaller.
- The UK model is a partial equilibrium solution with access to demand reduction and so this flexibility alleviate pressure for purely supply side decarbonisation.
- The UK and PET model have somewhat different policy and taxation assumptions in the near term.
- The two models have different assumptions on various technology assumption (e.g., the UK model is more optimistic on hydrogen vehicles), or the models have different depiction of technology options (e.g. the PET model includes industrial CCS options).

Table 5-4 summarises the electricity generation mix for the regional and the national model results. In 2050 the national model 172 Mt/y and the regional model capture 53 Mt/y CO_2. A reason for this difference is that in the 172 PJ higher for coal based CCS and 522 PJ higher for gas based CCS in the regional- compared to the national model.

No CO_2 was transported to Utsira in the national model and 73.5 Mt/y was transported from the United Kingdom through the regional transportation network in 2050. The model results vary widely regarding the CO_2 transportation to Utsira but it shows a possible range of outcome due to different assumptions.

Table 5-4: Electricity generation mix- United Kingdom – regional & national model results (PJ)

	Regional model results			National model results		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**
Coal	2	1	0	316	-	-
Coal CCS	536	641	461	205	205	276
Gas	133	53	15	61	40	-
Gas CCS	7	48	522	-	-	-
Nuclear	324	351	324	410	946	1,070
Oil	-	-	-	-	-	-
Hydro	31	33	43	31	31	31
Wind	346	398	700	173	194	771
Bio, oth.Ren & waste	86	113	114	62	58	59
Imports	82	56	78	73	93	96
Marine	1	57	216	-	51	64
Solar PV	-	-	-	-	-	-
Storage	10	10	10	5	1	5
Total	1557	1759	2482	1,336	1,619	2,372

5.3.2 The Netherlands

A main difference between the regional and national model is that the Dutch model only models the electricity and industrial sector. Residential, transport and services are not included in the model. Energy demand is an exogenous parameter in the Dutch model.

Table 5-1 summarise the electricity generation mix for the regional and the national model results. In 2050, the national model 98 Mt/y and the regional model capture 145 Mt/y CO_2. One reason for this difference is that in the national model has significant more coal based CCS (604 PJ in 2050) compared to the regional model.

One possible explanation could be that the Dutch model includes lower cost storage options than the German model. The regional model has switched to gas based CCS as it has lower specific CO_2 emissions than coal CCS. This solution can be more cost effective in combination with high cost storage options than coal CCS (more CO_2 to be stored per unit of electricity).

No CO_2 was transported to Utsira in the national model and 73.5 Mt/y was transported from the United Kingdom through the regional transportation network in 2050. The model results vary widely but it shows a possible range of outcome due to different assumptions.

Table 5-1: Electricity generation mix- The Netherlands – regional & national model results (PJ)

	Regional model results			National model results		
	2030	**2040**	**2050**	**2030**	**2040**	**2050**
Coal	51	0	0	0	0	0
Coal CCS	118	121	120	204	307	724
Gas	91	15	9	165	92	13
Gas CCS	5	98	305	-	53	107
Nuclear	14	-	-	14	-	-
Oil	-	-	-	-	-	-
Hydro	1	1	1	-	-	-
Wind	192	225	300	122	122	131
Bio, oth.Ren & waste	35	35	55	17	17	56
Imports	-17	43	-86	-19	-21	-232
Marine	-	-	-	-	-	-
Solar PV	-	-	11	-	-	-
Storage	-	-	-	-	-	-
Total	491	539	714	503	570	799

5.3.3 Germany

Since the national model results for Germany (WP3) are derived by using the PET-model the results of WP4 comply with the results of WP3. Some differences of results can be traced back to changes of carbon and electricity trade, which are driven by an update of CO_2 transport and storage data in the Pan-European model to meet the requirements of WP4.

In 2050, the difference in CO_2 capture between the regional and in the nation model is 24 Mt/y. From Table 5-2, which show the electricity mix for both models, has the regional model in 2050 43 PJ more coal based CCS and 66 PJ more natural gas based CCS. The differences in the model include the electricity- and the carbon trade in addition to the introduction of the CO_2 transportation network. No CO_2 is transported to Utsira in either model variant.

Table 5-2: Electricity generation mix- Germany – regional & national model results (PJ)

Electricity generation mix (PJ)						
	Regional model results			National model results		
	2030	2040	2050	2030	2040	2050
Coal	86	1	0	241	1	0
Coal CCS	772	1,174	993	703	1,183	951
Gas	197	73	98	201	84	97
Gas CCS	0	38	232	0	38	166
Nuclear	0	0	0	0	0	0
Oil	15	16	2	9	6	2
Hydro	117	117	117	117	117	117
Wind	550	651	973	550	651	973
Bio, oth.Ren & waste	177	199	251	167	197	243
Imports	217	85	-35	144	67	67
Marine	0	0	0	0	0	0
Solar PV	68	80	86	68	80	156
Storage	24	24	24	24	24	24
Total	2,223	2,459	2,740	2,224	2,449	2,796

5.3.4 Norway

An introduction of a CO_2 transportation network from the North European countries will not affect the amount of CO_2 captured in Norway.

The amount of CO_2 captured in Norway differs considerable from the regional and the national model because the regional model has included CO_2 capture from natural gas processing. This is not included in the national model. The regional model results have 7.7 Mt CO_2 captured from natural gas processing in 2030 declining to 1 Mt in 2040 due to end of gas production.

The current amount of CO_2 captured from natural gas processing is 1.7 Mt per year. Norway introduced an offshore CO_2 tax in 1991; this has resulted in injection of CO_2 to the Utsira formation at Sleipner. The natural gas produced from the Sleipner field contains more CO_2 than the sales specifications and CO_2 needs to be removed before it is further exported to Europe. Another location with CO_2 storage since 2008 is in the deep aquifer outside the LNG plant in Hammerfest. CO_2 is removed from the natural gas from the Snøhvit field before it is liquefied to LNG.

The existing CO_2 capture at Sleipner and Hammerfest is from natural gas at a high pressure. There is however more challenges related to atmospheric capture from flue gas compared to capture at a higher pressure. With a lower pressure, more energy and larger equipment are required and degradation of suitable amine solvents is higher.

The results for CO_2 capture from the industry are more consistent with each other. In 2050 the capture from industry is 2.2 Mt in the regional model and 2.9 Mt in the national model. Both models have included exogenous capture investments at the existing natural gas fired power plant at Kårstø.

5.3.5 Denmark

Since the national model results for Denmark (WP3) are derived by using the PET-model the results of WP4 comply with the results of WP3. Some differences of results may be due to changes of carbon and electricity trade, which are driven by an update of CO_2 transport and storage data in the PET-model to meet the requirements of WP4. This is particular important for Denmark, because electricity generation from wind power in the end of the period may be much larger than the national demand and beyond the validity of the currently available version of the model.

6 WP 5 – Non-technical conditions for the deployment of a CO_2 pipeline in the North Sea

Deliverable:
- *Possibilities, synergies and conflicts for a common CO_2 pipeline in the North Sea [22]*

WP 2, 3 and 4 looked at the integration of the Utsira in the CCS chains formation from a national and regional perspective. Results of these WPs indicate that Utsira can indeed play a main role, especially for the medium-long term (for further information we refer to the WP final reports). If this is to be the case, it is also important to understand the context on which an offshore CO_2 pipeline to Utsira could be build. *This report aims to provide insights into non-technical issues (e.g. policy, legislation, organization) that need to be in place for the construction of a trans-boundary pipeline network and to generate an inventory of potential synergies and barriers, as well as possible strategies to enhance or overcome them for such a network.* This report focuses on the work conducted on work package five (WP5). The focus of this study is on the countries around the North Sea, in particular Denmark, Germany, Norway, the Netherlands and the United Kingdom.

To identify barriers and synergies, the following areas were explored:

- Governmental position towards CCS
    - Official standpoints from national governments
    - CCS funding
    - Offshore/onshore preference from government and public
    - Norwegian government's position on storing trans-boundary CO_2 flows
    - Collaboration and network between governments on CCS
- Organizational analysis
    - Possible layouts of pipeline network
    - Organization models of network
    - Models for the organization of a cross boundary CO_2 transport infrastructure
- Legislation analysis
    - Domestic legislation
    - International legislation

The CO_2 pipeline in the North Sea is described in detail in deliverable [18]. Here the conclusions of the report are reproduced.

The potential to deploy CO_2 offshore in each country will be largely determined by the role that CCS could play in each country. One of the possible barriers may be the lack of adequate support from government, for instance in Denmark. Without a strong policy support, initiators would hesitate on their participations because they cannot foresee their short and long term investments and returns. Governments in Germany, the UK, Norway and the Netherlands have expressed their positive official standpoint with respect to CCS technology.

Based on subsidies established by governments to promote the development of pilot or demonstration plants on CCS in each country, it can be concluded that the construction of an offshore CO_2 network in the North Sea region from Norway, the Netherlands and the UK would be relatively feasible, considered the government's existing financial support on CCS pilot and demonstration projects. Construction of such a network might meet a financial barrier in Germany and Denmark because currently there is no governmental subsidy scheme for CCS in these two countries.

Although currently no government has officially issued its preferences for onshore and offshore storage, given their location of majority storage sites in the North Sea, offshore CO_2 storage has a preferable future in the UK and Norway. Opposition from public against onshore storage in the Netherlands, Denmark and Germany could become the main driving force to develop offshore construction. Nevertheless, permission recently given on continuing CO_2 storage project in Barendrecht by the Dutch government, indicates that the Dutch government is still trying to identify which CO_2 storage model would be cost-effective.

Trans-boundary transport of CO_2 is a relatively new topic and many organizational aspects are still unclear. Existing experiences from analogous activities and small-scale CCS projects provide valuable experience, in terms of models and prospective players to construct and operate a cross boundary CO_2 transport network in each country. The differences in types of models in each country, however, could become a potential barrier, particularly when constructing a system where large country collaboration is needed.

The current situations of announced projects indicate that a major barrier to develop optimized CCS chains come from financial aspects. A long term financial support from government or enforcement of mandatory regulations e.g. new plants fitted with CCS equipments, CO_2 tax, could be possible strategies to encourage the development.

There is no clarity in terms of prospective players in building a CCS network in these countries. However, considering the dominant players in natural gas pipeline transport as well as the parties which actively participate in crossboundary transport projects, indicate that private companies may play a large role in the development of CO_2 infrastructure. Nevertheless financial conditions at this moment do not encourage active industrial participation.

The domestic legislations will probably not constitute a major constrain to the development of the transport network but they could delay and complicate its deployment. With regard to the international legislations, barriers towards permanent storage of carbon dioxide in geological formations under the seabed in the London Protocol and the OSPAR Convention have (almost) been removed. However, problems could still arise in the cross-boundary CO_2 transport and amendments on Article 6 in the London Protocol and definition of CO_2 stream under the Basel Convention is required before constructing such a network.

7 WP 6 – Final results and Conclusions

The future role of the Norwegian Utsira formation as a storage location for CO_2 from North European countries depend on the actual properties of the formation, mitigation strategies, future energy costs, development of CCS technologies, public acceptance and political barriers.

The main limitation for the Utsira formation is the maximum annual injection rate for CO_2. This is a stronger limitation than the total storage capacity. The literature show simulating results of CO_2 injection up to 150 Mt per year in Utsira distributed over many storage and water production wells from the formation is necessary to reduce the pressure build up. Under stringent mitigation targets, the requirement of annual CO_2 capture can exceed 150 Mt per year in the North European countries. To obtain a better understanding of the limitation of the Utsira formation as a possible storage location for North European CO_2, further research on the injection rate capacity is required.

The European CO_2 reduction commitment is vital for the implementation of CCS technologies towards 2050 and the importance of CO_2 storage in the Utsira formation. All national models (United Kingdom, the Netherlands, Germany, Norway and Denmark) have considerable differences in the CCS implementation dependent on the emission reduction targets. National models have been analysed with both 20% and 80% emission reduction on the EU27+ in 2050. For example in Germany, the amount of CO_2 captured in 2050 is 22 Mt/y with a 20 % emission reduction and 238 Mt/y with an 80 % emission reduction.

When comparing the modelling results from national and regional level, we find that modelling with different geographic scale have an impact on the results. This is partly a result of different input, e.g. the regional model cover international aviation and the national models only cover domestic aviation. The national models have also a higher level of detail on demand changes, technologies, taxes and policies, thus generates a range of difference in sectors, resources and measures to meet CO_2 targets. However, once this is taking into account, differences are still expected in strategies that take into account only national targets or those that work at the regional level, and have therefore a larger and different spectrum for combining cost-effective measures.

With a tight climate target storage of CO_2 in the Utsira formation can be a cost effective option for North Europe. With an 80 % emission reduction target in 2050, up to 1.4 Gt CO_2 is projected to be captured annually in EU27+ in 2050 and the use of costly storages and long transport distances will be necessary. Under this condition the Utsira formation can be competitive and it represents a valuable CO_2 storage option. According to the European model results, CO_2 transport to Utsira from outside Norway comes mainly from the UK (60 to 75 Mt/y in and 2050) and from the Netherlands (20 to 50 Mt/y in 2040 and 2050). In the national models this amounts are even larger.

The United Kingdom profit from the comparably short transport distance to Utsira and the Netherlands utilise the Utsira formation due to limited domestic low cost storage fields and the use of the country as a regional hub for CO_2. In Germany and Denmark, the availability of domestic onshore saline aquifers determines the competitiveness of CO_2 storage in Utsira. If these aquifers are not usable, Utsira gains a competitive storage option.

The price development of oil, natural gas and coal influences the role of CCS in the energy system. At a stringent emission target CCS is inter alia in competition with renewable and nuclear technologies. Higher fossil fuel prices are in favour of the renewable technologies and lower energy prices is favour for the CCS technologies. Model results from the United Kingdom show that there is a competition between nuclear power and CCS technologies. When the energy prices increase, the power production from coal based CCS decrease and the nuclear power increase. Thus, the future role of the Utsira formation can depend on the political acceptance of future nuclear power in Europe. The utilisation of CCS technologies in a country will also be influenced by the national electricity supply options and the opportunity for cross-boundary CO_2 transport.

For the CO_2 transport to Utsira, three different network layouts have been analysed. The analysis showed that electricity generation structure of the neighbouring countries of the North Sea is not influenced by the type of network but rather by climate policies. Different CO_2 infrastructure layouts for the North Sea region primary affect the transported quantities of CO_2 from the Netherlands to Utsira. The different infrastructures options have little impact on the CO_2 storage from the other North Sea countries.

The deployment of a trans-boundary CO_2 offshore pipeline will require an active participation and commitment from the national governments. It is a relative new topic and many organisational aspects are still unclear. Even though the most likely organizational model would be one of public and private partnership, further insights are needed into the role of the government(s), funding conditions and the possibilities to streamline the various legal procedures at the national and regional level.

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