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A Comparison of national CCS strategies for Northwest Europe, with a focus on the potential of common CO_2 storage at the Utsira formation

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Abstract

Mega structures for CO_2 storage, such as the Utsira formation in the North Sea, could theoretically supply CO_2 storage capacity for several countries for a period of several decades. Their use could increase the cost-effectiveness of CCS in a region while minimizing opposition from the public to CO_2 storage. However, this will not only depend on their potential available capacity to store CO_2 flows but also on the cost effectiveness of such an option within national portfolios of mitigation measures. This article shows key results of a research project aiming to assess the potentials and costs of storing CO_2 in the Utsira formation for the time period 2015-2050. Countries included in the analysis are Denmark, Germany, Norway, the Netherlands and the United Kingdom. The starting point of the analysis are the national MARKAL and TIMES models developed for each country together with the 27 region Pan European TIMES model (PET). In the models scenarios, assumptions and parameters that are not country dependent (e.g. costs related with CO_2 capture technology development) have been harmonized. The results indicate that with stringent climate targets, CCS appears as a key mitigation option in the national portfolio of measures. Within the CCS portfolio, storage of CO_2 in the Utsira formation can indeed be a cost effective option for North Europe and it represents a valuable CO_2 storage option at the regional level. For instance, the United Kingdom will profit from the comparably short transport distance to Utsira while 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 competitiveness of CO_2 storage in Utsira is determined by the availability of domestic onshore saline aquifers. If these aquifers are not used, Utsira gains as competitive storage option. The main limitation for the common use of the Utsira formation appears, from a modeling point of view, to be the maximum annual injection rate for CO_2 that has been assumed in the project (150 Mt CO_2/yr).

Keywords: CO_2 infrastructure; sink-source matching; Utsira formation

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1. Introduction

The role that mega-structures such as the Utsira formation could play for the large scale deployment of CCS in the North Sea region has gained 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 utilization of the reservoir in the range between 20 to 60 Gt [1]. The use of the Utsira field 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 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 article summarizes key findings of the FENCO ERA-NET project titled "Analysis of potentials and costs of storage of CO_2 in the Utsira aquifer in the North Sea". 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 included country specific characteristics in the analyses while harmonizing parameters and assumptions that are not country dependent (e.g. costs related with CO_2 capture technology development). The project had as sub-goals:

- 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.
- 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.
- 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.

In this article a brief overview of the methodology and key results for the national models are presented. A detailed analysis of these results as well as results of the regional model will be presented in a full article, which is under preparation.

2. Methodology

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. The starting point of the analysis are the national MARKAL and TIMES models developed by each of the national partners (Norway, Denmark, Germany, the Netherlands, United Kingdom), together with the 27+2 region Pan European TIMES model (PET). MARKAL is the acronym for MARKet Allocation while TIMES stands for The Integrated MARKAL/EFOM System. MARKAL and TIMES are integrated energy systems modeling platforms that can be tailored to analyze energy, economic and environmental issues at the global, national and municipal level over several decades. This modeling platform is currently used by over 100 modeling teams worldwide and has been heavily utilized for analytical insights for energy policy (e.g., [2], [3]).

All models were run under the latest (2008) fuel price data from the International Energy Agency's World Energy Outlook (WEO) [4]. As these projections encompass recent upwards movements, a sensitivity case was carried out on IEA WEO 2007 which had a lower set of fuel prices. Developments of import-export of electricity for each national model, were based on results provided by the PanEU-TIMES model, as this is an EU model covering regional electricity markets. For parameters such as final electricity demand, load curve of electricity, final heat demand, vintage structure of existing electricity generation, no harmonization attempt was made. Similarly, national policy and fiscal circumstances were kept model specific. Parameters related to efficiencies, learning rates, costs of mitigation technologies have been harmonized among the models (see Table 1).

Table 1. Costs and efficiencies of electricity production with and without CCS as implemented in the models

		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
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

To determine the costs for CO_2 transport and storage the following assumptions were made:

- CO_2 is transported by pipelines. Transport by ship, train or truck is not taken into account.
- CO_2 is transported in supercritical phase (>80 bar). Booster stations are included when distances are larger than 150 km in order to keep a maximum pressure drop of 30 bars.
- Calculations are based on pure CO_2 streams. Impurities could impact phase boundaries of the supercritical CO_2 streams and could affect pipeline requirements due to corrosive properties. Although it is expected that

captured CO_2 includes certain levels of impurities, these effects cannot be taken into account in this study as of limited data availability

- Existing wells and surface facilities such as gas production platforms can be reused for CO_2 injection if the depleted gas or oil field is available for CO_2 injection within two years of the abandonment date.

The cost of CO_2 transport varies with capacities, distances and terrain type. There are several costs equations available in the literature. In this study, investment costs have been estimated using equation 1 and 2 [3]. The investment costs of a 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. 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 while in other countries (e.g. Germany) the opposite situation exists. Figure 1 illustrates CO_2 transport costs by capacity and distance for alternate terrain factors.

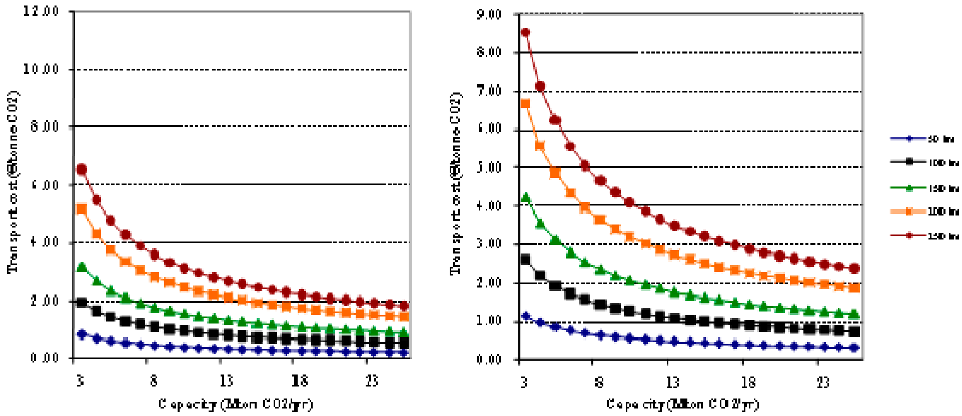

Figure 1: CO_2 transportation cost for different capacities and distances for Ft = 0.9 (left) and Ft = 1.2 (right).

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

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

Where, I = investment cost of (€), $Ft_{Land\ use}$ = 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).

Costs of storage are calculated independently in each national model. They are dependent on the storage location, potential storage capacity, injectivity rate, possibility to reuse infrastructure etc. Costs of CO_2 storage for the Utsira field were harmonized among the models. In this project conservative assumptions were used (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.

Finally, 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 (C-20 scenario), or a linear reduction of 80% by 2050 is imposed (C-80 scenario) based on the estimated CO_2 reduction required for developed countries to keep global temperature rise below 2 ºC. Sensitivity scenarios include the following:

- No CCS scenario.
- 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+2 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.

Table 3. 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. Results

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-80 scenario follows (see also Figure 2). Unless otherwise specified, the results presented are for energy prices from WEO 2008. The results showed here focus on the development of the power generation sector.

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. All of the CO_2 is stored in national fields (offshore aquifers). 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 and 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. In both cases (WEO 2007 and WEO 2008), a major trade-off is found 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 use of coal as a fuel effectively ends, with a reduction from 2169 PJ to a mere 4

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

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.

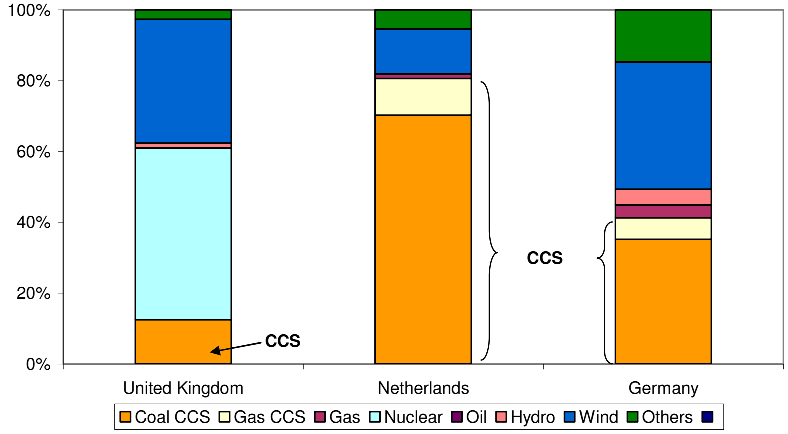

Figure 2. Electricity generation mix in 2050 for the C-80 scenario

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 about 80% in 2050 (70% coal/biomass and 10% gas). The total capacity of power generation with CCS is estimated at 34 GW. The amount of CO_2 to be stored is 145 Mt of CO_2 by 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). 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. This 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. 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. 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, the share of coal based electricity generation with CCS is up to 85% capturing 237 Mt CO_2 in 2050. When lower energy prices are assumed (WEO 2007), 159 Mt CO_2 is projected to be captured in 2050. In 2050, domestic saline aquifers and hydrocarbon fields are primarily used. The storage quantities in aquifers increase to a maximum of 243 Mt in 2050 in the C-80 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, 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 Netherlands increase leading to an increased use of Utsira via the Dutch pipeline system. In the case of assuming WEO 2007 prices, electricity generation changes from coal based CCS technologies to natural gas technologies. If CCS technologies are not 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 substitution 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, model results will be determined by 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 will most likely do not play a role at only, in the model results only 1 PJ of electricity will be produced by this type of plants and is unlikely that such a plant would be deployed (under WEO 2007 prices coal based power plants are not selected by the model). 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 Mt (10 if WEO 2007 energy prices are used). Most of the CO_2 is stored in national aquifers. However, a small amount (about 2 Mt/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.

Norway: Primary energy demand in this scenario is estimated at 1040 PJ in 2050. In addition to the CO_2 capture unit at the existing NGCC power plant, 3 Mt CO_2 are captured from the industrial sector in 2050 (1 Mt from cement production and 2 Mt from the refineries). 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. Final remarks

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 results of this research indicated that:

- With stringent climate targets, storage of CO_2 in the Utsira formation can be a cost effective option for North Europe and it represents a valuable CO_2 storage option at the regional level.
- The United Kingdom profits from the comparably short transport distance to Utsira. The Netherlands utilises the Utsira formation due to limited domestic low cost storage fields and because it acts 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 becomes a competitive storage option.
- In this study, the main limitation for the Utsira formation appears to be the maximum annual injection rate for CO_2. This is a stronger limitation than the total storage capacity. The literature shows simulation results

of CO_2 injection up to 150 Mt per year in Utsira by using many storage wells while at the same time water production wells are 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 price development of oil, natural gas and coal influences the role of CCS in the energy system. With lower energy prices, more CO_2 is captured in the United Kingdom, 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. Lower energy prices increase the total amount of CO_2 injected into the Utsira formation.

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