# Analysis of potentials and costs of storage of CO2 in the Utsira aquifer in the North Sea

Final report for the FENCO ERA-NET project

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

## Final Report for the FENCO ERA-NET project

A joint research project:

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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 possibilities of $CO_2$ storage into the Utsira formation and analysed carbon capture, transport and storage of $CO_2$ from countries in the North Sea region into the formation.

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, input data to the national and regional models were harmonised including cost and performance of fossil fuel based power plants. However, a full harmonisation of input data was not possible as the level of detail in some of the national models were higher compared to the European model. 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 depend 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. 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 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 in the EU27+

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.

By 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 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, which generates a range of difference in sectors, resources and measures to meet CO2 targets.

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 the regional analysis results in approximately 575 Mt $CO_2$ captured annually, while the sum of the five national models give approx 475 Mt $CO_2$ captured. Up to 1.4 Gt $CO_2$ will be captured annually in 2050 according to the regional analysis for the EU27+. This will increase the need for storages, and also long transport distances will be of interest. Under this condition the Utsira formation can be a competitive $CO_2$ storage option.

According to the European model results $CO_2$ transport to Utsira from outside Norway mainly comes from the UK (60 to 75 Mt/a in and 2050) and from 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 storages. 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. At a stringent emission target CCS technologies competes with renewable and nuclear power production. 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 fossil fuel 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 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 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 Gasifier 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 |
| 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 (IEA) |
| WP | Work Package |

# 1 Introduction

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”. The possibilities of $CO_2$ storage into the Utsira formation are studied and the carbon capture, transport and storage of $CO_2$ from countries in the North Sea region into the formation is analysed.

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 [6]. The use of Utsira as a European reservoir will not only depend on the available capacity to store $CO_2$ flows but on the cost effectiveness of this option within national portfolios of mitigation measures. Therefore, the possibility of storing $CO_2$ in Utsira has been assessed by taking into account national $CO_2$ reduction targets and temporal and spatial aspects. 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 Denmark, Germany, Norway, the Netherlands and the United Kingdom have been carried out. This is done by developing a modelling tool on the basis of the Pan European TIMES (PET) model and by national MARKAL/TIMES models. The models were used to assess how national energy systems with a $CO_2$ infrastructure can be developed against minimal costs within the time horizon 2005 to 2050. 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. Further, capture technologies and infrastructure for $CO_2$ with their possible levels and timing for each of the countries around the North Sea were assessed.

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

This project is organised into three parts, see Figure 1-1. WP1 and WP2 contain analysis of the assumptions needed for the project. WP 3, WP 4 contain the analysis of the CCS pathways at both national and regional level while WP 5 presents an overview of non-technical issues that are relevant for the deployment of an international pipeline network. In WP 6 the outcome of WP 1-5 is summarised into a final report and conclusions.

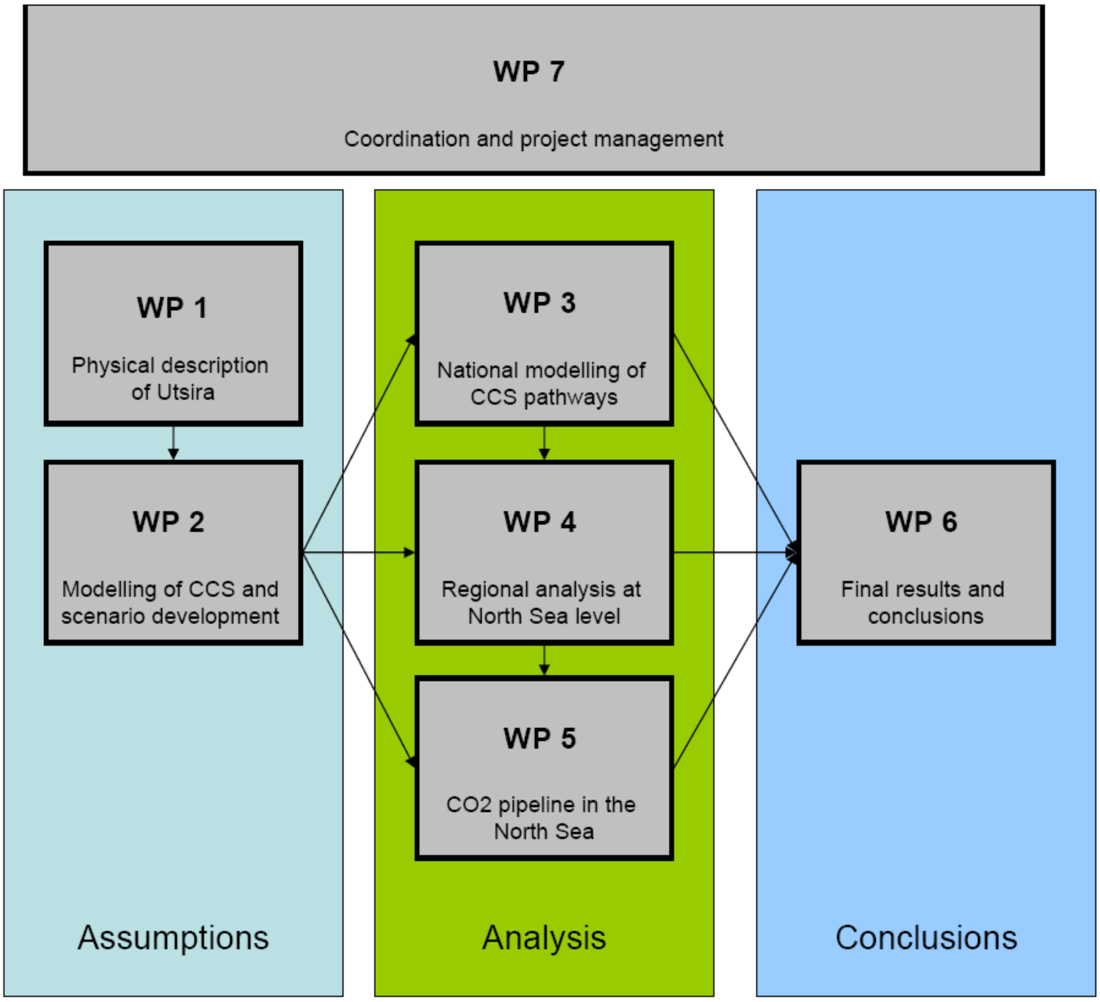

*Figure 1-1: Project structure*

## 2 WP 1 – Physical description of Utsira

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

A physical description of the Utsira formation is described in detail in the deliverable [1]. Here the main results of the report are presented.

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].

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 x $10^{11}$ $m^3$ [3].

Using a typical solubility 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].

The dominating uncertainty for $CO_2$ storage in the Utsira Formation is the volume of the 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].

### Experiences with $CO_2$ storage in Utsira

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. As an alternative to vent the $CO_2$ and pay the $CO_2$ tax, 1 Mt of $CO_2$ has been captured and injected annually in the formation since 1996.

The $CO_2$ capture at Sleipner is from natural gas at a high pressure. There are however more challenges related to atmospheric capture from flue gas with lower partial pressure of $CO_2$. Capture from flue gas, example post combustion, requires more energy, larger equipment and have higher degradation of the amine solvent.

### Injection rate to Utsira

The injection well at the Sleipner field gives an example of how much $CO_2$ that 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 fluid into a formation gives a pressure increase at the injection

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

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

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 make place for the $CO_2$ and reduce pressure build up. In order to store several hundred 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.

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 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.

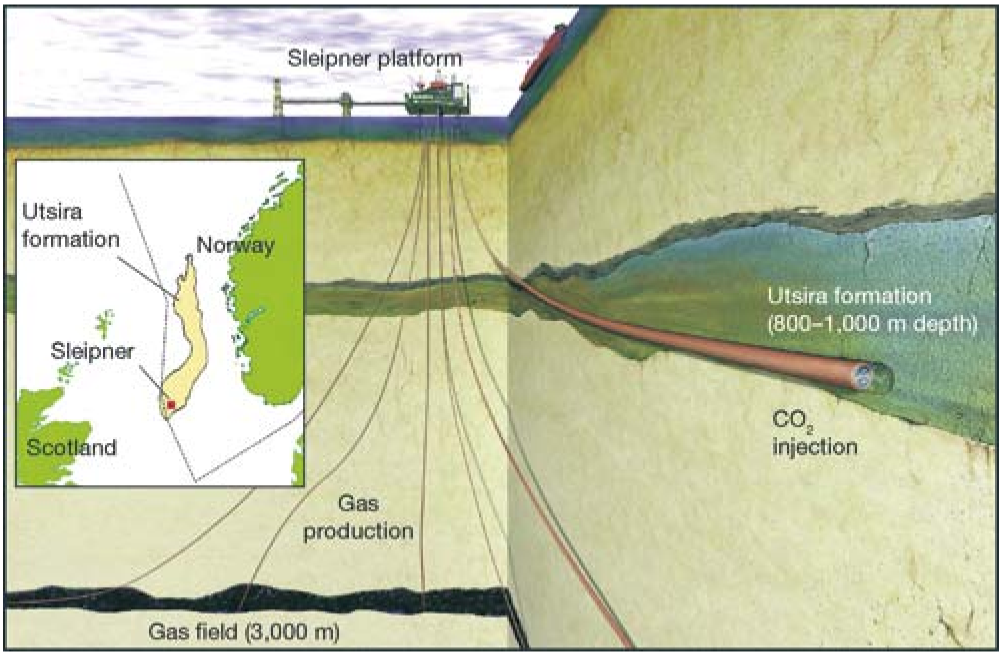

*Figure 2-1: Illustration of $CO_2$ injection to the Utsira formation and map of the formation [8]*

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:

| | |
|---|---|
| Maximum annual injection rate: | 150 Mt $CO_2$ |
| Maximum storage capacity: | 42 Gt $CO_2$ |
| Lifetime injection well: | 25 year |
| Injection cost: | 22 M€/ capacity (1 Mt/ y) |

# 3 WP 2 – Modelling of CCS and scenario development

Deliverable:

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

The CCS modelling and scenario development are described in detail in the report of WP2 [9]. The aim of WP 2 was to assure consistent use of parameters, assumptions and data among the MARKAL and TIMES models used for the national and regional modelling. The assessment on which parameters needed to be harmonized is briefly summarized below.

## 3.1 Scenario driven parameters

The national models and have been analysed with the following two scenarios:

- C-20 (20 % $CO_2$ reduction in 2020 to 2050)
- C-80 (gradually increasing to 80 % $CO_2$ reduction in 2050)

The two main scenarios are based on reduction in $CO_2$ on the EU27+[3] level, C-20 is 20 % $CO_2$ reduction in 2020 to 2050 (from 1990 level) and C-80 is 20 % $CO_2$ reduction in 2020 and 80 % $CO_2$ reduction in 2050. The targets are applied to the national model by national reduction targets as projected by the PET model. The C-80 scenario is based on the $CO_2$ reduction required for developed countries to keep the global temperature rise below 2 °C.

*Table 3-1: Upper limit for the $CO_2$ emissions for the 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 |

A 20 % reduction on the EU27 level does not indicate a 20 % reduction in each country because it can be more favourable and cost effective with more $CO_2$ reductions in some

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[3] EU27+ : Europe + Switzerland, Iceland and Norway

countries compared to others. The national upper limit for $CO_2$ emissions for the two scenarios is given in Table 3-1.

In this project the Pan EU model has mainly been used to analyse the C-80 scenario.

In addition, sensitivity analyses have been carried out on both scenarios with the following sensitivities:

- Lower energy prices
- No CCS
- Increased Utsira storage

The first sensitivity is on the energy price. The basic assumption is that energy prices follow the forecast provided by the International Energy Agency (IEA) World Energy Outlook (WEO) 2008. Lower energy prices according to WEO 2007 are included as sensitivity. The oil and gas price trends used for both cases are depicted in Figure 3-1. For WEO 08 the coal price forecast was 120 and 110 USD/tonne and for the WEO 07 the coal price forecast was 58 and 73 USD/ tonne for 2010 and 2030 respectively.

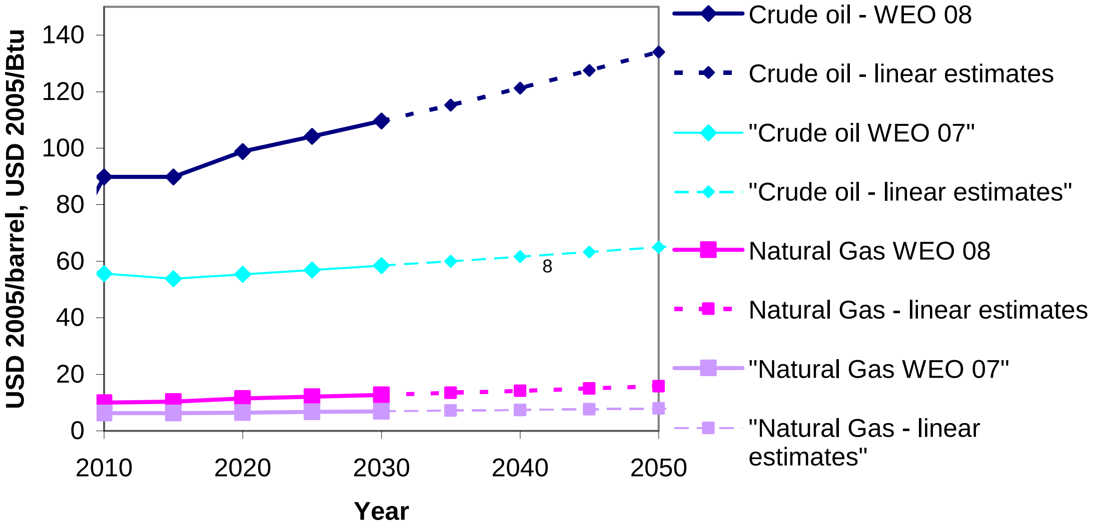

*Figure 3-1 – Crude oil and Natural gas price forecast [10][11]*

The other two general sensitivity scenarios include a no CCS scenario and the increased potential in the Utsira formation scenario with a maximum injection rate at 500 Mt $CO_2$ per year and a total storage capacity at 100 Gt $CO_2$. Additional sensitivity scenarios were carried out in the national reports for specific conditions.

## 3.2 Cost and performance of fossil fuel based power plants and CCS technologies

Table 3.1 shows the basic cost and performance data used in the model runs for the different time periods. In deliverable [9] the ranges found in the literature and in the original models can be found. The capture rate is 94 % for oxyfuel- and 85 % for post combustion and pre-combustion $CO_2$ power plants.

*Table 3-2: 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 |
| **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 |
| **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 |

## 3.3 $CO_2$ transport

This chapter has direct citation selected parts of the deliverable report [9].

$CO_2$ transport costs are harmonised between the models. The transport cost of $CO_2$ for varies with capacities, distances and terrain factors. The difference in cost of transport over different terrain types is represented by the terrain factors that differ from country to country. For the Netherlands, offshore transport is cheaper than onshore transport, mainly as a result of limited land available. In e.g. Germany, off shore transport is likely more expensive than on shore transport in most situations.

To estimate the diameter of the pipeline, the Ecofys model is used, see Eq. 1. The Ecofys model results are below the average of these seven models assessed as show in Figure 3-2.

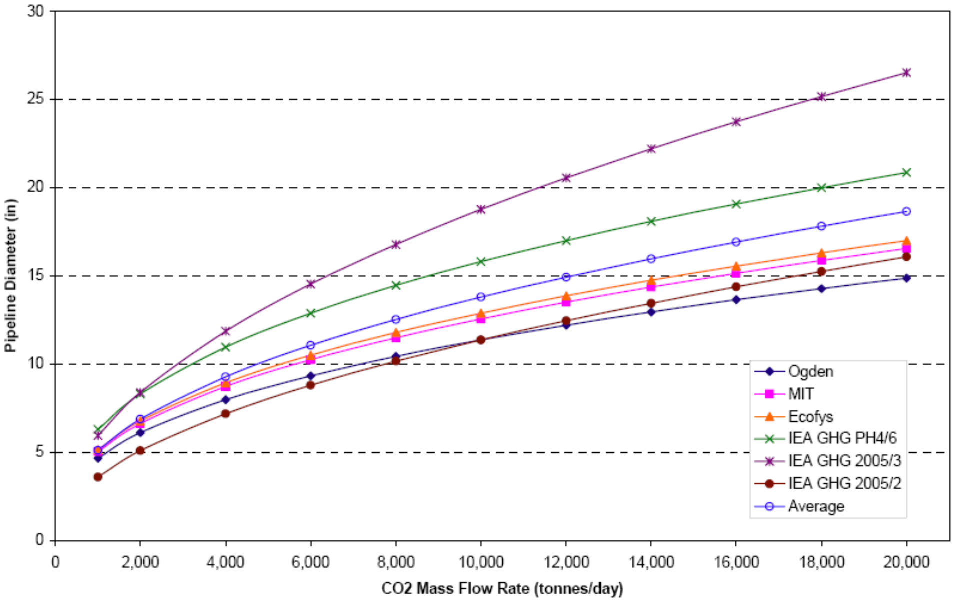

*Figure 3-2: Model Comparison: Pipeline diameter vs. $CO_2$ mass flow rate (L = 100 km) [9]*

Figure 3-3 presents pipeline diameters as functions of capacity and distance.

*Table 3-3: Formula for estimation of pipeline diameter [9]*

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

D = diameter of the pipeline (m)
$\lambda$ = friction factor (0.015)
M = mass flow of $CO_2$ (kg/s)
$\rho$ = $CO_2$ density (800 kg/$M^3$)
$\Delta P$ = pressure drop ($3*10^6$ Pa)
L = Length pipeline (m)

Eq. 1

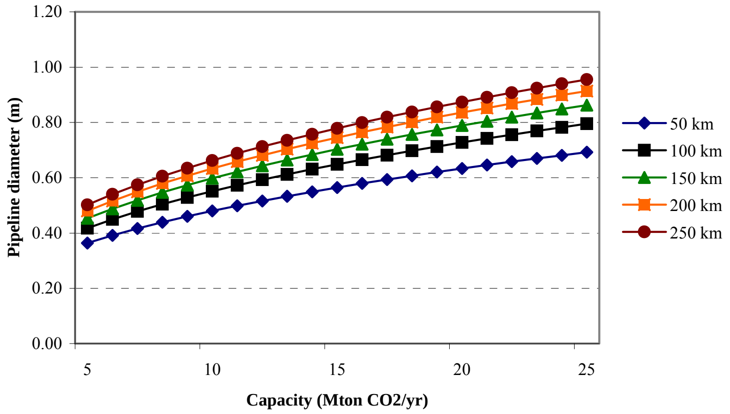

*Figure 3-3: Diameter of the pipeline as a function of the $CO_2$ mass flow [9]*

The investment costs are calculated using equation 2. 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 $\Delta P$ 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 $CO_2$. Figure 3-4 illustrates $CO_2$ transport costs by capacity and distance for alternate terrain factors.

*Table 3-4: Formula for estimating the pipeline investment cost [9]*

| | | |
|---|---|---|
| $I = Ft_{Land\,use} * C * D * L$ | I = investment cost (€)<br>$Ft_{Land\ use}$ = terrain factors for different land use types (table x)<br>C = Constant factor (1600 €/$m^2$)<br>D = diameter pipeline (m)<br>L = length pipeline (m) | Eq. 2 |

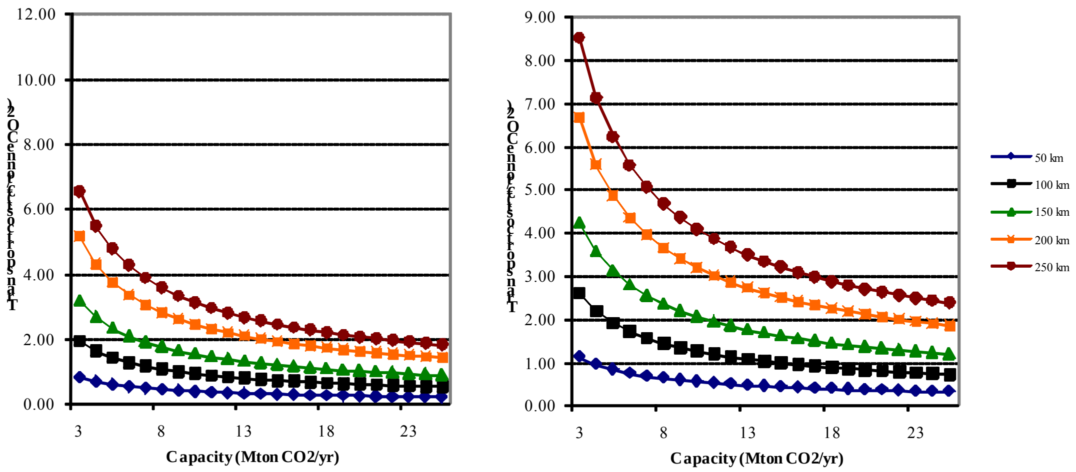

Figure 3-4: $CO_2$ transportation cost for different capacities and distances for Ft = 0.9 (left) and Ft = 1.2 (right) [9].

## 3.4 Harmonisation with the PET model

All models have used a 5 % discount rate and no technology specific discount rate.

The German and Danish model is derived by using a version of the Pan-European TIMES model that is run by IER, Stuttgart. These models are therefore fully harmonised with the PET model. For the other countries; United Kingdom, The Netherlands and Norway there have been made efforts to harmonise the national input data with the PET model.

The harmonised net electricity import/ export are shown in Table 3-5. After 2015 the Netherlands and Norway are net exporters while the United Kingdom is a net importer.

*Table 3-5: 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 |

Table 3-6 show the carbon price used in all national models. The carbon price is significantly higher for the C-80 scenario than the C-20 scenario. In 2050 the carbon price is 17 times higher for the stringent emission scenario.

*Table 3-6: Carbon price, EUR/ ton $CO_2$*

| Scenario | 2005 | 2010 | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|---|
| C-20 | 0 | 5.2 | 21.0 | 24.5 | 15.6 | 11.1 | 41.3 | 41.9 |
| C-80 | 0 | 4.6 | 21.7 | 11.9 | 22.0 | 41.3 | 141.3 | 705.6 |

## 3.5 Test of Mixed Integer Linear Programming (MILP)

The benefits and the properties of mixed integer linear programming (MILP) has 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 applied 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 5GW per 5 year period (1GW/annum) is chosen with the current UK system at 84 GW. A range of runs, all with $CO_2$ emission reduction of 80% are run and investments in nuclear and on CCS compared in table 4.1.

*Table 3-7: 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 |

Table 3-7 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.

# 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 national CCS pathways are described in detail in the deliverables [12, 13, 14, 15 and 16]. The starting point of the analysis is the national MARKAL and TIMES models for United Kingdom, the Netherlands, Germany, Denmark and Norway developed by each of the partners involved. The models are used with the harmonised modelling assumptions and scenarios (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.

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:

**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. CCS plays a role (19 % of the generation capacity) when this scenario is combined with WEO 2007 energy prices. In this case, about 62 Mt $CO_2$/year is stored in 2050. $CO_2$ is stored for enhanced oil recovery and offshore aquifers in the North Sea (35 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.

**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 power plants with CCS is projected to be 8 GW in

2050 producing about 36 % of the electricity. The amount of $CO_2$ stored in 2050 is estimated at 43 Mt per year. During the first decades (2020-2040) $CO_2$ is stored in (national) onshore gas fields. Offshore storage becomes cost-effective when capacity of onshore sinks for $CO_2$ storage is depleted (in 2050). In total in 2050, 14 % of the $CO_2$ is stored offshore including 8 % in the Utsira formation and 6 % in depleted offshore gas fields.

**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 in. The electricity supply increases to a level of 2.2 EJ, with 1.1 EJ being produced from renewables. The share of electricity from fossil fuels of total electricity supply declines. 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, there is a significant increase in the use of biomass, mainly for electricity and heat. The very dominant feature is the variation of wind power and electricity export. In this scenario CCS technologies do not play a role.

**Norway**: Primary energy demand in 2050 is estimated at 1033 PJ. Electricity generation is dominated by renewables. 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.

The results with stringent mitigation targets (C-80) 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. This $CO_2$ is stored in national aquifers (no EOR). If lower prices are assumed (WEO 2007), the amount of $CO_2$ capture increases significantly (210 Mt) with about 24% of this flow being stored at Utsira. The general ordering of costs of CCS transport and storage are: Enhanced Oil Recovery (EOR), the lower portion of the supply curve for UK aquifers, the lower portion of the supply curve for UK oil/gas reservoirs, Utsira, higher cost UK aquifers and finally higher cost oil/gas fields.

**Netherlands:** Electricity generation is projected to increase to 1031PJ 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 34GW. Similar to the C-20 scenario, $CO_2$ is initially stored in onshore gas fields. Due to the rapid increase in CCS, offshore storage of $CO_2$ in the Utsira formation and in offshore gas fields in the Netherlands starts already in 2030. Storage of $CO_2$ in the Utsira formation is however still marginal in 2040 (2.4 Mt $CO_2$/yr), but increases rapidly to 105 Mt in 2050. In 2050, 80% of total CO2 captured in the Netherlands is projected to be stored in the Utsira formation.

**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. 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%. Amount of $CO_2$ captured amounts to 237 Mt. At lower energy prices (WEO 2007) 159 Mt $CO_2$ are captured. For carbon storage domestic saline aquifers (243 Mt) and hydrocarbon fields (25 Mt) are primary used. Only minor quantities of $CO_2$ are transported and stored abroad. In 2050 the next exchange balance is determined by import quantities from Poland (50Mt) and exports to Denmark (20Mt) and the Netherlands (25 Mt). Storage at the Utsira formation is done via a pipeline from the Netherlands. Direct transport of $CO_2$ to Utsira appears not to be cost-effective.

**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 [17] 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. This is consistent with the result for $CO_2$ export from Germany to Denmark as shown in Figure 5-8, below. 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. So far this feature has not been implemented and tested in the Pan European model.

**Norway:** Primary energy demand in this scenario is estimated at 1040 PJ. In addition to the $CO_2$ capture unit to the existing NGCC power plant (see C-20 scenario), 2.9 Mt CO2 are captured from the industrial sector in 2050 (0.82 Mt from cement production and 2.1 Mt from the refineries). All $CO_2$ is stored at Utsira.

Table 4-1 shows the total amount of $CO_2$ stored in the national models and Table 4-2 shows the total amount of $CO_2$ stored in the Utsira formation.

In the C-20 scenario the Netherlands and Germany use $CO_2$ capture to meet their emissions targets with 43 and 22 Mt captured in 2050 respectively. The Netherlands is the only country with injection to the Utsira formation with 3 Mt/ year. With lower costs C-20-07 the capture rate for Germany and the Netherlands decrease while 61 Mt/ year of $CO_2$ is captured in the United Kingdom. With lower energy prices (including coal prices), nuclear power is phased out and substituted with coal CCS in the United Kingdom. In Germany and in the Netherland lower energy prices decrease the coal based power production and increases the natural gas fired power production.

*Table 4-1: Comparison of national results – total $CO_2$ storage in 2050 ($MtCO_2$/ year)*

| Country | C-20 | C-80 | C-20-07 | C-80-07 |
|---|---|---|---|---|
| **UK** | 0.0 | 53.0 | 61.2 | 222.5 |
| **NL** | 43.0 | 144.7 | 29.6 | 154.1 |
| **DE** | 21.7 | 268.3 | 19.8 | 240.4 |
| **NO** | 0.0 | 2.9 | 0.0 | 2.9 |
| **DK** | 0.0 | 9.4 | 0.0 | 10.2 |

*Table 4-2: Comparison of national results –$CO_2$ storage in Utsira 2050 ($MtCO_2$/ year)*

| Country | C-20 | C-80 | C-20-07 | C-80-07 |
|---|---|---|---|---|
| **UK** | 0.0 | 0.0 | 0.0 | 53.7 |
| **NL** | 3.4 | 105.2 | 0.0 | 119.7 |
| **DE** | 0.0 | 0.0 | 0.0 | 0.0 |
| **NO** | 0.0 | 2.9 | 0.0 | 2.9 |
| **DK** | 0.0 | 1.4 | 0.0 | 2.0 |

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 is increased. Lower energy prices increase the total amount of $CO_2$ injected to the Utsira formation. The total of the storage rate in 2050 exceeds the maximum annual injection rate at 150 Mt from WP2.

The national model for the United Kingdom has an upper limit for $CO_2$ injection to the Utsira formation at 53.7 Mt/ y. The UK's allocation of these limits was calculated based on a (year 2000) population share of 35.8% of the countries adjoining the North Sea. With no limitations on the annual injection to Utsira the national model transport and store 109.4 Mt/y $CO_2$ to Utsira in 2050. This sensitivity scenario emphasise the possible role of the Utsira formation as a storage location for the United Kingdom.

Table 3-4 shows the usage of power production with carbon capture for the C-80 and the C-80-07 scenario in 2050 for each country. Carbon capture to coal power plants play a significant role to obtain the emission targets in the larger countries including the United Kingdom, The Netherlands and Germany. In the UK the usage of coal CCS increase four times due to lower energy prices due decreased nuclear power with lower energy costs. The usage of carbon capture to natural gas based power plants play also considerable role in the mitigation portfolio of the Netherlands and Germany. The usage of this technology increase with lower energy prices for both countries.

*Table 4-3: Comparison of national results, CCS power production in 2050 (PJ)*

| **Scenario** | **C-80** | **C-80-07** | **C-80** | **C-80-07** |
|---|---|---|---|---|
| **Country** | **Gas-CCS** | **Gas-CCS** | **Coal-CCS** | **Coal-CCS** |
| **UK** | 0.0 | 0.0 | 276 | 1081 |
| **NL** | 107 | 165 | 724 | 681 |
| **DE** | 124 | 334 | 1140 | 1137 |
| **NO** | 0 | 0 | 0 | 0 |
| **DK** | 28 | 31 | 1 | 0 |

# 5 WP4 – Regional analysis at North Sea level

Deliverable:

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

In this chapter there are direct citations from the deliverable report [18].

The regional analysis is described in detail in deliverable [18]. This WP represents the coordinated analysis of CCS for the countries of the North Sea for the time period 2010 – 2050, with a focus on the national and regional implications of offshore $CO_2$ transport to the Utsira formation. The pan-European energy system model TIMES PanEU is applied, which has been developed in the European FP 6 research project NEEDS and enlarged and updated by IER, University of Stuttgart and further used in several national and European research projects like. 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 EU27 as well as common infrastructure usage of Utsira connection.

## 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 (Figure 5-1). 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, see Figure 5-2

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 sup pipelines, see Figure 5-3.

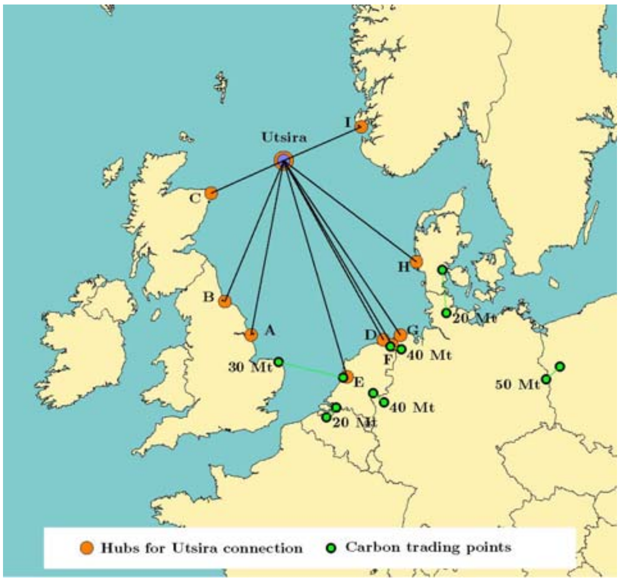

*Figure 5-1: Network I [18]*

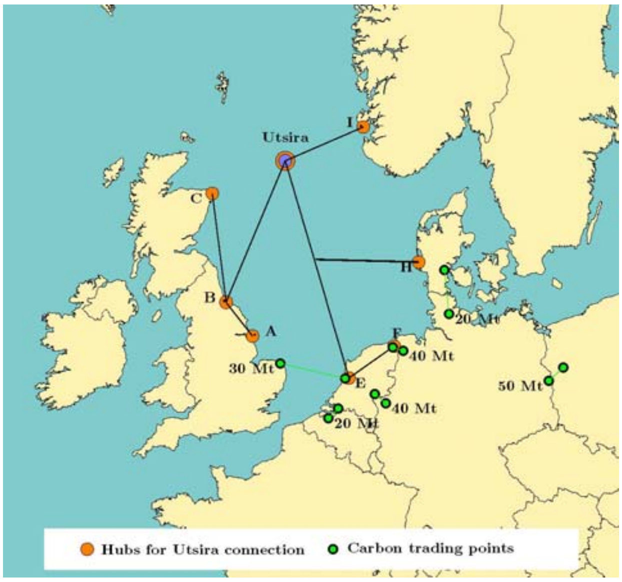

*Figure 5-2: Network II [18]*

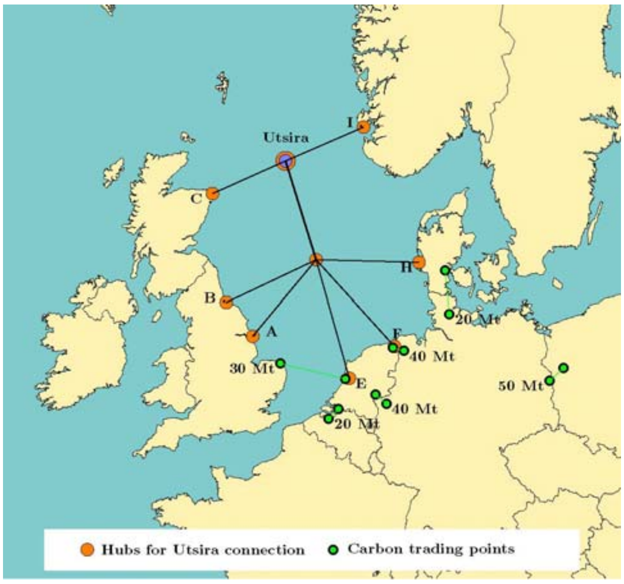

*Figure 5-3: Network III [18]*

## 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 climate policy regime up to 1.4 Gt/y of $CO_2$ can be captured in 2050 for Europe (nine times the assumed maximum injection rate to Utsira). 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.

### 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 increases from 1160 TWh in 2000 to almost 2000 TWh in 2050 (Figure 5-4). 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.

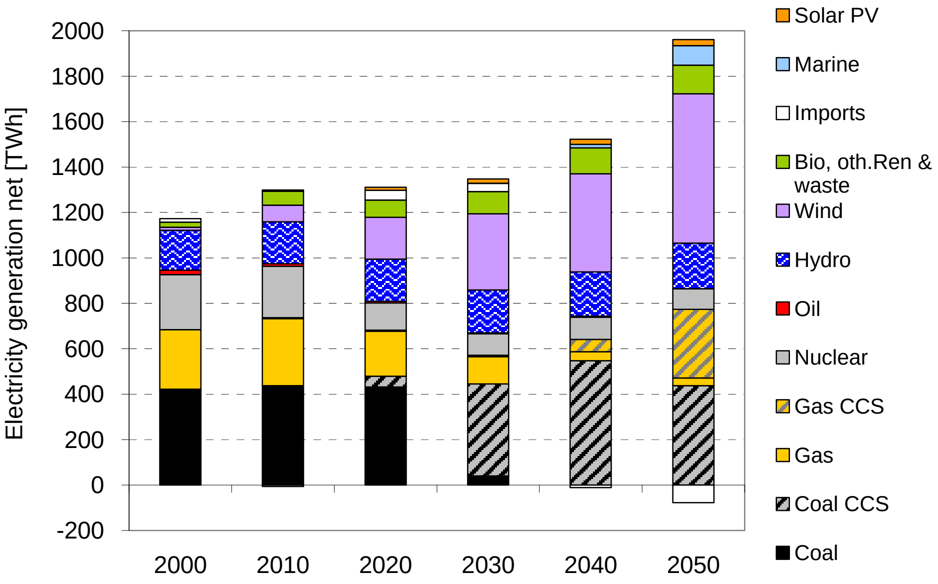

*Figure 5-4: Electricity generation in the neighbouring countries of the North Sea [18]*

The $CO_2$ quantities captured increase from 50 Mt in 2020 to 350 Mt in 2030 and 570 Mt in 2050 (Figure 5-5). $CO_2$ is primary captured from CCS technologies of public electricity and heat generation (90 % in 2050).

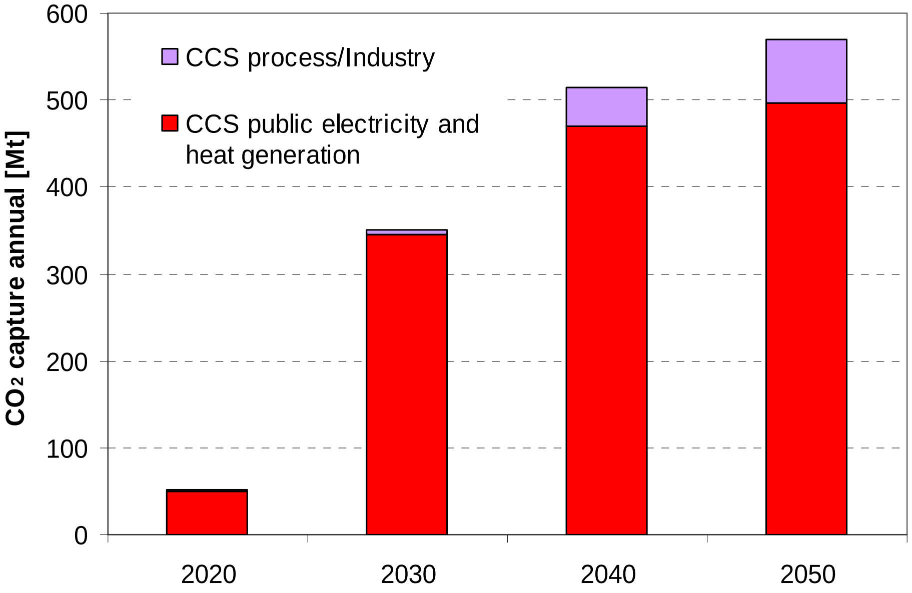

*Figure 5-5: $CO_2$ capture in the neighbouring countries of the North Sea by emission source [18]*

Large $CO_2$ quantities are captured in Germany, reaching a level of almost 200 Mt in 2030 and 300 Mt in 2040 and 2050. Capture in the UK amounts to 110 Mt in 2030, 150 Mt in 2040 and 170 Mt in 2050. Carbon capture in the Netherlands increases from 45 Mt in 2030 to 60 Mt in 2040 and 100 Mt in 2050. Denmark reaches a maximum annual level of 15 Mt and Norway 10 Mt.

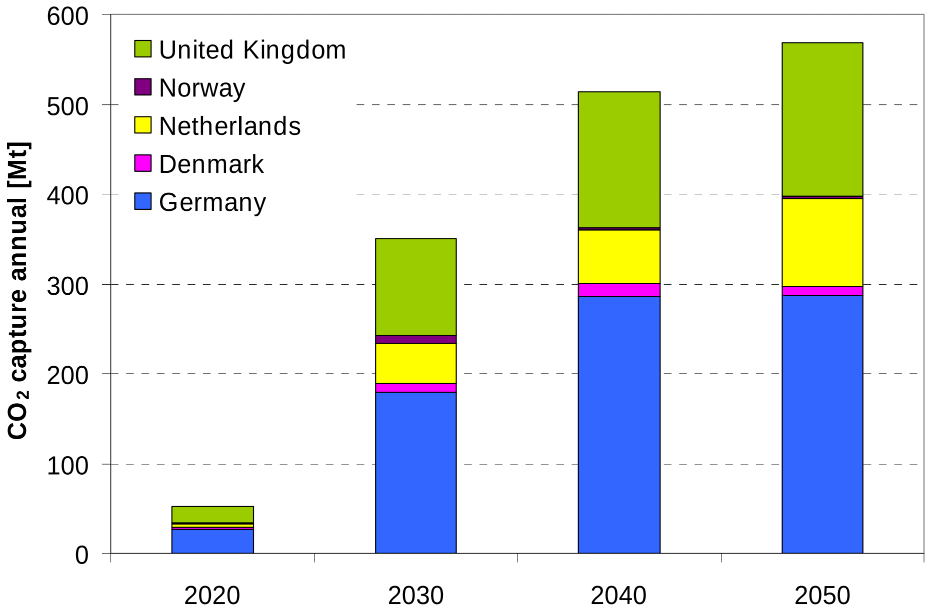

*Figure 5-6: $CO_2$ capture in the neighbouring countries of the North Sea by country [18]*

$CO_2$ 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 60 Mt $CO_2$ are stored in 2020, increasing to 380 Mt in 2030, 580 Mt in 2040 and 640 Mt in 2050 (Figure 5-7 ).

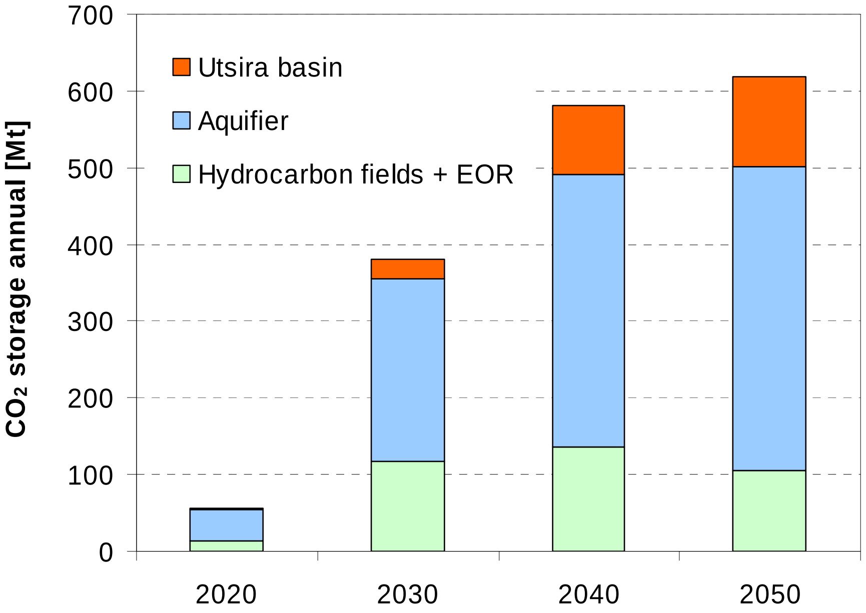

*Figure 5-7: $CO_2$ storage in the neighbouring countries of the North Sea by storage type [18]*

The $CO_2$ is primary stored in saline aquifers with 40 Mt in 2020 increasing drastically to 240 Mt in 2030, almost 355 Mt in 2040 and 400 Mt in 2050. Storage in onshore aquifers amounts to 140 Mt in 2030 and 220 Mt in 2040 and 2050. In offshore aquifers 95 Mt in 2030 are stored, growing to 135 Mt in 2040 and 180 Mt in 2050. Consequently offshore locations represent 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 are 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.

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 120 Mt in 2040 and 110 Mt in 2050 (Figure 5-8). 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 almost 40 Mt due to the storage in Dutch hydrocarbon fields. 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 can not be stored in the Netherlands. In 2050 the Netherlands even deliver $CO_2$ to the UK due to the lack of domestic storages.

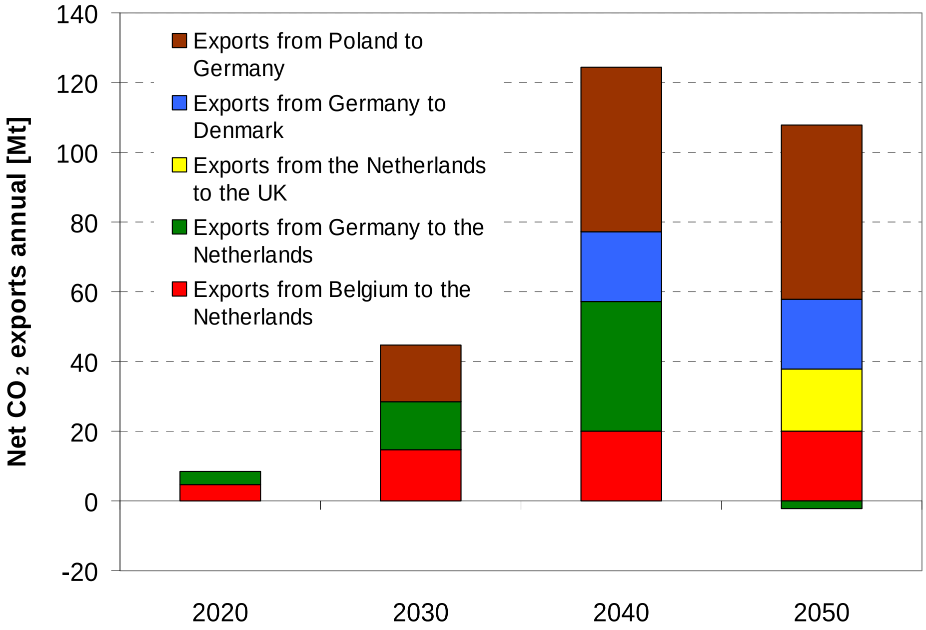

*Figure 5-8 : Cross boundary $CO_2$ exchange [18]*

### 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 different network layouts changes of the costs for the $CO_2$ transport to Utsira within a range between 0 and 4 €/t$CO_2$.

Comparing the three infrastructure schemes it can be concluded, that the total amount of $CO_2$ storage in the North Sea countries is not influenced by different pipeline network systems. The total quantities remain on a level of 590 Mt in 2040 and 640 Mt in 2050 independent from the network, whereas the $CO_2$ quantities transported to Utsira differ slightly (Figure 5-9). In 2040 and 2050 the transport via network III results to additional 8 Mt of $CO_2$ compared to network I. Under network II 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.

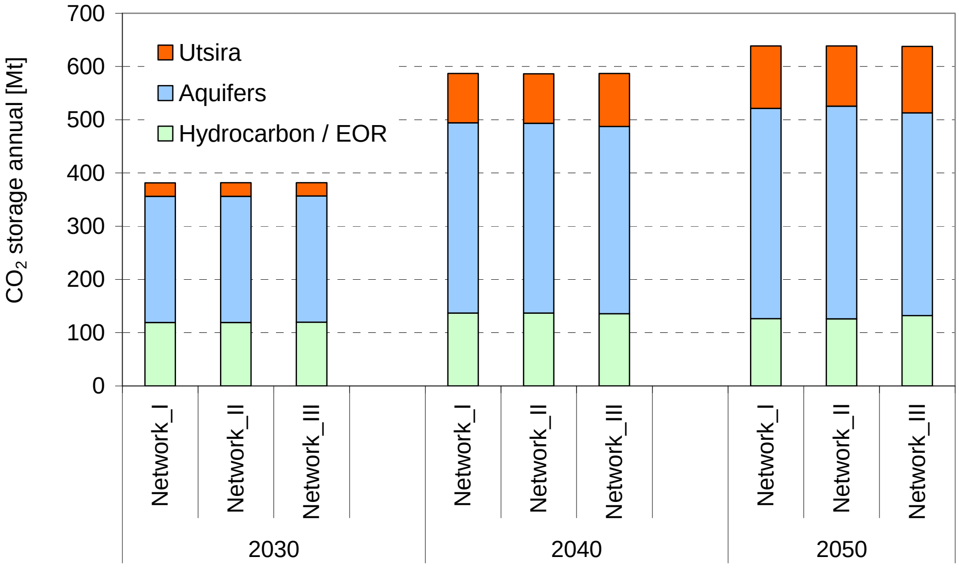

*Figure 5-9: CO$_2$ storage in the neighbouring countries of the North Sea in the different infrastructure scenarios in the high capacity case [18]*

## 5.3 Comparison WP3 and WP4

The regional Pan European model does not cover the same detail level as the national model for The United Kingdom, The Netherlands and Norway. With different input data, like for example nuclear assumptions, the models will give different results. Because the national model for Germany and Denmark are derived from the PET model they have the same structure and technology assumptions in both models.

Another reason for the different outcomes from the regional- and the national model is that the regional model have included carbon trade and use a transportation network for $CO_2$ transport to Utsira. Cost benefits from the transportation network can make CCS technologies more competitive.

*Table 5-1: Comparison of national and regional results – Total $CO_2$ captured (C-80)*

| **Year** | **2030** | **2040** | **2050** |
|---|---|---|---|
| **Regional (Infra I)** | | | |
| *United Kingdom* | 108.0 | 151.8 | 171.8 |
| *The Netherlands* | 44.2 | 59.6 | 97.5 |
| *Germany* | 179.3 | 286.4 | 287.6 |
| *Norway* | 8.7 | 1.7 | 2.2 |
| *Denmark* | 10.4 | 14.3 | 9,8 |
| ***Total*** | **381.1** | **581.0** | **638.8** |
| **National** | | | |
| *United Kingdom* | 37.7 | *38.0* | *53.0* |
| *The Netherlands* | 46.2 | 68.6 | 144.7 |
| *Germany* | *163.9* | *285.4* | *264.0* |
| *Norway* | 0.7 | 0.0 | 2.9 |
| *Denmark* | 3.6 | 10.1 | 9.4 |
| ***Total*** | **286.4** | **429.9** | **578.3** |

Table 5-1 lists the total amount of $CO_2$ captured for the regional model with the C-80 scenario and the network I option compared with the national model results presented in Chapter 4. Table 5-2 lists the amount of $CO_2$ stored in the Utsira formation for the regional model with the C-80 scenario and the network I option compared with the national model results.

The results in Table 5-2 include the possibility of onshore aquifer storage in Germany and in Denmark. By assuming no onshore aquifer storage (due to public opposition) the requirement for storage in the Utsira formation increases. For Germany the storage in Utsira will be 19.8, 79.2 and 108.2 Mt/ year and for Denmark the storage to Utsira will be 5.2, 25.5 and 24.7 Mt/ year in 2030, 2040 and 2050 respectively.

This shows that the storage in Utsira depends on the public acceptance of onshore storage in these countries. With no onshore aquifer storage in Denmark and Germany the total injection rate in the Utsira formation exceeds the maximum injection rate at 150 Mt $CO_2$ per year. This indicates that the Utsira formation could face a high demand for $CO_2$ storage in the case that onshore aquifer storage acceptance is low. Under these circumstances measures for the increased use of Utsira can be valuable.

*Table 5-2: 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** |

### 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 in 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 5-3 summarise 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 5-3: 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

Table 5-4 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 5-4: 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 Pan-European TIMES 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 5-5, 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 5-5: 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. The main difference is 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 liquiefied 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 is more energy and larger equipment required and degradation of suitable amine solvents is higher.

The $CO_2$ capture from the industry is 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 Pan-European TIMES 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 Pan-European 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 – $CO_2$ pipeline in the North Sea

Deliverable:

- *Possibilities, synergies and conflicts for a common $CO_2$ pipeline in the North Sea [19]*

The $CO_2$ pipeline in the North Sea is described in detail in deliverable [19]. Here the conclusions of the report are reproduced.

WP 2, 3 and 4 have 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. 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. In WP5, national and regional analyses will be conducted to identify potential barriers and synergies in terms of non-technical issues (e.g. policy, legislation, organization), particularly for the construction and operation of a trans-boundary pipeline network in the North Sea.

The deployment of a trans-boundary $CO_2$ offshore pipeline infrastructure will require the active participation and commitment of industry and national governments. Key potential synergies and barriers identified in the report are mentioned below.

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 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 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 wells and water production 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 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 CO2 targets.

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 $CO_2$ will 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).

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 storages. 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 technology. 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. A $CO_2$ transportation network needs governmental support, suitable domestic and international legislation and a financial plan.

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