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CCS in the North Sea region: A comparison on the cost-effectiveness of storing CO_2 in the Utsira formation at regional and national scales

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ABSTRACT

The potential scale of carbon dioxide capture and storage (CCS) under long-term decarbonisation scenarios means that analysis on the contribution of large international CO_2 storage reservoirs is critical. This paper compares the potentially key role of CCS within cost-optimizing energy systems modelling at the national level (ensuring country-specific technical, economic and policy detail), and the regional level (ensuring transboundary electricity and CO_2 trade). Analysis at alternate model scales investigates the full range of drivers on the feasibility and trade-offs in using the Utsira formation as a common North Sea CO_2 storage resource. A robust finding is that low carbon electricity is a primary decarbonisation pathway and that CCS plays a key role (32–40%) within this portfolio. This paper confirms that the overall driver of the amount of CCS utilized is the climate policy, with by 2050 a total of 475–570 $MtCO_2$ captured and stored (of which 110–120 $MtCO_2$ is stored in Utsira) under an 80% CO_2 reduction target. Modelled country differences are much larger due to specific national policies and to regional (EU) commodity trading. From 2030 onwards, Utsira plays a key role within the CO_2 storage cost curve, with the Netherlands and the UK being the largest contributors, followed by transboundary flows of CO_2 from other countries. However, overall regional CCS flows may be larger (for example under low fossil fuel prices) than the estimated (and uncertain) maximum annual injection rates into Utsira which could potentially represent a significant constraint.

1. Introduction

For the European Union (EU) as a whole, two key goals of energy policy[1] are climate change mitigation and energy supply security. Carbon dioxide capture and storage (CCS) is one of the options to respond to these policy objectives, via the reductions in carbon dioxide (CO_2) emissions from the power and industrial sectors, which could enable the use of fossil fuels – including domestic reserves of coal and natural gas – within a low carbon energy portfolio. In terms of climate change mitigation, the current EU target of a 20% reduction in CO_2 and other greenhouse gases (GHGs) below 1990 levels by 2020 has been supplemented by a 60–80% reduction target in GHGs by 2050, in line with the EU objective to limit anthropogenic global climate change to 2 °C above pre-industrial levels, via long term stabilization of atmospheric levels of GHGs at around 450 ppm(v) CO_2 equivalent (EC, 2007).

CCS has received considerable attention as a key CO_2 emissions mitigation option under stringent climate policy. The International Energy Agency's (IEA) most recent Energy Technology Perspectives report (IEA, 2010) clearly indicates that without climate policy (base scenario) CCS technologies will not be implemented, but with different climate policies (e.g. 450 ppm CO_2e, 550 ppm CO_2e, Hi-renewables, Hi-nuclear) will result on significant differences in the penetration rate of CCS. van Alphen et al. (2010), compares the development of CCS in 5 countries (Netherlands, Norway, US, Canada and Australia), and concludes that without overarching long-term climate policies, CCS deployment at the national scale will not be successful. Baker et al. (2009) shows how advances in CCS show minimal impact on emissions reductions in the absence of climate policy (i.e. a carbon price), while Bosetti et al. (2009),

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[1] Competitive markets, and equitable access to energy services (fuel poverty) are further energy policy goals.

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confirm that the degree and speed of CCS penetration in the world power generation mix is dependent on the climate targets established (e.g. no policy, 450 ppm, 550 ppm).

The deployment of CCS will require an efficient and cost-effective CO_2 pipeline, or network of pipelines, connecting significant sources of CO_2 with potential CO_2 sinks. Three types of sinks are considered as having the largest potential for CO_2 storage: deep saline formations (aquifers), depleted oil fields and gas fields (IPCC, 2005). They will most likely play different roles in the (possible) development of a CO_2 infrastructure; due to differences in costs, capacity, time availability, etc. There is greater geological uncertainty over the potential to store CO_2 in saline aquifers (compared to depleted oil and gas fields). To date saline aquifers have not been well characterized geologically because of their limited economic value. Nonetheless, they are regarded as a key part of CCS deployment because: (i) they are widely distributed around the globe; (ii) they commonly have very large pore volumes; and (iii) they have been used successfully for natural gas storage onshore and CO_2 storage offshore, e.g. at the Sleipner field in the Utsira formation (Norwegian sector) (IPCC, 2005; Bachu and Adams, 2003; Haszeldine, 2006).

Different storage reservoirs are heterogeneous (in their physical characteristics, size, location, etc.) and this will impact how and when they are utilized. Keating et al. (2011) assesses the impact of reservoir uncertainty (parameters such as permeability, porosity, formation thickness) and conclude that reservoir uncertainty is a major driver of the entire CCS infrastructure system. This finding is echoed in other studies (Ambrose et al., 2008). Ramirez et al. (2010), explored the differences in availability-time, costs and capacities of the storage fields in the Netherlands, while CO2Europipe (2010), undertakes a similar study for Europe.

In fact, studies of trans-boundary transport crossing the North Sea have indicated that common use of North Sea geological aquifers, such as the Utsira formation, may be indispensable when large amounts of CO_2 need to be stored in the region (e.g., Markussen et al., 2002; Damen et al., 2009; Broek et al., 2010a). In addition to its potential large storage capacity (estimated at about 42 $GtCO_2$ (Bøe et al., 2002)), its access to a number of countries could increase the cost-effectiveness of CCS in the region. Nevertheless, these studies also recognize that there is a considerable lack of knowledge on how and at what costs CO_2 storage at the Utsira formation could be cost-effectively tuned to the development of national energy supply systems in the countries and as part of a regional strategy in the North Sea region. Prior studies (Mendelevitch et al., 2010; Morbee et al., 2010), have investigated a trans-European CO_2 network. More specifically, a previous technical report (IEA-GHG, 2005) covers a number of the same issues as this paper for a North Sea regional CCS strategy, but excluded large aquifers with large potential CO_2 storage (such as Utsira), matched CO_2 sources and sinks at lowest cost but without the use of a dynamic systems model, only focused on transport and storage costs but with no capture cost, only considered current point sources of CO_2 (but no future projections of CO_2 producing sectors), and had no optimization (as no projections) in the context of comparison to other mitigation options. This paper addresses these weaknesses in evaluating a North Sea CCS strategy and compares findings at a national and regional level. This is at the core of this article.

Exporting CO_2 to Utsira would require the deployment of a large (and costly) CO_2 infrastructure. The development of such a network will be driven by the role of CCS in each country, costs and availability of local storage. Until now, most European energy (or just electricity) system studies dealing with the development of CCS as a part of the portfolio of mitigation measures either take a regional (e.g., Odenberger and Johnsson, 2010; Uyterlinde et al., 2006), or a national perspective (e.g., Kemp and Kasim, 2008; Martinsen et al., 2007). In the first case, most studies fail to include specific local technical, economic, political or physical constraints, making it difficult for local stakeholders and policy makers to interpret the significance of the results. In the second case, the development of the national energy systems (including CCS) are mostly optimized for local conditions disregarding the influence of developments taken place outside the national frontiers. In comparison to these cases as well as the studies cited earlier, an assessment of the cost-effectiveness of storage of external CO_2 storage options such as Utsira as *both* part of national *and* regional strategies will provide further insights into the feasibility of this option.

The aim of this study is to investigate the role of CCS – and specifically shared regional North Sea storage resources such as the Utsira formation in long-term decarbonisation pathways at the national and regional level. The paper focuses on countries in the North Sea region (Denmark, Germany, Netherlands, Norway and the UK) and examines the time period 2010–2050. The specific research questions are:

- What is the potential role of the Utsira formation as a common CO_2 storage resource for the countries in the North Sea region?
- Does this role change from a national or regional modelling perspective on decarbonisation pathways?
- Will the capacity of Utsira (cumulative and per year) be sufficient over time according to the national and regional models?
- Would different network layouts influence the cost and deployment of CCS and Utsira in the region?

This paper hence focuses on the innovative use of national and regional energy systems models to investigate the economic feasibility and range of trade-offs in using the Utsira formation as a large common North Sea resource for CCS. The layout of this paper is as follows: Section 2 summarizes methods, including the partial harmonization of the national and regional models, together with common (and sensitivity) scenarios undertaken. Section 3 presents core decarbonisation scenario results from the national MARKAL/TIMES models for the countries bordering the North Sea (United Kingdom (UK), the Netherlands, Germany, Denmark and Norway) and from the regional Pan European TIMES (TIMES PanEU) model, with Section 4 presenting sensitivity scenarios. Section 5 presents a discussion on the results obtained, while Section 6 presents conclusions for the role of North Sea CO_2 storage resources within national and regional decarbonisation pathways.

2. Methodology

2.1. Modelling approach

The starting point of this analysis is the three national techno-economic linear optimization MARKAL (MARket Allocation) models that are developed for the Netherlands, Norway and the UK. In addition, the regional Pan European TIMES (The Integrated MARKAL/EFOM System) model (see Blesl et al., 2010), that includes all member states of the EU-27 plus Norway, Iceland and Switzerland, was used for the region as a whole and for Germany and Denmark with national boundaries. MARKAL and TIMES are integrated energy systems modelling platforms that can be tailored to analyze energy, economic and environmental issues at the global, national and municipal level over several decades. These modelling platforms are currently used by over 100 modelling teams worldwide and have been heavily utilized for analytical insights for energy policy (e.g., Loulou et al., 2009; Strachan et al., 2009; Chen, 2005; Smekens, 2004). MARKAL and TIMES are partial economic equilibrium models formulated as linear optimization problems (Loulou et al., 2004). MARKAL/TIMES computes energy balances

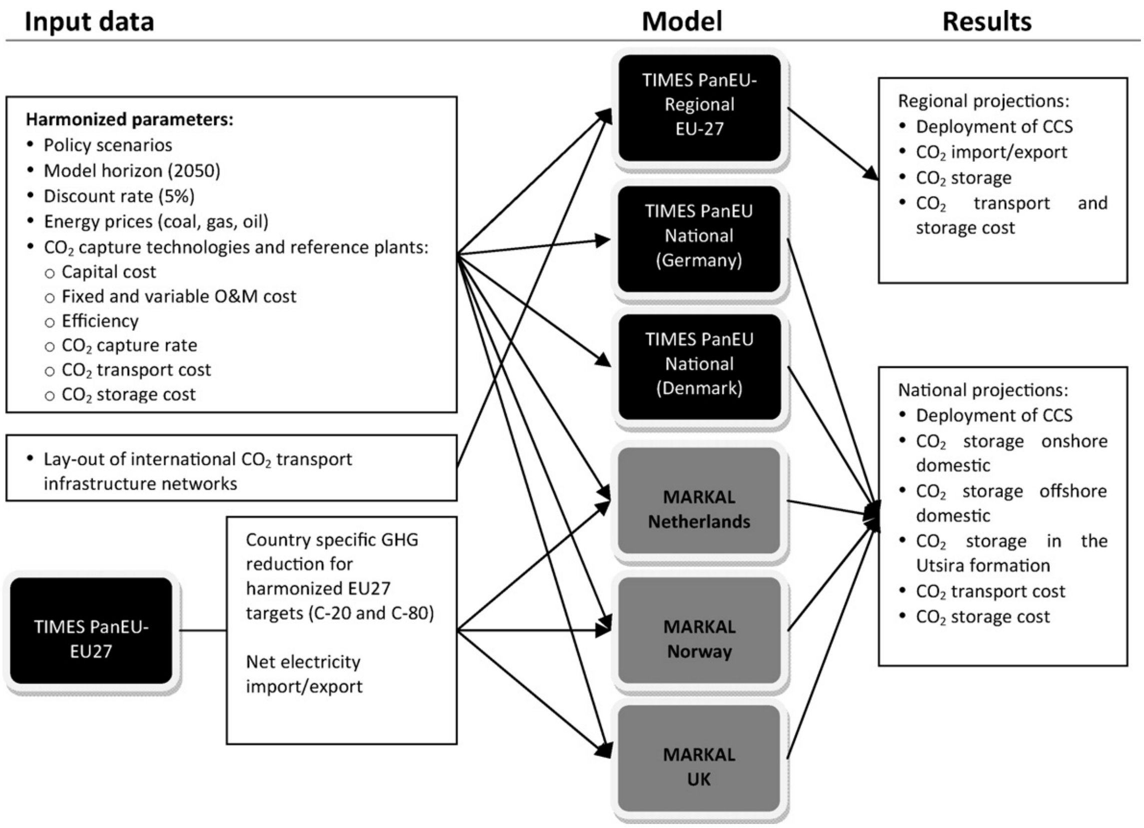

Fig. 1. Schematic diagram of the modelling approach.

at all levels of an energy system: primary resources, secondary fuels, final energy, and energy services. The models aim to supply energy services at minimum global cost by simultaneously making technology investment and operating decisions, primary energy resource supply decisions, and behaviour change (by region as required). They calculate the technological configuration of an energy system by minimising the net present value of all energy system costs. Linear programming bases its decisions on 'perfect foresight', which means that the model can 'look ahead' to the end of the model period to find the least-cost energy configuration over the whole period, which in this study is in 5-year time steps from 2010 to 2050.

The input parameters of the MARKAL and TIMES models used were harmonized for parameters that directly impact the potential of CCS technologies (Section 2.2). Fig. 1 depicts the overall modelling approach of this study. We have harmonized a wide range of inputs assumptions, as well as the scenarios that all models ran (Section 2.5). Some harmonized parameters come from external sources as discussed, and others come from the regional model itself. However there is a trade-off in further harmonization efforts as due to level of detail on the policy landscape and/or in the depiction of behavioural change that are specific to the national models; or at the other end of the spectrum, the issues related to flows of energy and emissions around the target countries (and other EU countries) that is the domain of the regional model. In striking this balance, we have tried to retain the strengths of both modelling approaches.

2.2. Harmonized parameters

Table 1 summarizes the partial harmonization process between the models, designed to facilitate comparability, while retaining

Table 1
Key model parameters and harmonization.

Parameter	Harmonized	Country/model specific
Model horizon (to 2050)	√[a]	
Discount rate (5%)	√[a]	
Energy prices	√[a]	
Final electricity demand		√
Trade of electricity (from TIMES PanEU model)	√[a]	
Load curve of electricity		√
Vintage structure of electricity portfolio	√[b]	
Final heat demand		√
Other CO_2 mitigation options (including behavioural change)		√
Policy scenarios	√[a]	
CO_2 capture technologies and reference plants		
Type	√[b]	
Capital costs	√[b]	
Variable O&M costs	√[b]	
Fixed variable O&M costs	√[b]	
Efficiency	√[b]	
CO_2 capture rate	√[a]	
CO_2 sources considered for capture		√[c]
CO_2 transport costs	√[a]	
CO_2 storage potential and costs for storage in Utsira	√[d]	
CO_2 storage costs[a]		√[d]

[a] Full harmonization.
[b] Harmonized to the reference values (Table 9, Appendix A) only for parameters for which the divergence was significant.
[c] A list of CO_2 sources considered in the models is depicted in Table 3.
[d] CO_2 storage costs and potentials in the models are summarized in Table 4.

Table 2
Development of fossil fuel prices for two different scenarios (€2007/GJ).

		2000	2005	2010	2015	2020	2025	2030	2040	2050
WEO 2008 (HP: high fossil fuel price scenario)[a]										
Oil	€/GJ	4.5	7.5	13.4	13.4	14.7	15.5	16.4	18.1	20
Natural gas	€/GJ	2.4	4.1	8.1	8.4	9.3	9.8	10.3	11.7	13.2
Coal	€/GJ	1.3	2	3.9	3.9	3.8	3.6	3.5	3.4	3.2
WEO 2007 (LP: low fossil fuel price scenario)[a]										
Oil	€/GJ	4.5	7.6	8.1	7.9	8.1	8.3	8.5	8.7	8.9
Natural gas	€/GJ	2.4	4.8	4.9	4.9	5.1	5.3	5.5	5.8	6.1
Coal	€/GJ	1.3	1.9	1.8	1.9	1.9	2	2	2.1	2.2

[a] 1 USD_{2007} = 0.77 $€_{2007}$.

the individual detail for each model. The model horizon, discount rate, energy prices (Table 2) were fully harmonized amongst the models included in this article. The discount rate used (5%) represents a trade-off between a pure social discount rate and a higher commercial rate of return. Electricity trade (import/export) in the national MARKAL models were harmonized with the projections of the TIMES PanEU model as an EU model covering price differential and physical interconnector capacity in regional electricity markets. This is implemented as a fixed or upper bound constraint in the national models.

Cost and efficiency data of power plants with CCS and the fossil fuel reference plants included in the models were harmonized if the divergence to the reference data was significant. A full comparison of the data used by the different models and reported in the literature can be found in Hoefnagels and Ramirez (2010). The reference data is summarized in Table 9 (Appendix A).

2.2.1. Fossil fuel prices

For energy prices, the core assumption follows the forecast to 2030 provided by the International Energy Agency (IEA) World Energy Outlook (WEO) 2008, and reflect substantial rises in the price of oil, natural gas and coal. Lower energy prices according to WEO 2007 are included as a sensitivity in national model runs. Fossil fuel prices are extrapolated from 2030 to 2050. The coal, oil and natural gas price trends used for both cases are shown in Table 2.

Similar fossil fuel prices are used for climate constrained runs (see Section 2.5). In terms of how endogenous fuel prices would be to the climate policy, this depends on legislated CO_2 targets for non-OECD countries, as well as the overall use of coal and other fossil fuels (i.e. conventional vs. CCS) in a climate constrained world. Because of these uncertainties, and as we are focusing on the role of CCS rather than on price responses to climate targets, we are using the same fuel prices in different climate regimes. We also note that the paper has a sensitivity of overall lower fossil fuel prices (see Table 2).

2.3. CO_2 sources

Table 3 depicts the CO_2 sources from power generation and industries available for CO_2 capture in the TIMES PanEU and national models. The sources for Germany and Denmark are similar to the regional TIMES PanEU model because they use the same model. Post-combustion and pre-combustion CO_2 capture is available in all models, but the Norwegian model is limited to gas fired power plants. Note that CO_2 capture from steam methane reforming (SMR) is available in all models for hydrogen production, but includes co-generation of electricity in the Norwegian model and is therefore listed with the CO_2 capture options from power plants. Oxyfuel (coal and gas) CO_2 capture is only available in the TIMES PanEU model.

All models also include a range of industrial sources available for CO_2 capture of which hydrogen production is available in all models. Hydrogen is currently mainly used for chemical processes, but the future demand might potentially increase from other users such as hydrogen fuelled vehicles. The future hydrogen demand in the Dutch model is based on current users of hydrogen and industrial sector projections. This might result in an underestimation of the CO_2 capture potential from hydrogen production compared to the other models.

2.4. CO_2 transport and storage

2.4.1. Domestic transport and storage

The cost of CO_2 transport was estimated using a harmonized approach. As point of departure, the following assumptions were made:

- All CO_2 is transported by pipeline. Transport by ship or truck is not considered.
- CO_2 is transported in supercritical phase through pipelines (>80 bar). For distances larger than 150 km, booster stations are included to prevent pressure drops below 80 bar and related phase changes.
- Calculations are based on pure CO_2 streams. Even though impurities could impact thermodynamic properties of the CO_2 stream and could affect pipeline requirements, this is not considered in this research.

Several studies have addressed the potential benefits of economies of scale for CO_2 pipeline networks. For instance, Kuby

Table 3
CO_2 sources available in the TIMES PanEU and national models.

	TIMES PanEU model[a]	Netherlands	Norway	UK
CO_2 capture from power plants				
Coal, post combustion capture (amine)	X	X[b]		X
Coal, oxyfuelling	X			
Coal, pre-combustion capture (IGCC)	X	X[b]		X
Gas, post combustion capture (amine)	X	X[b]	X	X
Gas, oxyfuelling	X			
Gas, pre-combustion capture (SMR, $GTCC_{H2}$)			X	
CO_2 capture from industries				
Cement production	X	X	X	
Ammonia production	X	X		X
Hydrogen production	X	X	X	X
Iron and steel	X	X		
Refinery/chemical industry		X	X	
Ethylene (oxide) production		X		

[a] Used for the regional projections and the national projections of Germany and Denmark.
[b] Including retrofit.

Table 4
Technical and economic parameters for CO_2 transport to the Utsira formation.

Model	Country	Distance to Utsira[a] (km)	Booster stations	Pipeline diameter (m)	Terrain factor	CO_2 flow rate ($MtCO_2$/yr)	Trans-port cost (€/t CO_2)	Storage cost[e] (€/t CO_2)
National models	Netherlands	750–890	1[b]	1.22	N/A[c]	60	3.8	2.1
	Norway	170	1	0.24	1.2	1	2.5	2.2
	UK	730	5	0.78	0.9[d]	20–40	4.6	2.4
TIMES PanEU model	Denmark	493–618				10–15	3.4–5.3	3.9
	Germany	638–884				20–30	3.9–6.3	3.9
	Netherlands	624–695				20–30	3.8–5.3	3.9
	Norway	238				10	2.2	3.9
	UK	229–790				20–25	1.4–5.3	3.9

[a] The distance depends on the location of the landfall and the network route selected.
[b] The approach for the Netherlands is different from the other models. Only one booster station was assumed at the start of the pipeline. A dedicated model was used to calculate the required pressure at the inlet of the pipeline to keep pressure above 80 bar at the end of the pipeline. The pumping pressure was calculated to be 120–130 bar for the 60 $MtCO_2$/yr pipeline (Broek et al., 2010a).
[c] The offshore pipeline costs to Utsira formation for the Dutch model are calculated with a dedicated model based on oil and gas pipeline costs (Broek et al., 2010b).
[d] This represents offshore transport only (originating from the east coast of the UK).
[e] Based on a methodology from Broek et al. (2010a), the national models all have the same storage costs within currency price fluctuations, but the EU regional model use a supplemental cost values to represent the uncertainties in costs of higher amounts of CO_2 storage.

et al. (2011), use a case study of the Midwest USA and the SimCCS model (based on GIS) to compare the economic benefits of networks against dedicated pipelines. Their results indicate that for systems involving more than one source–sink, total costs average 6.5% lower for networked systems than for direct systems (savings on 2% source costs, 34% on transport costs and 22% on sink costs). Similarly, earlier studies using the SimCCS model (Middleton and Bielicki, 2009; Bielicki, 2008) find significant savings due to economies of scale are although these returns to scale are not continually constant as the system expands. Chandel et al. (2010) also examined the potential of economies of scale for some case studies in the USA, and report significant savings (in the order of 34%) if trunk line based networks are built instead of dedicated lines. The savings are not only due to economies of scale in the pipeline itself but also to a decrease on the number of required booster stations with increasing diameter (and carrying capacity of the pipeline). Furthermore, besides cost–benefit improvements, investing in integrated networks could catalyze the large scale deployment CCS technologies by consolidating permitting procedures, reducing the cost of connecting CO_2 sources with sinks and ensuring that captured CO_2 can be stored as soon as the capture facility becomes operational (Morbee et al., 2010).

Hence similar to Broek et al. (2010a), a hub and spoke network was considered to be used to transport CO_2 from the capture sources via satellite pipelines to regional centres. Large trunk lines are used to transport CO_2 to the sink region to reduce costs by economies of scale. Smaller satellite pipelines are used transport CO_2 from the sink region to the sinks (Fig. 2).

The cost of CO_2 transport varies with capacities, distances and terrain and has been estimated using Eqs. (1) and (2) (Broek et al., 2010a, 2010b):

$$I = Ft_{Land\,use} \times C \times D \times L \tag{1}$$

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

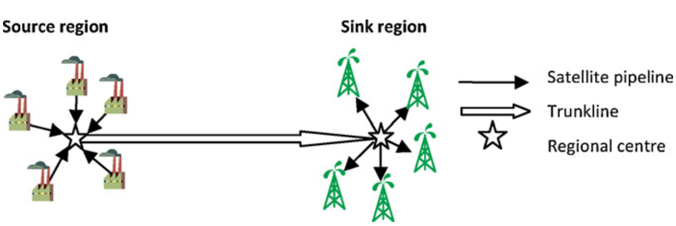

Fig. 2. CO_2 transport system (Broek et al., 2010b).

where I is the investment cost (€), $Ft_{Land\,use}$ the terrain factors for different land use types, C the constant factor (1600 €/m^2), D the diameter pipeline (m), L the length pipeline (m), λ the friction factor (0.015), M the mass flow of CO_2 (kg/s), ρ the CO_2 density (800 kg/M^3), and ΔP the pressure drop (3×10^6 Pa). For pipelines longer than 150 km, a booster station is required to reduce the pressure drop to 3 MPa (30 bar). Finally, it is important to note that the terrain factor in Eq. (1) can vary from country to country as shown in Table 4.

2.4.2. Transport and storage to the Utsira formation

For this study, the TIMES PanEU model (also used to model Denmark and Germany) and the national MARKAL models of the UK and Norway have been extended with the option to transport CO_2 offshore to the Utsira formation. Table 4 depicts the technical and economic parameters used for transport and storage of CO_2 in the Utsira formation used in these national models and the regional TIMES PanEU model. For the Dutch MARKAL model, an alternative approach was applied: a single booster station onshore or near shore at the landfall[2] of the CO_2 pipeline was assumed to be applied. Here, CO_2 is pressurized to the level that CO_2 will still leave the pipeline above 80 bar at the Utsira sink. To calculate the required pressure, a dedicated physical model was used. For additional information see Broek et al. (2010b).

For the connection of the regional CO_2 source hubs to the Utsira formation, the analysis at the regional level (using the TIMES PanEU model) considered three different network lay-outs (Fig. 3). The first layout (Network I), represents individual network connections between each landfall and country and the Utsira formation. This Network does not advantage from economies of scale. Single pipelines are dimensioned relatively small and are often not operated at full load.[3] Network II includes a single trunk line from the UK to Utsira whereas the Netherlands and Denmark share a trunk line. Note that since Germany can also export CO_2 to Denmark via an onshore network in the TIMES PanEU model as it is indirectly connected to the Utsira sink. Network III is characterized by a trunk

[2] A landfall is a location where offshore and onshore pipelines can be connected. In the case of the Netherlands, there are currently only 5 landfall locations. New location could be chosen in the future, but governments tend to encourage the use of current ones.
[3] It may be more cost effective to build a larger pipeline that will not be used at full load in the beginning than building multiple pipelines when demand increases (Broek et al., 2010b).

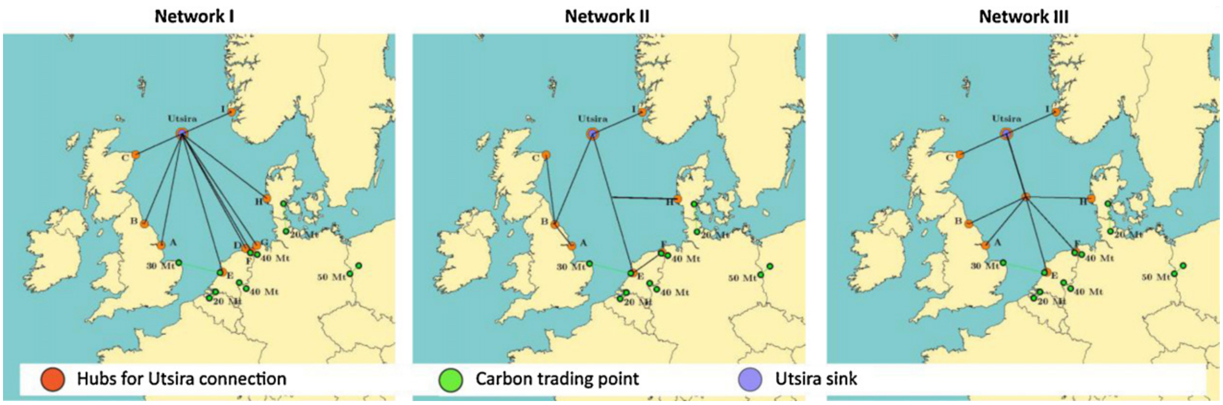

Fig. 3. North Sea network options for CO_2 transport to Utsira in the TIMES PanEU model.

Table 5
North Sea CO_2 network infrastructure options in the TIMES PanEU model.

Hub	Landfall location	Massflow per pipeline (Mt/a)		Network layout I			Network layout II			Network layout III		
		CAP+	CAP−	Dist. to Utsira (km)	Transport costs (€/t CO_2)		Dist. to Utsira (km)	Transport costs (€/t CO_2)		Dist. to Utsira (km)	Transport costs (€/t CO_2)	
					CAP+	CAP−		CAP+	CAP−		CAP+	CAP−
A	Easington (UK)	25	20	539	3.5	3.9	594	3.4	3.9	615	3.6	3.8
B	Teesside (UK)	25	20	458	2.9	3.3	458	2.9	3.3	611	3.5	3.8
C	St. Fergus (UK)	25	20	229	1.2	1.4	790	4.7	5.3	229	1.2	1.4
D	Eemsmond NL	30	20	624	3.8	4.8						
E	IJmond (NL)	30	20	695	4.3	5.3	695	4.3	5.3	695	3.9	4.5
F	Emden (DE)	30	20	655	4	5	884	5.2	6.3	676	4.2	4.2
G	Dornum (DE)	30	20	638	3.9	4.9						
H	Nybro (DK)	15	10	493	4.2	5.3	493	4.3	5	618	3.4	3.9
I	Karsto (NO)	10	10	238	2.2	2.2	238	2.2	2.2	238	2.2	2.2

pipeline from the Utsira formation to the boundaries of the Norwegian exclusive economic zone. Here, individual sub pipelines connect the landfall hubs to the Utsira trunk line. In all network options, a direct pipeline of Norway to the Utsira formation was assumed. The base case in this study uses Network I. To assess the influence of different lay outs in the results, sensitivity analysis were done using Networks II and III with high (CAP+) and low (CAP−) pipeline capacities (Table 5).

Based on the cost and experiences with the current injection well at Sleipner in the Utsira formation and the work of Lindeberg et al. (2009), the maximum storage capacity for the formation is assumed to be 42 $GtCO_2$ (Bøe et al., 2002) with a maximum annual injection rate of 150 $MtCO_2$. This equates to using approximately 100 injectors (and 100 water producers to control pressure and ensure storage integrity) (Lindeberg et al., 2009) over a time span of 300 years (see Wangen, 2009 for full derivation). Note that there is no mismatch in assumptions between Utsira's potential storage and other aquifers (e.g., the UK continental shelf) as national data on engineering derived data on storage has been checked against the detailed reservoir database in the physical Dutch model (Broek et al., 2010a). In addition a higher Utsira storage sensitivity case was run in the national models as detailed in Table 6.

Table 6
Assumed maximum cumulative and annual CO_2 storage at the Utsira formation.

Scenario	Cumulative storage ($GtCO_2$)	Annual storage ($MtCO_2$)
Standard Utsira case	42	150
High Utsira sensitivity case	100	500

Bøe et al. (2002) and Wangen (2009).

2.5. Policy scenarios

This study focuses on two core policy scenarios using standard fossil fuel price assumptions (HP):

- *C-20 scenario*: a 20% reduction (from 1990 levels) in 2020 (which follows the EU mitigation target), this target is then maintained through 2050. It is considered to represent a lenient climate policy.
- *C-80 scenario*: a 20% reduction (from 1990 levels) in 2020, then a linear reduction to −80% by 2050. This is considered to represent a stringent climate policy.

These two core CO_2 scenarios are based on reduction at the EU27+ level (EU, plus Switzerland, Iceland and Norway). This implies that a cost-optimal solution will result in a distribution of mitigation effort across countries in the EU region. CO_2 reduction targets are then applied to the national models by using outcomes of the TIMES PanEU model, with expected difference in effort (and costs) of CO_2 reductions compared to targets set at the individual country level.

Finally, a set of sensitivity scenarios were conducted to assess the robustness of the results:

- LP: Lower fossil fuel prices (WEO, 2007). Only for the national models.
- No CCS scenario. Only for the national models.
- High Utsira capacity, with a maximum injection rate at 500 $MtCO_2$ per year and a total storage capacity of 100 $GtCO_2$ (Table 6). Only for the national models.
- No storage onshore. For the Danish, German and regional models.

- Alternate North Sea CCS network layouts. Only for the regional TIMES PanEU model.

2.5.1. Country specific CO_2 reduction

To harmonize the country specific CO_2 mitigation targets and electricity trade, scenario runs for the C-20 and C-80 scenarios have been made by the TIMES PanEU model. The country specific results of these projections have been integrated in the national models. However, CO_2 emission reductions differ per country as this regional model optimizes the reduction of CO_2 for the EU-27 as a whole. This is because TIMES PanEU includes transboundary CO_2 transport from additional countries and hence the results of the TIMES PanEU model deviate from the projections used as input to the national models.

Furthermore, supranational policy scenarios for CO_2 reduction were applied to the TIMES PanEU model. The policy scenarios for CO_2 reduction targets were applied for the EU-27 as a whole. Country specific reduction targets were calculated with the TIMES PanEU model based on cost effectiveness. This implies that countries with the lowest marginal mitigation costs of CO_2 will have higher country specific reduction targets than countries with relatively higher marginal mitigation costs. The results for net CO_2 reductions and net electricity imports/exports for the Netherlands, Norway and the UK were exogenously applied to the MARKAL models to improve consistency between the regional projections and the national model projections.

3. Results

This section summarizes national analyses of long term CCS scenarios using the MARKAL and TIMES PanEU models for the UK, Netherlands, Germany, Denmark and Norway. This section includes the results on an aggregated regional level to show the difference between the national and regional models for CCS deployment and the use of Utsira as a (common) CO_2 storage resource. The models and full results are discussed in detail in Strachan (2009), Hoefnagels et al. (2009), Kober and Blesl (2010a), Grohnheit (2010), and Seljom (2009) respectively. It is important to note that optimization at a regional scale can give configurations that go beyond a national energy systems – for example in excess offshore wind capacity in Denmark's territorial waters to serve German markets.

Results focus on the role of CCS in the electricity generation mix, as well as the storage options for CCS, as these metrics allow focus on the evolution of the energy system. Full model outputs are given in detailed tables with national model results (Tables 10 and 11) and regional model results (Table 12) presented in Appendix B.

3.1. Energy system and CCS

Fig. 4 depicts the development of the electricity generation mix as projected by the national models and the TIMES PanEU model. Fig. 5 focuses on generation from CCS plant. The C-20 scenario was not modelled with the TIMES PanEU model as it proved to be of irrelevance concerning CO_2 storage in the Utsira formation (Kober and Blesl, 2010b).

C-20 scenario

- Total electricity generated in the North Sea region is projected to increase by 21% from 4431 PJ in 2010 to 5350 PJ in 2050. Main growth of electricity generation is projected in the Netherlands (36%), Norway (42%) and Denmark (115%) whereas electricity generation in the UK (18%) and Germany (5%) remains relatively stable over the projected period.
- The share of fossil fuel generating plants (coal and natural gas) decreases from 55% in 2010 to 44% in 2050, especially seen in the sharp decline of overall generation from natural gas fired plants. Natural gas plants are still heavily utilized for peaking electricity production. This relates to the assumed high cost of natural gas, and as from a systems perspective there is an emphasis on early CO_2 reductions in the power sector vs. more intractable sectors (e.g. transport). The generation from renewable technologies grows strongly (to 42%) in 2050.
- New power plants with CCS are projected to be commissioned from 2020 onwards (107 PJ in 2020) and the total share of electricity generation from power plants with CCS increases to 6% in 2050 (323 PJ). CCS units are all coal fired.
- Power with CCS is projected to be generated in Germany (34% in 2050) and the Netherlands (66% in 2050).

C-80 scenario (national models and TIMES PanEU model)

- In the C-80 scenario, electricity generation is projected to increase from 4408 PJ in 2010 to 6946 PJ in 2050 (national models). TIMES PanEU model projections deviate slightly from national models with 4656 PJ in 2010 and 6784 PJ in 2050. This additional (low carbon) electricity meets a variety of end-use applications in industry, buildings (heat pumps, electric boilers and appliances), as well as electricity vehicles in various transport modes.
- In both the national model projections and the TIMES PanEU model projections, the share of carbon mitigation technologies for electricity generation increases to meet the 80% reduction target. The share of renewables increases from 24% in 2010 to 49% (national models) and 53% (TIMES PanEU model) in 2050.
- The share of fossil fuel generating plants decreases from about 57% in 2010 to 34% (national models) and 41% (TIMES PanEU model) in 2050. 95% of the fossil fuel generating plants are equipped with CO_2 capture and in both the national and TIMES

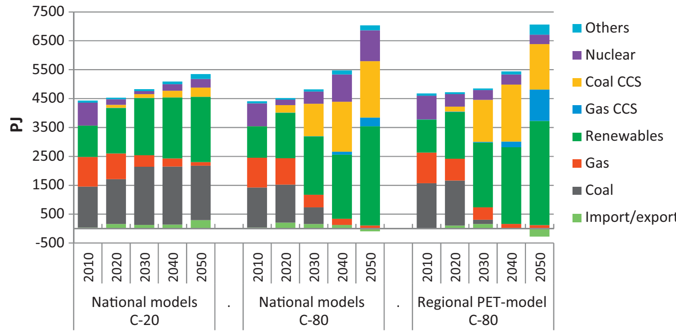

Fig. 4. Total electricity generation (PJ) in the C-20 and C-80 scenarios of the national models and the C-80 scenario of the TIMES PanEU model for the DE, DK, NL, NO and the UK.

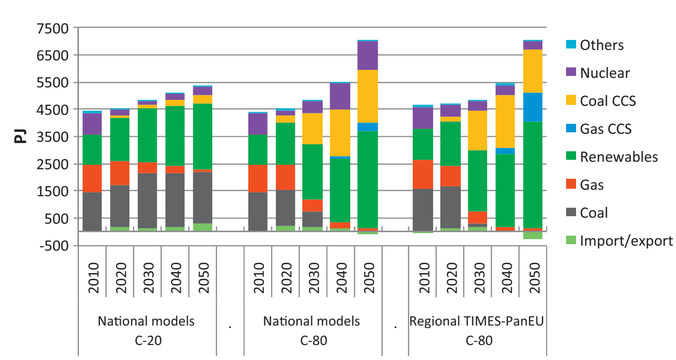

Fig. 5. Electricity generation from CCS power plants (PJ) in the C-20 and C-80 scenarios of the national models and the C-80 scenario of the TIMES PanEU-model for the DE, DK, NL, NO and the UK.

Table 7
CO_2 capture transport and storage in the C-20 and C-80 scenarios.

	C-20 National models				C-80 National models				C-80 TIMES PanEU model			
	2020	2030	2040	2050	2020	2030	2040	2050	2020	2030	2040	2050
Netherlands												
Net import[a]	0	0	0	0	0	0	0	0	8	29	60	0
Domestic capture	2	10	44	75	11	46	69	145	4	44	60	98
Domestic storage	2	10	44	60	11	46	66	39	12	69	85	56
Export to Utsira	0	0	0	15	0	0	2	105	0	5	34	41
Norway												
Net import[a,b]	0	0	0	0	0	0	0	0	0	0	0	0
Domestic capture	1	1	0	0	1	1	0	3	2	9	2	2
Domestic storage	0	0	0	0	0	0	0	0	0	0	0	0
Export to Utsira	1	1	0	0	1	1	0	3	2	9	2	2
Germany												
Net import[a]	0	0	0	0	−2	−26	−58	4	−4	2	−10	32
Domestic capture	17	15	16	22	51	164	285	264	27	179	286	288
Domestic storage	17	15	16	22	49	138	228	268	23	182	277	320
Export to Utsira	0	0	0	0	0	0	0	0	0	0	0	0
Denmark												
Net import[a]	1	2	2	0	1	1	4	20	0	0	20	20
Domestic capture	1	1	1	0	1	1	4	9	2	10	14	10
Domestic storage	2	3	3	0	2	2	8	28	2	10	34	30
Export to Utsira	0	0	0	0	0	0	0	1	0	0	0	0
United Kingdom												
Net import[a]	0	0	0	0	0	0	0	0	0	0	0	18
Domestic capture	0	0	0	0	0	38	38	53	17	108	152	172
Domestic storage	0	0	0	0	0	38	38	53	17	96	95	116
Export to Utsira	0	0	0	0	0	0	0	0	0	12	56	74
North Sea region												
Net import[a,c]									5	31	70	70
Domestic capture	22	27	61	96	64	250	395	474	52	351	514	569
Domestic storage	21	26	61	82	63	249	393	364	54	356	491	522
Export to Utsira	1	1	0	15	1	1	2	110	2	26	93	117

[a] CO_2 import/export from neighbouring countries, e.g. Poland and Belgium. Negative means net export of CO_2.
[b] Net import of Norway excludes the Utsira formation.
[c] The sum of net import is not valid for the national models because they are not linked.

PanEU model projections, coal fired power plants without CCS are phased out in 2050 due to the strict climate policies assumed.

- Policy assumptions on nuclear power were not harmonized between the national model for the UK and the TIMES PanEU model. The TIMES PanEU model does not allow for large increases in nuclear generation capacity whereas nuclear power is one of the major carbon mitigation options in the national UK model increasing from 250 PJ in 2010 to 1070 PJ in 2050 (but holding relatively steady at 320 PJ in the TIMES PanEU model). In other countries, nuclear power is phased out in both the national and TIMES PanEU model projections. The amount of power generated with CCS in the UK is therefore much larger with the TIMES PanEU model (280 PJ in 2050) than projected with the national UK model (990 PJ in 2050) (Fig. 5).

3.2. CO_2 capture, transport and storage

Fig. 6 and Table 7 present the amount of CO_2 captured and stored in the C-20 and C-80 scenarios of the national and regional TIMES PanEU model for the countries of the North Sea region. Export of CO_2 from/to neighbouring countries was also considered in the TIMES PanEU model used for the regional projections and the national projections of Germany and Denmark.

The results indicate that in the C-20 scenario total CO_2 captured and stored begins with 27 $MtCO_2$ in 2020. Such early capture of CO_2 represents new build CCS power plants (commissioned in 2020) in countries with available infrastructure and storage, and is driven by CO_2 prices in the national models of up to €43/tCO_2. CCS accounts for 65 $MtCO_2$ in 2050 of which 67% is captured in the Netherlands and 33% is captured in Germany. CCS is not deployed in the UK, Norway and Denmark. The national storage capacity of Germany (aquifers) and the Netherlands (empty gas fields) is almost sufficient to meet the amount of CO_2 captured in this scenario. Only in 2050, 3 $MtCO_2$ is projected to be exported to the Utsira formation from the Netherlands.

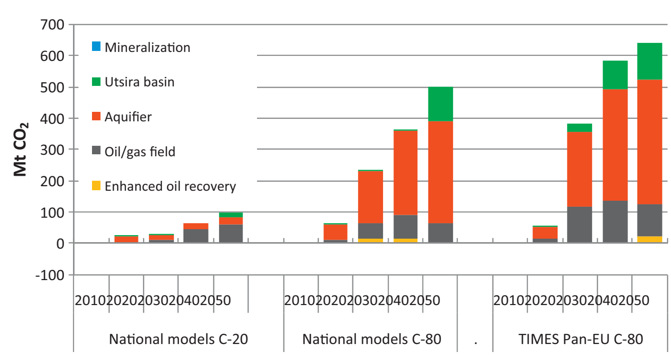

Fig. 6. Total CO_2 captured, imported and stored in the C-20 and C-80 scenarios of the national models and the C-80 scenario of the TIMES PanEU model for the DE, DK, NL, NO and UK per storage type.

Note that in an exploratory sensitivity case using Mixed Integer Programming[4] for infrastructure options, no CO_2 would be exported to Utsira as large "lumpy" investments for CO_2 transport for such low quantities of CO_2 as in the C-20 scenario would make the option unattractive.

For the C-80 scenario two different projections are obtained: one based on (the sum of) the national model projections and one

[4] Mixed Integer Programming (MIP) is used when some of the optimization variables in the model are integers. For energy models, this approach is valid when some investments are "lumpy" in nature: e.g., Broek et al. (2010a) models CO_2 pipeline segments as integers.

projected by the TIMES PanEU model for the countries in the North Sea Region. In the national model projections, the total amount of CO_2 captured increases from 64 Mt in 2020 to 474 $MtCO_2$ in 2050 whereas the TIMES PanEU model projects 569 $MtCO_2$ to be captured in 2050 (Table 7). The almost 100 $MtCO_2$ difference between the amount of CO_2 captured in the national models and the TIMES PanEU model are partly explained by the policy assumptions on nuclear power in the UK, and partly on difference in the type of plant (coal vs. gas) where CCS is deployed, and the resultant amount of CO_2 captured per unit of electricity.

In addition, about 70 $MtCO_2$ is projected to be imported from Poland and Belgium to Germany and the Netherlands respectively. From the European perspective these quantities captured and stored in the neighbouring countries of the North Sea represent a significant potential for the application of CCS technologies in Europe (50–60%). The reasons behind this are on the one hand the comparably favourable CO_2 storage conditions in depleted oil and gas fields, aquifers and the Utsira formation and on the other hand the opportunity of scale effects for CO_2 transport due to the existence of large coal and lignite based power plant sites, which profit from low specific transport costs, if they are completely equipped with CCS (Blesl and Kober, 2010).

The national model of *the UK* projects all of the CO_2 to be stored in national offshore aquifers (53 $MtCO_2$ in 2050). The general ordering of costs of CO_2 transport and storage is: enhanced oil recovery (EOR), the lower portion of the supply curve for UK aquifers, the lower portion of the supply curve for the UK oil and gas reservoirs, Utsira, higher costs UK aquifers and higher costs oil/gas fields. The TIMES PanEU model projects 95 $MtCO_2$ to be captured in the UK of which 74 Mt is projected to be stored in the Utsira formation in 2050. For the high fossil fuel prices, nuclear power competes with CCS in the national model of the UK whereas the TIMES PanEU model assumes that no new nuclear generation capacity is allowed to be built in the UK. Note that if lower fossil fuel prices are assumed, the cost effectiveness of nuclear power decreases significantly as shown in the sensitivity analyses (Section 4).

In *Germany*, captured CO_2 in 2050 is primarily stored in domestic saline aquifers (243 $MtCO_2$) and depleted hydrocarbon fields (25 $MtCO_2$). Over the whole model horizon, a cumulative quantity of 5700 $MtCO_2$ is stored in aquifers and 300 $MtCO_2$ in hydrocarbon fields. Only minor quantities of CO_2 are transported and stored abroad (to fields in the Netherlands and Denmark). There are no significant differences between the results obtained at the national and regional level since in both cases the TIMES PanEU model was used.

In *the Netherlands*, results based on the national model indicate that about 145 $MtCO_2$ are stored in 2050. In this case, CO_2 is initially stored in onshore gas fields, increasing from 7 $MtCO_2$ in 2020 to 48 $MtCO_2$ in 2030. Due to the rapid increase in deployment of CCS, offshore storage of CO_2 both in the Utsira formation and in the Dutch national aquifers starts already in 2030. The use of the Utsira formation however has a marginal role in the period 2030–2040 (2.4 $MtCO_2$ corresponding to about 3% of the total amount being stored). In the period 2040–2050, the results show a rapid increase in the use of Utsira reaching 105 $MtCO_2$ in 2050 (72% of CO_2 stored). The TIMES PanEU model projects 41 $MtCO_2$ from the Netherlands (42%) to be stored in the Utsira formation in 2050. The amount of CO_2 is mainly lower due to the greater share of gas fired CCS plants in the TIMES PanEU model projections compared to the national model projections for the Netherlands (Fig. 4) and the option to store CO_2 from the Netherlands in reservoirs located in the UK, which was not taken into account in the national model.

For *Norway*, all domestic captured CO_2 (maximum 9 $MtCO_2$ in 2030) is exported to the Utsira formation as it is the only source assumed to be available in the model. If imported CO_2 to the Utsira formation is taken into account, Norway is the largest importer (110 Mt to 117 $MtCO_2$ in 2050). Finally, in *Denmark*, 28 Mt (national model) to 30 $MtCO_2$ (TIMES PanEU model) is projected to be stored in domestic aquifers of which 20 $MtCO_2$ is projected to be imported from Germany in 2050. Due to the large national storage capacities, only 1 $MtCO_2$ is projected to be stored in the Utsira formation according to the national run.

4. Sensitivity analysis

Note that additional sensitivity runs as detailed in Section 2.5 are highlighted in the discussion below, and discussed in full in Fidje et al. (2010).

4.1. Fossil fuel prices (national models)

To assess the impact of fossil fuel prices assumptions, additional model runs were conducted with *the national models* using the WEO 2007 (IEA, 2007) low fossil fuel price (LP) assumptions (Table 2). These prices are relatively low compared to the WEO 2008 (IEA, 2008) fossil fuel price (HP) assumptions. The results for 2030 and 2050 are depicted for the base scenarios with WEO 2008 (C-20-HP and C-80-HP) and the reduced fossil fuel prices WEO 2007 (C-20-LP and C-80-LP) in Table 8.

Lower fossil fuel prices in the *C-20-LP scenario*, result in a shift in the electricity generating mix with more than four times more electricity from natural gas fired power plants in 2050 relative to the C-20-HP scenario due to the lower fuel costs. Nuclear power and coal become less attractive in the C-20-LP scenario. In 2050, power generated from nuclear and coal CCS power plant reduces with 60% and 25% respectively relative to the C-20-HP scenario. Total CO_2 storage reduces from 96 $MtCO_2$ in the C-20-HP scenario (of which 15 Mt is in the Utsira formation) to 49 $MtCO_2$ in the C-20-LP scenario. Utsira is no longer used as a storage field in the C-20-LP scenario due to the reduced amount of CO_2 captured. There is no significant impact on the share of renewables in the electricity generation mix if lower fossil fuel prices are assumed in the C-20 scenario.

Similar to the C-20-LP scenario, the *C-80-LP scenario* with lower fossil fuel prices results in increased deployment of natural gas fired power plants and reduced electricity generation from nuclear power plants. However in this scenario, over 150% more electricity is generated from gas fired power plants with CCS. Gas fired power plants without CCS only increase with 20% in this scenario while nuclear power reduces with 45%. The difference in CCS power generation between the C-80-HP and C-80-LP scenario is mainly the result of shifts from nuclear power to fossil fuel generation with CCS in the UK. Total CO_2 storage in the C-80-LP scenario is 20% higher relative to the C-80-HP scenario and 60% more CO_2 is stored in the Utsira formation in 2050 due to the larger amounts of CO_2 that are captured.

Note that in a further sensitivity case with no CCS allowed, this lack of access to CCS reverberates across the energy system (illustrating the usefulness of energy-economic models) giving an altered electricity portfolio, less overall (and higher cost) low carbon electricity, and a series of trade-offs in extra mitigation from other resources, sectors and demand changes.

4.2. CO_2 transport network layout (regional TIMES PanEU model)

The sensitivity of the results of the regional TIMES PanEU model for alternative North Sea CO_2 transport networks to the Utsira formation are depicted in Fig. 7. The design and parameters of the alternative networks with higher (CAP+) or lower (CAP−) capacities are provided in Fig. 3 and Table 5.

Alternate assumptions on Utsira appear to make little difference in the total amount of CCS or make-up of electricity portfolios, but

Table 8
Sensitivity scenarios for fossil fuel prices (from national models).

	2030				2050			
	C-20-HP	C-20-LP	C-80-HP	C-80-LP	C-20-HP	C-20-LP	C-80-HP	C-80-LP
Electricity generation (North sea region) (PJ)								
Total	4827	4710	4817	4752	5350	5030	6946	6640
Renewables	2006	1918	2046	1931	2399	2348	3573	2867
Gas	401	606	436	614	121	516	110	132
Coal	2015	1840	577	386	1886	1583	0	12
Gas CCS	6	6	6	15	0	0	301	760
Coal CCS	127	132	1128	1524	323	243	1952	2132
Nuclear	106	45	424	81	297	117	1070	587
Import/export[a]	127	123	162	162	293	190	-90	123
Others[b]	39	39	39	39	31	33	32	27
Electricity generation with CCS (PJ)								
North sea region (total)	133	138	1134	1539	323	243	2252	2892
Denmark	7	7	16	10	0	0	29	0
Germany	76	84	703	722	108	111	1116	964
Norway	6	6	6	6	0	0	0	0
The Netherlands	44	41	204	155	215	132	831	847
United Kingdom	0	0	205	646	0	0	276	1081
Total CO_2 storage (of which in Utsira) ($MtCO_2$)[c]								
North sea region (total)	27 (1)	36 (1)	250 (1)	340 (21)	96 (15)	49 (0)	474 (110)	564 (178)
Denmark	1 (0)	1 (0)	1 (0)	2 (0)	0 (0)	0 (0)	9 (1)	10 (2)
Germany	15 (0)	17 (0)	164 (0)	159 (0)	22 (0)	20 (0)	264 (0)	186 (0)
Norway	1 (1)	1 (1)	1 (1)	1 (1)	0 (0)	0 (0)	3 (3)	3 (3)
The Netherlands	10 (0)	17 (0)	46 (0)	44 (0)	75 (15)	30 (0)	145 (105)	154 (120)
United Kingdom	0 (0)	0 (0)	38 (0)	135 (20)	0 (0)	0 (0)	53 (0)	210 (54)

[a] Positive = net electricity import; negative = net electricity export.
[b] Oil, storage.
[c] The figures in parentheses are the amount of CO_2 stored in the Utsira formation.

can switch the ordering of CCS reservoirs, and hence the network configuration – this is seen in the TIMES PanEU model's sensitivity on Denmark and Germany's lack of access to domestic aquifers (Kober and Blesl, 2010a) – and also in the UK MARKAL sensitivity under large Utsira capacity (Strachan, 2009). Regardless of the infrastructure design, Germany and Denmark do not export CO_2 to the Utsira formation in the C-80-HP scenario. As Utsira is the only available option for CO_2 storage for Norway and CO_2 capture plants are exogenous to the model, the amount of CO_2 stored in Utsira is similar for all variants (2 $MtCO_2$ in 2040–2050). For the UK, CO_2 transport and storage in the Utsira formation is almost similar amongst all variants (56–57 $MtCO_2$ in 2040 and 73–75 $MtCO_2$ in 2050). For the Netherlands, the amount of CO_2 exported to Utsira is sensitive to the network infrastructure assumed. For Network I, 14 Mt less CO_2 is exported to Utsira in 2050 if lower capacities are assumed. For Network 3 Cap+, 9 Mt more CO_2 is exported from the Netherlands to Utsira in 2050 compared to Network I Cap+.

5. Discussion

As detailed in Section 2, a broad range of input assumptions as well as scenarios run were all harmonized. In order to go further in terms of harmonization, one starts to hit the issue of level of

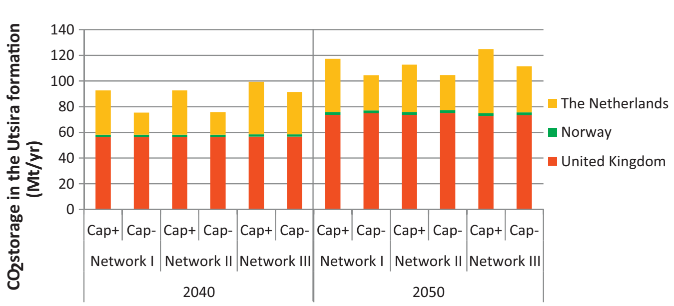

Fig. 7. CO_2 storage in the Utsira formation by country of origin for the C-80 scenario with different CO_2 transport network structures and high and low capacity cases.

detail on the policy landscape or in the depiction of behavioural change that are specific to the national models; or at the other end of the spectrum, the issues related to flows of energy and emissions around the target countries (and other EU countries) that is the domain of the regional model. In striking this balance, we have endeavoured to retain the strengths of both modelling approaches.

Comparing energy system modelling at different scales (national vs. regional) gives a range of insights into the potential role of CCS and shared North Sea CO_2 storage resources.

- The regional TIMES PanEU model includes an improved depiction of electricity and CO_2 trade, especially transboundary CCS flows between neighbouring countries.[5]
  - The regional TIMES PanEU model also includes aviation (and associated CO_2 emissions) to and from the entire EU-27 nations, whereas some of the national models only have aviation on a domestic basis, which is much smaller and others (e.g. MARKAL Netherlands) do not include it.
  - The regional model also allocated national level mitigation efforts on a EU-level cost optimal basis, giving differences in the level of mitigation required in individual countries
- Apart from CO_2 policies, the national and regional models have somewhat different policy, behaviour and taxation assumptions in the near term, with the national models having much more detail.
  - Policy variables are a key difference, as EU policies are harmonized, while national policy and fiscal circumstances are kept model specific. For example in the UK model's case this includes existing energy specific fiscal mechanisms, specific renewable support polices, and specific buildings conservation and efficiency measures. In the Dutch model the policy plans to construct renewable energy capacity up to 2015 are included.

[5] Note that the partial harmonisation process for the national models (Table 1), used EU-level electricity trade as an upper bound and excluded transboundary CO_2 trade in order that runs with TIMES-PanEU model could illustrate these differences.

- Generally speaking national level models have more technological detail (and hence more substitution options in key sectors).
  - The models have different optimistic and pessimistic assumptions on various (non-CCS) technology assumptions (e.g., vehicles fuelled on hydrogen or bio-derived fuels) and inclusion or not of key decarbonisation options (e.g. industrial CCS options). For example, the Dutch MARKAL model assumes hydrogen only for conventional industrial use. If also hydrogen is included for e.g. transport sectors, the demand of hydrogen could potentially be much larger. However, the impact may be limited since additional analysis for the Netherlands has already shown that the potential of hydrogen vehicles is limited (van Vliet et al., 2010).
  - Some national models – in addition to supply side energy system optimization – have energy demands that are endogenous to prices changes, and rely of national specific price elasticities. This functionality ensures a degree of flexibility that the TIMES PanEU model does not.
  - The cost of CO_2 transport from landfalls to the Utsira formation in the Dutch model were based on a dedicated model (Broek et al., 2010b) including pipeline capacities of 60 $MtCO_2$/yr. The other models assumed maximum capacities of 30 $MtCO_2$/yr (Table 5). The sensitivity results show that the regional TIMES PanEU model results for the Netherlands are somewhat sensitive to transport capacities and infrastructure designs.

Finally, there are two points that should be highlighted in relation to the use of Utsira. First, the maximum cumulative storage capacity (42 $GtCO_2$) and maximum annual injection rate (150 $MtCO_2$/yr) were based on experience with the current injection well at the Sleipner gas field and Lindeberg et al. (2009). Nevertheless, the scientific basis for these assumptions is weak resulting in large uncertainty on these assumptions.

Second, most of the national models assume that the whole capacity of Utsira will be available (no competition with flows coming from other countries). Thus when the results of all separate models are put together, the assumed maximum annual injection rate (150 $MtCO_2$) can be exceeded. Whether there is need to allocate Utsira's capacity and if so, under which conditions, is a point that needs to be further researched in the context of using Utsira as a common CO_2 storage resource in the region. This would be even more important if CCS continues to be used – beyond as a transitional mitigation technology – and CO_2 storage requirements extend well beyond 2050 (the horizon for modelling in this analysis).

6. Conclusions

This paper investigated the potential role of the Utsira formation as a common CO_2 storage resource for countries in the North Sea region (UK, Netherlands, Germany, Denmark and Norway). CCS modelling analyses requires a range of model types and a range of model scales. Energy systems models such as MARKAL/TIMES are highly appropriate tools as the role of CCS is embedded in wider electricity and energy system interactions and trade-offs, and CO_2 storage supply and demand is dynamically matched in a long-term optimization framework. Hence, the cost effectiveness of CCS is embodied in its key role in long-term cost optimal pathways to met decarbonisation targets.

Previous modelling of CCS has either focused at an EU or a national level. Building from this prior work, this paper first utilizes insights from energy systems modelling at the national level – this ensures that country specific technical, economic and policy detail are considered. This is then compared to regional (EU) level modelling – this ensures that electricity trade, transboundary CO_2 flows and alternate emissions allocations are considered. As far as possible – while retaining the strengths of both modelling scale approaches – parameters and scenarios have been harmonized. Hence it is this model comparison that derives new insights in the potential exploitation of the Utsira CO_2 storage formation within the EU energy system. The focus of our core and sensitivity analysis is to look at the role of the climate target, fossil fuel prices, the CCS network and the storage capacity.

Regarding the potential role of the Utsira formation as a common storage field for the countries in the North Sea region, the following conclusions can be drawn:

- In context of moderate carbon policies (C-20 scenario), the Utsira formation does not play a significant role as a CO_2 storage field for countries other than Norway to 2050. Storage in domestic aquifers and empty gas fields in combination with alternative mitigation technologies such as renewables proved to be sufficient and more cost effective compared to CO_2 storage in the Utsira formation.
- In case of stringent carbon reduction targets (C-80 scenario), CCS was projected to be a key option for CO_2 mitigation in electricity and industry sectors. In 2050, 32–40% of power generation includes CCS and 475–570 $MtCO_2$ is captured and stored of which 110–120 $MtCO_2$ is transported and stored in the Utsira formation. If imported CO_2 from Belgium and Poland are included for the countries in the North Sea region, the total amount of CCS rises to 640 $MtCO_2$ in 2050. Thus the neighbouring countries of the North Sea represent a significant potential for the application of CCS technologies in Europe.

From comparing the projections of the national models and the regional TIMES PanEU model for the C-80 scenario, it can be concluded that:

- The role of the Utsira formation, as projected by the national and regional TIMES PanEU model is in the same range from a regional perspective for the North Sea region. The national models project 23% (110 Mt) of total captured CO_2 in the North Sea region to be stored in the Utsira formation whereas the share of the Utsira formation in projections of the TIMES PanEU model is 21% (120 Mt) in 2050. In both cases, the total amount of CO_2 stored in the Utsira formation is below the maximum assumed injection rate of the Utsira formation (150 $MtCO_2$/yr).
- Lower energy prices can considerably increase the use of CCS (e.g., due to a shift from nuclear to CCS in the UK). The share of the Utsira formation increases to 32% (180 $MtCO_2$) in 2050 of which 120 Mt comes from the Netherlands and 55 Mt comes from the UK. Note that in this case the combined results of the national models are larger than the overall storage limit assumed for the Utsira formation (150 $MtCO_2$/yr).
- On a country level, the differences between results of the national models and the regional TIMES PanEU model for CCS in general and for CO_2 storage in the Utsira formation are larger. The TIMES PanEU model projects over three times more CO_2 capture in the UK (170 $MtCO_2$ in 2050) than the national model for the UK (50 $MtCO_2$ in 2050) due to an aggregated treatment of nuclear power policy in the regional TIMES PanEU model for the UK. In contrast, the national model for the Netherlands projects an additional 50 $MtCO_2$ to be captured than the TIMES PanEU model for the Netherlands partly due to differences in coal vs. gas CCS uptake.

Furthermore the findings of this research indicate that different network layouts, including individual pipelines or shared pipelines that benefit from economies of scale for transporting CO_2 from the landfall locations in countries of the North Sea region to the Utsira formation, can change the placing of various reservoir options (including Utsira) in the storage cost curve, but not the overall level of CCS and low carbon electricity.

Utsira plays a key role within the CO_2 storage cost curve, with the Netherlands and the UK being the largest contributors. Other countries provide a modest contribution, with Germany (despite being the largest user of CCS), only directly utilizing Utsira if transport costs fall or restrictions are placed on domestic aquifers. However the role of transboundary flows of CO_2 is important – both for access to national aquifers and for Utsira – and occurs due to countries not having cost effective CO_2 storage, being closer to other country's low cost storage, or for economies of scale in CO_2 flows. The cumulative storage capacity of 42 $GtCO_2$ did not prove to be a limitation for both the national and regional model projections (at least through 2050). The maximum annual injection rate (150 $MtCO_2$/yr) however proved to be too low in the C-80 scenario with low fossil fuel prices to 2050. Considering the weak scientific basis of the assumed annual injection rate, more research is required on the physical constraints of injecting CO_2 in large storage fields such as the Utsira formation. Furthermore, more research is required on (shared) offshore transport networks that might have larger capacities than assumed in the regional model (max. 30 Mt/yr) and result in economic advantages for large distance CO_2 trade.

This comparison of energy system and CCS modelling at the national and North Sea regional level highlights the benefits and drawbacks that analysis at alternate geographic scale can have. The design of strategies to implement CCS networks, and allocation of the common North Sea Utsira CO_2 storage resource must be cognizant of the role of transboundary flows of CO_2, electricity and allocation of emissions mitigation, while also recognising the importance of detailed policy and behavioural responses for a range of competing mitigation options. As no model can encompass all of these drivers, this supports continued use of model soft-linking and comparison as detailed in this analysis.

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Appendix A.

See Table 9.

Table 9
Cost and performance of fossil fuel generation plants for harmonization (€$_{2007}$).

Technology	Reference plant				CCS			
	2010	2020	2030	2040	2010	2020	2030	2040
Investment costs (€/kW)								
NGCC	676	608	608	608	1146	1014	938	838
PC	1598	1487	1448	1352	2546	2328	2110	1892
Retrofit					1149	1149	1149	1149
Capture ready retrofit					946	946	946	946
IGCC	2005	1798	1691	1521	2769	2374	2130	1956
Capture ready retrofit					676	676	676	676
Wind onshore	908	795	714	641				
Wind offshore	1800	1500	1420	1400				
Nuclear	2652	2652	2652	2652				
PV	3200	2000	1000	700				
Fixed O&M costs (€/kW/yr)								
NGCC	19	17	16	16	33	24	22	19
PC	77	72	66	61	95	81	75	68
Retrofit					14	14	14	14
Capture ready retrofit					19	19	19	19
IGCC	71	66	60	53	92	76	70	63
Capture ready retrofit					21	21	21	21
Wind onshore	32	25	23	20				
Wind offshore	96	91	86	81				
Nuclear	66	66	66	66				
PV	40	25	13	9				
Variable O&M costs (€/MWh)								
NGCC	0.02	0.02	0.02	0.02	0.41	0.40	0.36	0.35
PC	0.36	0.35	0.33	0.33	1.29	1.25	1.08	0.95
Retrofit					0.94	0.94	0.94	0.94
Capture ready retrofit					0.94	0.94	0.94	0.94
IGCC	0.29	0.25	0.20	0.19	0.51	0.41	0.27	0.27
Capture ready retrofit					0.22	0.22	0.22	0.22
Wind onshore								
Wind offshore								
Nuclear	0.69	0.69	0.69	0.69				
PV								
Efficiency (% LHV)								
NGCC	58	60	63	64	49	52	56	58
PC	46	49	52	53	36	40	44	47
Retrofit					28	29	29	29
Capture ready retrofit					36	37	37	37
IGCC	46	50	54	56	38	44	48	50
Capture ready retrofit								

Broek et al. (2010a).

Table 10
Results of the national models for the C-20 scenario.

C-20 National models	United Kingdom					Denmark					Germany					Norway					The Netherlands				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
Electricity generation mix (GW)																									
Coal	24	20	36	37	38	5	3	2	2	2						–	–	–	–	–	4	8	7	6	5
Coal CCS	–	–	–	–	–	–	0	0	0	–						–	–	–	–	–	–	1	2	5	8
Gas	25	30	25	28	27	2	3	4	4	3						–	–	–	–	–	17	16	16	17	16
Gas CCS	–	–	–	–	–	–	–	–	–	–						–	0	0	–	–	–	–	–	–	–
Nuclear	12	5	4	9	11	–	–	–	–	–						–	–	–	–	–	0	0	0	–	–
Oil	8	7	–	–	–	1	–	–	–	–						–	–	–	–	–	–	–	–	–	–
Hydro	2	2	2	1	1	–	–	–	–	–						31	34	35	35	35	–	–	–	–	–
Wind	5	13	14	16	16	4	9	11	11	12						0	3	5	6	4	3	7	12	12	12
Biowaste and others	4	6	6	4	5	1	1	1	1	1						0	0	0	0	0	1	1	1	1	12
Imports	2	4	4	3	3	–	–	–	–	–						–	–	–	3	4	–	–	–	–	–
Marine	–	–	–	–	5	–	–	–	–	–						–	–	2	4	5	–	–	–	–	–
Solar	–	–	–	–	–	–	–	–	–	–						–	–	–	–	–	–	–	–	–	–
Storage	2	1	1	1	1	–	–	–	–	–						–	–	–	–	–	–	–	–	–	–
Total	83	89	91	99	108	13	16	18	19	19						31	37	43	48	49	25	33	38	40	53
Electricity generation (PJ)																									
Coal	319	423	958	928	919	65	39	21	23	43	928	939	900	915	792	–	–	–	–	–	105	150	136	142	132
Coal CCS	–	–	–	–	–	–	7	7	7	–	1	85	76	83	108	–	–	–	–	–	–	15	44	137	215
Gas	538	500	61	40	–	20	13	9	9	10	269	176	159	95	42	–	–	–	–	–	197	199	172	137	69
Gas CCS	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6	6	–	–	–	–	–	–	–
Nuclear	254	100	92	225	297	–	–	–	–	–	526	79	–	–	–	–	–	–	–	–	14	14	14	–	–
Oil	10	4	–	–	–	–	–	–	–	–	30	21	9	9	7	–	–	–	–	–	–	–	–	–	–
Hydro	23	22	19	16	16	–	–	–	–	–	106	113	113	113	113	437	501	521	521	521	–	–	–	–	–
Wind	49	136	152	170	173	34	84	115	121	126	171	334	550	607	664	2	27	50	54	42	26	64	122	122	122
Bio, oth. Ren. and waste	64	63	63	67	72	15	19	22	24	27	122	146	167	204	243	–	–	–	–	–	15	16	17	17	55
Imports	41	22	19	44	43	– 10	– 22	– 30	– 38	61	– 57	176	157	117	150	–	–	–	41	60	63	– 15	– 19	– 21	– 21
Marine	–	–	–	–	64	–	–	–	–	–	–	–	–	–	–	–	–	29	58	76	–	–	–	–	–
Solar PV	–	–	–	–	–	–	–	–	–	–	21	48	68	80	86	–	–	–	–	–	–	–	–	–	–
Storage	8	6	5	–	–	–	–	–	–	–	24	24	24	24	24	–	–	–	–	–	–	–	–	–	–
Total	1306	1276	1369	1490	1584	123	140	143	146	146	2142	2140	2223	2247	2229	439	534	607	673	699	357	458	504	554	592
CO_2 capture and storage																									
All CCS	–	–	–	–	–	–	1	1	1	–	–	17	15	16	22	–	1	1	–	–	–	2	10	44	75
CCS electricity	–	–	–	–	–	–	1	1	1	–	–	–	–	–	–	–	1	1	–	–	–	–	–	–	–
CCS process/industry	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Enhanced oil recovery	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil/gas field – low transport	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil/gas field – high transport	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	2	10	44	47
Aquifier	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	13
Utsira basin	–	–	–	–	–	–	2	3	3	–	–	17	15	16	22	–	–	–	–	–	–	–	–	–	–
Mineralization	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	1	–	–	–	–	–	–	15
Net exports	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
CO_2 and system costs																									
CO_2 emissions ($MtCO_2$)	541	497	465	474	474	50	42	40	44	52						35	26	23	21	20	164	184	184	177	193
Marginal cost of CO_2 (€2000/t)	–	–	–	10	10	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	28	43	26	19	19
Undiscounted energy system cost (€billion)	101	142	187	202	226	17	22	26	21	21						–	–	–	–	–	–	–	–	–	–
Discounted energy system cost (€billion)	–	–	–	–	–	12	10	8	4	3						–	–	–	–	–	10	11	12	13	14

Table 11
Results of the national models for the C-80 scenario.

C-80 National models	United Kingdom					Denmark					Germany					Norway					The Netherlands				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
Electricity generation mix (GW)																									
Coal	24	18	12	12	12	5	3	1	–	–	55	37	18	5	–	–	–	–	–	–	4	7	7	4	3
Coal CCS	–	–	8	8	13	–	0	1	2	2	0	8	31	50	52	–	–	–	–	–	–	1	8	11	27
Gas	25	33	25	22	15	2	3	4	4	6	31	26	24	16	16	–	–	–	–	–	17	16	14	11	13
Gas CCS	–	–	–	–	–	–	–	–	–	2	–	–	–	3	6	–	0	0	–	–	–	–	–	3	7
Nuclear	12	5	16	36	41	–	–	–	–	–	19	3	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil	8	7	–	–	–	1	–	–	–	–	5	2	1	1	0	–	–	–	–	–	–	–	–	–	–
Hydro	2	2	3	3	3	–	–	–	–	–	5	5	5	5	5	31	34	35	35	35	–	–	–	–	–
Wind	5	13	16	19	111	4	9	11	15	28	27	44	62	74	102	0	3	5	6	6	3	7	12	12	13
Biowaste and others	4	6	6	3	4	1	1	2	1	2	7	7	8	9	11	0	0	0	0	0	1	1	1	1	12
Imports	2	4	4	3	3	–	–	–	–	–	–	–	–	–	–	–	–	–	3	4	–	–	–	–	–
Marine	–	–	–	4	5	–	–	–	–	–	–	–	–	–	–	–	–	2	4	5	–	–	–	–	–
Solar	–	–	–	–	–	–	–	–	–	–	6	14	20	24	26	–	–	–	–	–	–	–	–	–	–
Storage	2	1	1	1	1	–	–	–	–	–	6	6	6	6	6	–	–	–	–	–	–	–	–	–	–
Total	83	89	90	112	208	13	16	18	22	40	161	152	175	193	225	31	37	43	48	51	25	32	42	42	75
Electricity generation (PJ)																									
Coal	320	433	316	–	–	64	33	20	–	–	899	738	241	1	–	–	–	–	–	–	106	113	–	–	–
Coal CCS	–	–	205	205	276	–	7	16	34	1	1	221	703	1183	951	–	–	–	–	–	–	30	204	307	724
Gas	538	500	61	40	–	21	13	9	–	–	272	204	201	84	97	–	–	–	–	–	198	196	165	92	13
Gas CCS	–	–	–	–	–	–	–	–	10	28	–	–	–	38	166	–	6	6	–	–	–	–	–	53	107
Nuclear	254	100	410	946	1070	–	–	–	–	–	526	79	–	–	–	–	–	–	–	–	14	14	14	–	–
Oil	10	4	–	–	–	–	–	–	–	–	30	21	9	6	2	–	–	–	–	–	–	–	–	–	–
Hydro	23	22	31	31	31	–	–	–	–	–	106	113	117	117	117	437	501	521	521	521	–	–	–	–	–
Wind	49	136	173	194	771	34	84	115	145	288	171	334	550	651	973	2	27	50	58	57	26	62	122	122	131
Bio, oth. Ren. and waste	64	66	62	58	59	15	19	23	25	30	122	146	167	197	243	–	–	–	–	–	15	16	17	17	56
Imports	41	22	73	93	96	−10	18	−36	−51	−82	−57	148	144	67	67	–	–	–	41	61	63	18	−19	−21	−232
Marine	–	–	–	51	64	–	–	–	–	–	–	–	–	–	–	–	–	30	58	76	–	–	–	–	–
Solar PV	–	–	–	–	–	–	–	–	–	–	21	48	68	80	156	–	–	–	–	–	–	–	–	–	–
Storage	8	6	5	1	5	–	–	–	–	–	24	24	24	24	24	–	–	–	–	–	–	–	–	–	–
Total	1307	1289	1336	1619	2372	123	138	146	163	264	2116	2076	2224	2449	2796	439	534	608	677	714	422	449	503	570	799
CO_2 capture and storage																									
All CCS	–	–	38	38	53	–	1	4	10	9	–	51	164	285	264	–	1	1	–	3	2	11	46	69	145
CCS electricity	–	–	38	38	53	–	1	4	9	7	–	–	–	–	–	–	1	1	–	–	–	–	–	–	–
CCS process/industry	–	–	–	–	–	–	–	–	1	2	–	–	–	–	–	–	–	–	–	3	–	–	–	–	–
Enhanced oil recovery	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil/gas field – low transport	–	–	14	14	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil/gas field – high transport	–	–	–	–	–	–	–	–	–	–	–	–	3	10	25	–	–	–	–	–	2	11	46	48	21
Aquifer	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	18	18
Utsira basin	–	–	24	24	53	–	2	8	28	28	–	49	135	217	244	–	–	–	–	–	–	–	–	–	–
Mineralization	–	–	–	–	–	–	–	–	2	1	–	–	–	–	–	–	1	1	–	3	–	–	–	2	105
Net exports	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
CO_2 and system costs																									
CO_2 emissions ($MtCO_2$)	497	474	355	237	118	50	40	35	22	3	757	677	411	275	111	35	26	22	21	15	164	171	138	109	60
Marginal cost of CO_2 (€2000/t)	–	–	9	53	175	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	28	45	55	57	100
Undiscounted energy system cost (€ billion)	141	187	204	226	255	17	22	26	21	21	242	283	314	250	257	–	–	–	–	–	–	–	–	–	–
Discounted energy system cost (€ billion)	–	–	–	–	–	12	10	8	4	3	164	129	97	52	36	–	–	–	–	–	10	11	14	16	22

Table 12
Results of the TIMES PanEU model for the C-80 scenario.

C-80 PET-model	United Kingdom					Denmark					Germany					Norway					The Netherlands				
	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050	2010	2020	2030	2040	2050
Electricity generation mix (GW)																									
Coal	21	16	1	1	0	5	3	1	–	–	56	40	15	4	–	–	–	–	–	–	5	4	2	2	1
Coal CCS	–	3	26	41	31	–	0	2	2	2	0	4	32	55	46	–	–	–	–	–	–	0	4	5	5
Gas	39	44	40	27	26	2	3	3	4	5	33	26	22	20	28	0	0	0	0	0	16	17	15	11	5
Gas CCS	0	0	0	3	27	–	–	0	0	2	–	–	–	3	16	0	0	0	0	0	–	–	0	7	21
Nuclear	12	13	12	13	12	–	–	–	–	–	19	3	–	–	–	–	–	–	–	–	0	0	0	–	–
Oil	7	7	4	0	–	1	0	–	–	–	5	2	1	1	1	–	–	–	–	–	0	0	–	–	–
Hydro	2	2	2	2	3	–	–	–	–	0	5	5	5	5	5	28	28	28	29	30	0	0	0	0	0
Wind	4	16	31	36	69	4	9	11	15	28	28	45	62	74	102	1	1	0	12	12	4	8	17	20	26
Biowaste and others	3	4	5	6	22	1	1	1	1	2	8	7	8	9	11	0	0	0	0	0	1	2	2	2	3
Imports	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Marine	0	0	0	4	20	–	–	–	–	–	–	–	–	–	–	–	–	–	–	7	–	–	–	–	–
Solar	–	–	–	–	–	0	0	0	0	0	6	14	20	24	26	–	–	–	–	–	0	0	0	0	3
Storage	3	3	3	3	3	–	–	–	–	–	6	6	6	6	6	1	1	1	1	1	–	–	–	–	–
Total	91	108	124	138	212	12	16	19	22	39	165	151	171	201	241	30	30	30	42	50	26	32	41	46	64
Electricity generation (PJ)																									
Coal	496	424	2	1	–	70	47	6	–	–	916	990	86	1	–	–	–	–	–	–	91	94	51	–	–
Coal CCS	–	64	536	641	461	–	9	34	34	1	1	96	772	1174	993	–	–	–	–	–	–	3	118	121	120
Gas	569	392	133	53	15	16	14	9	0	0	271	200	197	73	98	0	0	0	0	0	206	154	91	15	9
Gas CCS	7	7	7	48	522	–	–	0	10	29	–	–	–	38	232	8	11	11	0	0	–	–	5	98	305
Nuclear	275	340	324	351	324	–	–	–	–	–	526	79	–	–	–	–	–	–	–	–	14	14	14	–	–
Oil	9	0	–	0	–	–	0	–	–	–	32	25	15	16	2	–	–	–	–	–	–	0	–	–	–
Hydro	28	28	31	33	43	–	–	–	–	0	106	113	117	117	117	492	492	493	515	527	0	1	1	1	1
Wind	25	155	346	398	700	34	84	115	145	280	171	334	550	651	973	3	4	4	112	112	30	83	192	225	300
Bio, oth. Ren. and waste	53	66	86	113	114	15	19	22	25	30	120	146	177	199	251	3	4	5	4	5	30	39	35	35	55
Imports	22	80	82	56	78	– 10	−32	−40	−50	−82	−57	79	217	85	−35	−39	−85	−82	−113	−151	63	63	−17	43	−86
Marine	0	1	1	57	216	–	–	–	–	–	–	–	–	–	–	–	–	–	–	94	–	–	–	–	–
Solar PV	–	–	–	–	–	0	0	0	0	0	21	48	68	80	86	–	–	–	–	–	0	0	0	0	11
Storage	10	10	10	10	10	–	–	–	–	–	24	24	24	24	24	3	3	3	3	3	–	–	–	–	–
Total	1495	1565	1557	1759	2482	125	141	146	164	257	2132	2133	2223	2459	2740	469	428	434	521	589	435	452	491	539	714
CO_2 capture and storage																									
All CCS	1	17	108	152	172	–	2	10	14	10	0	27	179	286	288	2	2	9	2	2	–	4	44	60	98
CCS electricity	1	17	107	139	144	–	2	10	13	7	0	25	176	265	262	2	2	9	1	0	–	4	43	51	84
CCS process/industry	–	0	1	12	28	–	–	0	1	2	–	2	3	21	26	–	–	0	1	2	–	–	1	8	14
Enhanced oil recovery	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil/gas field – low transport	1	1	1	0	21	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Oil/gas field – high transport	–	–	–	–	0	–	–	–	–	–	0	2	50	51	49	–	–	–	–	–	–	12	69	85	56
Aquifier	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Utsira basin	–	17	95	95	95	–	2	10	34	30	–	21	132	226	271	–	–	–	–	–	–	–	–	–	–
Mineralization	–	0	12	56	74	–	–	–	0	0	–	–	0	–	0	2	2	9	2	2	–	0	5	34	41
Net exports	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
CO_2 and system costs																									
CO_2 emissions ($MtCO_2$)	521	475	346	230	73	49	43	31	24	8	760	704	435	257	136	36	39	32	20	12	167	161	138	103	45
Marginal cost of CO_2 (€2000/t)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Undiscounted energy system cost (€ billion)	256	278	333	261	278	17	22	26	20	22	273	304	350	265	253	14	27	22	34	39	83	89	104	89	85
Discounted energy system cost (€ billion)	173	127	103	54	39	11	10	8	4	3	184	139	108	55	36	9	12	7	7	5	56	41	32	18	12

Appendix B.

It is important to note that optimization at a regional scale can give configurations that go beyond a national energy systems – for example one dominant feature for Denmark is the variation of wind power and electricity export, which may by 2050 may be far beyond the national demand level of 137 PJ. Hence 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.

See Tables 10–12.

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