Project 11029

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Overview of available data on candidate oil fields for CO_2 EOR

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SUMMARY:

The objective of this report is to give an overview of available data on candidate oil fields for CO_2 EOR and storage in Denmark and Norway. In addition some studies of CO_2 EOR performed on specific fields and on large scale infrastructures are described.

KEYWORDS:

Oil fields, CO_2 storage, CO_2 EOR, Infrastructure projects

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Contents

6.2.1302 Overview of available data on candidate oil fields for CO_2 EOR

1. Objectives

Among the Nordic countries the production of hydrocarbons (HC) is performed in the Danish and Norwegian sectors. NORDICCS deliverable D6.1.1201 (Review of existing CO_2 storage databases) gives an overview of existence and availability of data for Danish and Norwegian hydrocarbon fields. In Denmark access to data on hydrocarbon fields are restricted but field locations and yearly production history can be found in the "Oil and gas production in Denmark 2012" published by the Danish Energy Agency (DEA).

In Norway, name, location, general description, status, reserves and produced HC for oil and gas fields are publicly available at the Norwegian Petroleum Directorate (NPD) fact pages together with data from all exploration wells on the Norwegian Continental Shelf (NCS) and in "FACTS The Norwegian Petroleum Sector 2013" published by NPD. In addition, characteristic properties for around 20 fields can be found in the SPOR Monograph (Skjæveland & Kleppe, 1992). Estimates of CO_2 storage capacity for the majority of Norwegian oil and gas fields can be found in the JOULE-II report (Holloway *et al.*, 1996) and the NPD storage atlas (Halland *et al.* 2012, 2013a, 2013b) also give estimates of the CO_2 storage capacity of depleted HC fields.

The Danish CO_2 storage capacity in hydrocarbon fields is first evaluated in the Joule II report (1996). The figures are later updated in the GESTCO project (2004) and in the GeoCapacity project (2009).

The objective of this report is to give an overview of available data on candidate oil fields for CO_2 EOR and storage in Denmark and Norway. In addition some studies of CO_2 EOR performed on specific fields and on large scale infrastructures are described.

2. Introduction

Depleted hydrocarbon fields are good candidates for CO_2 storage since they already have a proven seal and often are well understood and explored. The pressure is in most cases reduced and it is safe to assume that you can pressurize the field back to initial pressure without the risk of rupturing the seal. If the field has been subject to gas or water injection the storage capacity could be reduced but reproducing the injected volumes could help on this. A first assumption is therefore to use material balance for estimating storage capacity of depleted HC fields. To estimate storage capacity of depleted oil and gas fields characteristic properties such as average formation volume factor (for produced phases), average pressure and temperature are required.

Injecting CO_2 to increase recovery has shown to be a very promising approach, especially if the CO_2 is miscible with the reservoir oil. For already water flooded reservoirs (which is the majority of cases in the North Sea) the injected CO_2 can mobilise the residual oil by swelling and by reducing interfacial tension between oil and formation water. CO_2 EOR has been used as a recovery method on-shore in North America for more than 30 years yielding from 7 to 15 % extra oil (NPD, 2005). These high estimates are often related to short well distances giving large contact areas and sweep efficiency for the injected CO_2. Off-shore in the North Sea the well distances are often large and segregation of the injected CO_2 will give reduced sweep efficiency compared to on-shore fields and NPD has indicated a CO_2 EOR potential of 3 to 7 % (NPD Storage Atlas) in the North Sea to account for this. The sweep efficiency can be improved with larger CO_2 injection volume and/or using water alternating gas (WAG) injection.

3. Data on oil and gas fields

Norway

The Norwegian Petroleum Directorate (NPD) fact pages contain data for all Norwegian oil and gas fields and the data is openly available in digital form at the following web site: http://factpages.npd.no/factpages. A list of fields with updated numbers for resources is given in the Appendix. In addition to name, location, production history and status a general description of field development, reservoir and recovery strategy is given. For each field the exploration and appraisal well data is also available with for instance wellbore location and history, description and results of well tests (DST) if performed, list of cores and core photos if cores were taken, lithostratigraphy in the well and so called well data summary sheets (WDSS) for older wells. The location and outline of the fields, wells, licenses and sectors are also available in GIS format in NPD's FactMap (http://npdmap1.npd.no/website/NPDGIS/viewer.htm). Figure 3-1 shows outline of oil and gas fields in a part of the North Sea from the FactMap viewer.

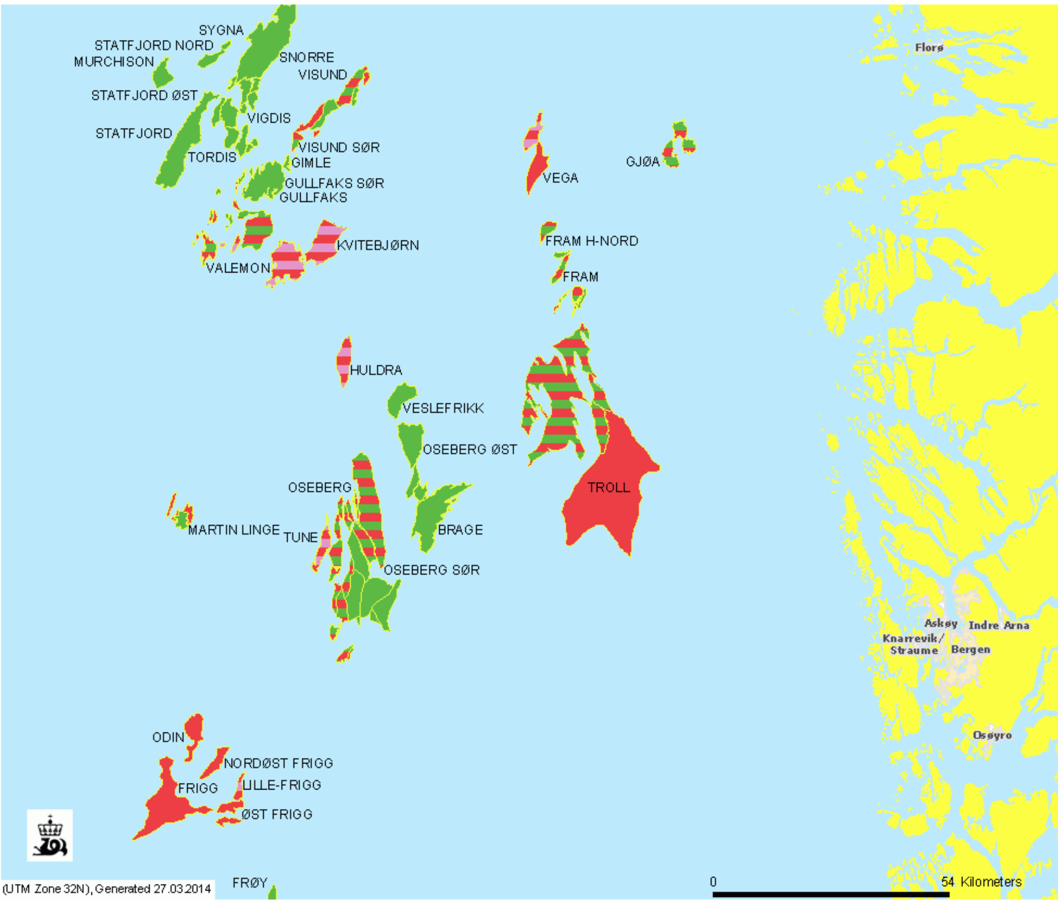

Figure 3-1 Outline and location of oil and gas fields in the North Sea west of Bergen. Figure from the NPD FactMap.

Updated HC reserve estimates are given for each field and the production history for each field are given in tables as monthly or yearly production. Figure 3-2 shows an example of production rate for the Draugen field taken from the NPD fact pages.

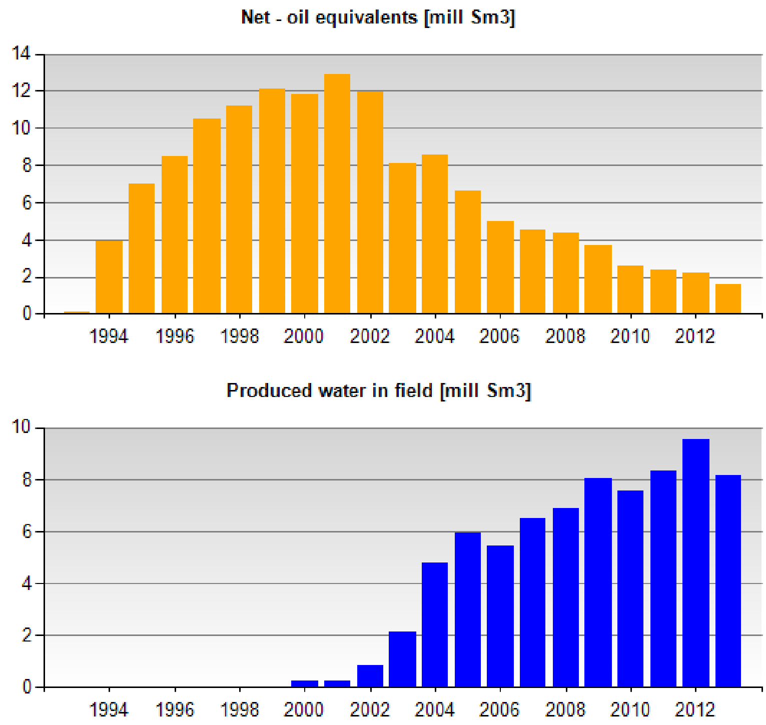

Figure 3-2 Example of production data from the NPD fact pages for the Draugen field. The figure show annual net production rate for oil equivalents (oil, gas and natural gas liquids) and annual production rate for water (bottom).

Information on geology and reservoir properties can for most fields be found in the exploration well data available at the web site. Table 3-1 below shows lithostratigraphy and list of cores from the Draugen exploration/appraisal well 6407/9-6 and Figure 3-3 show core photos from the same well in the Garn Formation.

Table 3-1 Litostratigraphy in exploration well 6407/9-6 and list of cores located at the NPD (from NPD fact pages).

⊟ Lithostratigraphy

Top depth [m]	Lithostrat. unit
301	NORDLAND GP
832	HORDALAND GP
832	BRYGGE FM
1342	ROGALAND GP
1342	TARE FM
1376	TANG FM
1540	SHETLAND GP
1571	CROMER KNOLL GP
1571	LANGE FM
1611	VIKING GP
1611	SPEKK FM
1643	ROGN FM
1660	FANGST GP
1660	GARN FM
1744	NOT FM
1775	BÅT GP
1775	ROR FM

⊟ Cores at the NPD

Core sample number	Core sample - top depth	Core sample - bottom depth	Core sample depth - uom
1	1646.0	1657.8	[m]
2	1660.0	1672.7	[m]
3	1672.7	1677.0	[m]
4	1678.8	1690.3	[m]

Figure 3-3 Core photo from coring interval 1665-1670 m measured depth (Garn Formation) in the Draugen appraisal well 6407/9-6. The cores are stored at NPD.

For evaluating CO_2 EOR potential of a HC field one need to know more than just the size, production history and porosity or pore volume and a full study with laboratory experiments on cores and fluid systems and reservoir simulations may be required. Characteristic properties for the hydrocarbon phases, pressure, temperature and formation properties such as heterogeneity, vertical to horizontal permeability ratio, dip and aquifer support could be used to calculate a first estimate of CO_2 EOR by the use of representative models or proxy functions. The SPOR monograph: Recent Advances in Improved Oil Recovery Methods for North Sea Sandstone Reservoirs (Skjæveland and Kleppe, 1992) have collected and listed characteristic data for around 20 oil fields in the North Sea and the Norwegian Sea. For each oil field properties of the formation, hydrocarbon system, formation water, pressure, temperature, size and resources are given.

Denmark

Oil and gas production in Denmark commenced in 1972, when the Dan field was put on production. All the hydrocarbon fields are located in the Danish sector of the North Sea (Figure 3-4).

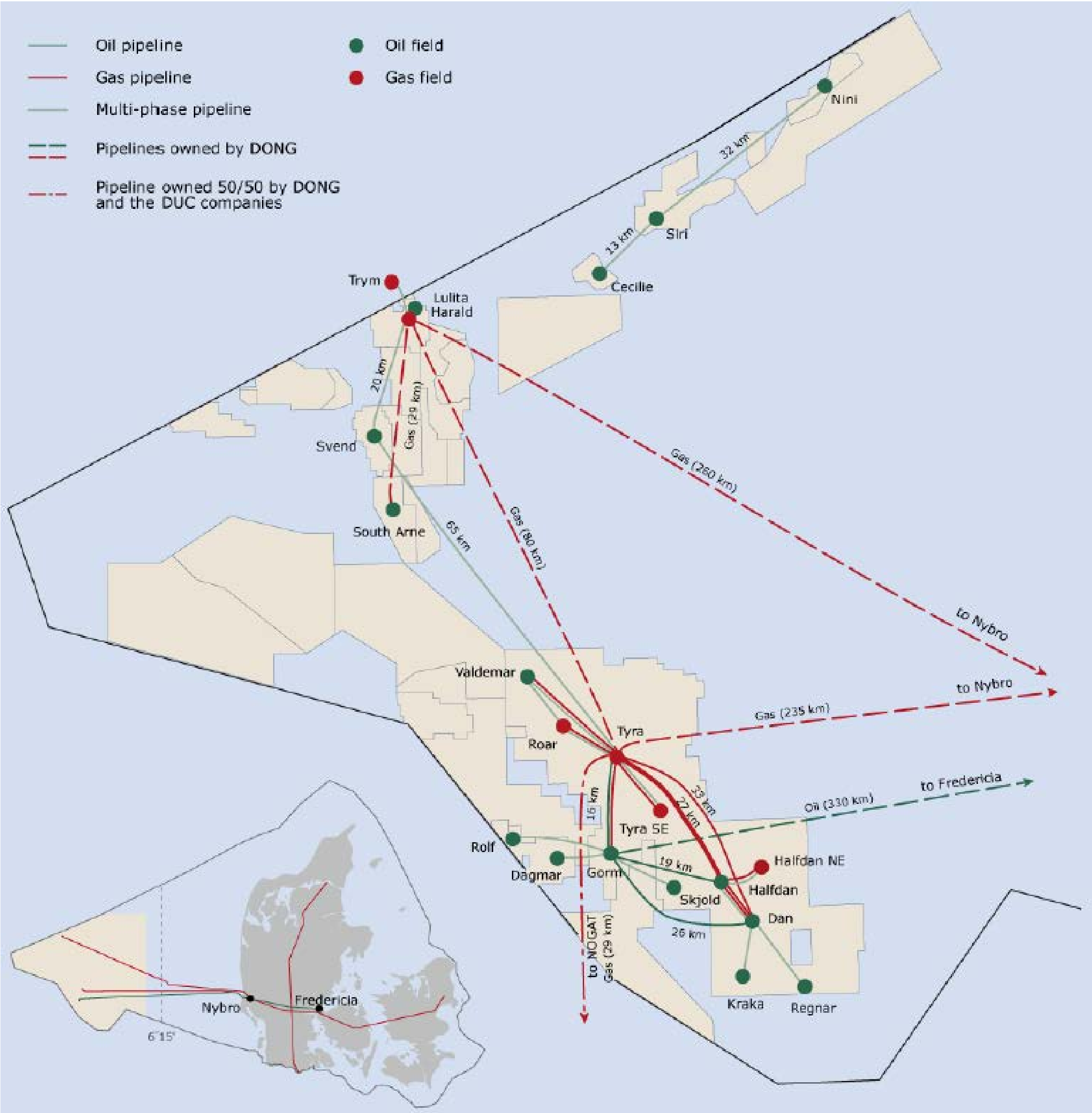

Figure 3-4 The Danish producing oil and gas fields in 2012. (Danish Energy Agency, 2013)

The majority of fields are producing from layers of Danian and Upper Cretaceous age with chalk as the primary reservoir rock. A few fields are producing from sandstone of Palaeocene or Middle Jurassic age. The chalk fields accounts for more than 95% of the remaining reserves. Five major chalk fields (Halfdan, Tyra, Dan, Valdemar and South Arne) account for more than 80% of the total oil production. The major chalk fields are developed with water injection as a secondary recovery mechanism.

Oil and gas exploration are focused offshore Denmark and in the Danish Central Graben (Fig. 3-5 and 3-6). Some fields are formed as domal structures overlying salt diapires of Zechstein age and some are anticlinal structures. The depth of top reservoir for the fields on production, are in the range of approx. 1400m to 3600m. The shallowest fields are located towards south west in the graben region.

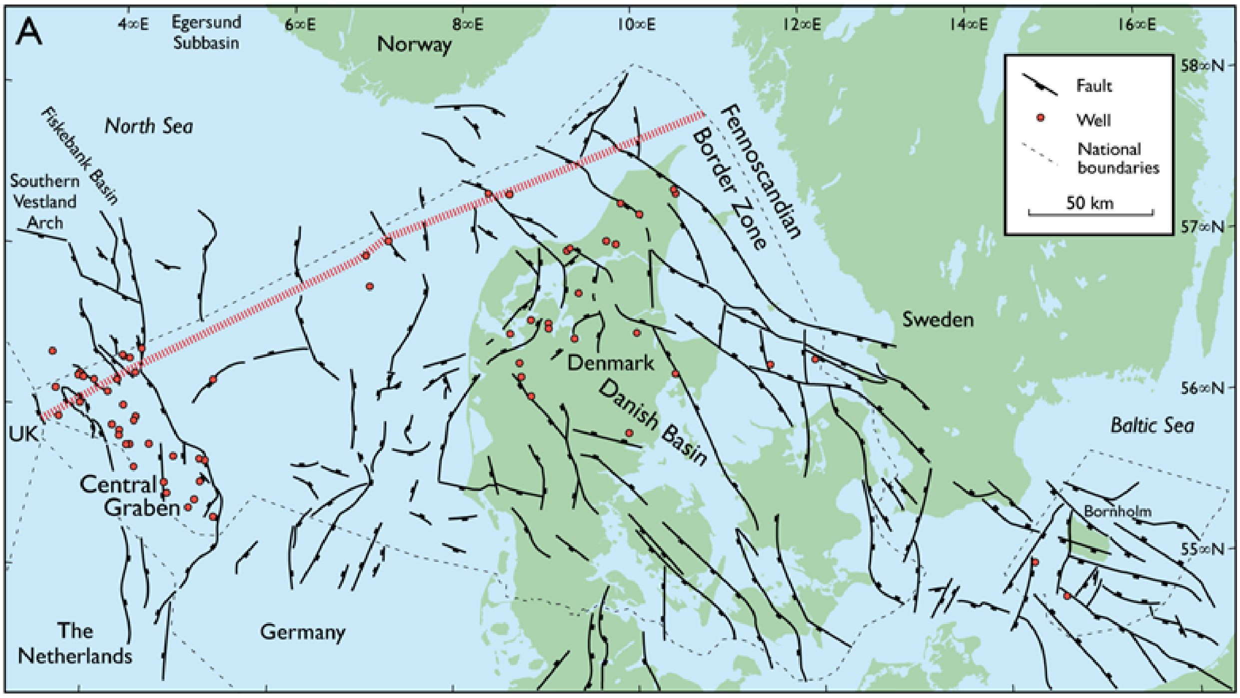

Figure 3-5 The Danish territory with an outline of the main Mesozoic elements; the Central Graben, The Danish Basin and the Fennoscandian Border Zone. The red line indicate the location of the geosection in Figure 3-6.

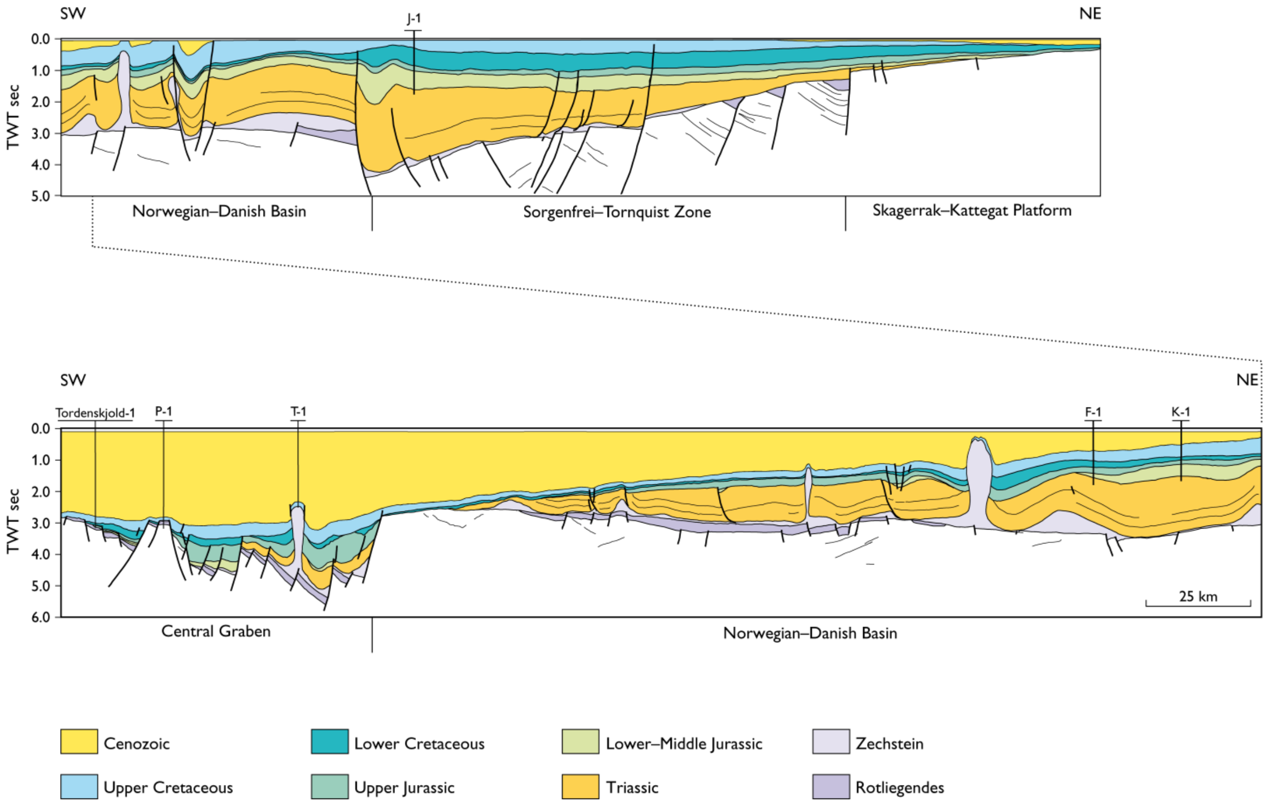

Figure 3-6 Geosection from the central Graben in the west to the Skagerrak-Kattegat Platform in the east. Location is shown on Figure 3-5. Modified from Vejbæk (1997), based on seismic line RTD-81-22.

Danish well data are restricted in 5 years, after this period a well data summary sheet are relished at the Geological Survey of Denmark and Greenland (GEUS) website and data are available for purchase. More information is found on http://www.geus.dk/geuspage-uk.htm

Public available data for the Danish hydrocarbon fields are yearly reported in the report "Denmark's Oil and Gas Production and Subsoil use" and can be downloaded from this page: http://www.ens.dk/en/oil-gas/reports-oil-gas-activities

4. CO_2 storage capacities in depleted HC fields

Norway

Estimates of CO_2 storage in depleted oil and gas reservoirs show a large potential for the Norwegian oil and gas fields. The NPD Storage Atlas (Halland *et al.,* 2012) and the JOULE II report (Halloway *et al.*, 1996) both gives estimates of CO_2 storage capacity in depleted oil and gas fields in the Norwegian part of the North Sea. In addition the NPD storage atlas for the Norwegian Sea and the Barents Sea (Halland *et al.*, 2013a, 2013b) also give CO_2 storage estimates for oil and gas fields north of 62°.

The JOULE II report(Holloway *et al.*, 1996) estimates a total CO_2 storage capacity in gas fields to be 7.2 Gt and in oil fields to be 3.5 Gt. The estimates are based on replacing the recoverable hydrocarbons with CO_2. For reservoirs subject to pressure support during production (e.g. water flooded reservoirs) the pressure increase from CO_2 injection could reduce the capacity. An option to increase the capacity is then to produce water from the reservoir. Table 4-1and Table 4-2 list characteristic parameters and estimated storage capacity for the evaluated gas and oil fields in the North Sea (from JOULE II).

Table 4-1 Estimates of CO_2 storage capacities in depleted gas reservoirs. Starting and termination years in parenthesis were at the time of the reporting of JOULE-II not decided yet.

Gas reservoirs	Production period		Pres-sure	Temper-ature	Recoverable resources		Density of CO_2	1/Bg	Mass of CO2
					Oil/Con.	Gas			
	start	end	[bar]	[°C]	[M Sm³]	[G Sm³]	[kg/m³]		[Mton]
Frigg	1977	1996	198	61	0.6	184.0	717	194	680
Odin	1984	1997	206	65	0.2	29.3	705	202	102
Nord-Øst Frigg	1983	1993	201	62	0.1	11.8	718	197	43
Øst Frigg	1988	1995	197	63		8.2	702	193	30
Lille-Frigg	1993	1999	200	63	2.7	7.0	708	196	25
Heimdal	1986	1997	217	76	4.2	35.6	658	211	111
Tommeliten Gam.	1988	1995	487	130	4.2	8.5	729	238	26
Tommeliten Alfa	1997	2005	487	130	4.0	7.8	729	238	24
Cod	1978	1995	590	161	2.9	7.4	717	300	18
Albueskjell	1979	2000	500	138	9.0	20.0	717	280	51
Sleipner Øst	1993	2002	300	104	30.3	50.0	648	213	152
Sleipner Vest	1996	2013	440	123	36.0	135.0	716	271	357
Loke	1994	2002	300	104	4.1	8.0	648	213	24
30/6 Gamma Nord	1991	2017	300	100	1.1	6.2	723	222	20
Midgard	(2002	2015)	251	90	14.3	87.0	641	214	261
Agat	(2005	2017)	455	118		43.0	741	271	118
Smørbukk	(2010	2022)	474	153	37.0	95.0	662	238	264
Smørbukk Sør	(2010	2022)	436	142	31.0	24.0	661	232	68
Troll Øst	1996	2032)	158	68	19.2	825.0	565	151	3087
Troll Vest (gas)	(2020)	(2050)	158	68	10.8	463.0	565	151	1733
West Ekofisk	1977	2000	498	131	12.7	28.6	733	1.37	13
Total					224.4	2084.4			7207

Table 4-2 Estimates of CO_2 storage capacities in depleted oil reservoirs. Starting and termination years in parenthesis were at the time of the reporting of JOULE-II not certain.

Oil reservoirs	Production period		Pres-sure	Temper-ature	Recoverable resources		Density of CO_2	Bo	Mass of CO2
					Oil/Cond.	Gas			
	start	end	[bar]	[°C]	[M Sm³]	[G Sm³]	[kg/m³]		[M ton]
Ekofisk	1971	2030	485	131	410.7	146.6	725.1	1.78	530.1
Eldfisk	1979	2025	470	119	109.3	52.7	747.8	2.35	192.1
Tor	1978	2005	492	136	28.3	11.7	716.7	1.85	37.5
Valhall	1982	2013	452	90	116.7	25.1	821.7	1.65	158.2
Gullfaks inc G. V.	1986	2006	317	76	319	21.2	778.4	1.3	322.8
Statfjord (Brent)	1979	2009	404	100	463.8	51.9	759.9	1.58	556.9
Statfjord (Statfj.)	1979	2009	383	89	276.1	14.6	781.5	1.58	340.9
Gyda	1990	2010	594	154	35.1	7	733.9	1.69	43.5
Gyda Sør									
Murchison	1980	1997	444	110	13.1	0.3	756.6	1.28	
Snorre	1992	2011	383	92	133.3	6.7	771.2	1.38	141.9
Ula	1986	2009	491	143	71.8	4.3	698.3	1.35	67.7
Veslefrikk	1989	2008	321	122	45.2	3.5	607.7	1.5	41.2
Brage	1994	2010	210	86	47.2	1.7	585.4	1.27	35.1
Frøy	1995	2010	206	65	14	3	705	1.3	12.8
Statfjord Nord	1994	2015	398	98	31	2.5	755.5	1.28	30.0
Statfjord Øst	1994	2010	398	98	13.4	2	755.5	1.28	13.0
Tordis inc. T. Ø.	1994	2007	400	95	33.5	2.5	773.28	1.3	33.7
Draugen	1993	2010	165	71	68	3	564.4	1.19	45.7
Heidrun	1996	2011	252	85	87.3	37.8	666.9	1.28	168.5
Oseberg	1988	2017	281	100	288.6	81	638.48	1.43	496.5
Balder	(2005)	(2021)	177	77	32.2	0	724.43	1.6	20.7
Gullfaks Sør	(2005)	(2021)	460	125	40	59.5	724.43	1.6	179.6
Njord	2002	2015	390	116	35	7.2	697.7	1.59	38.8
Total					2712.6	545.8			3507.1

The NPD CO_2 Storage Atlas for the North Sea estimates a total capacity of 3 Gt in depleted oil fields and 10 Gt in producing fields. The estimates for the Norwegian Sea and the Barents Sea are estimated to 1.1 Gt and 0.2 Gt in producing fields respectively. The Frigg field has been studied specifically by NPD showing large potential for CO_2 storage (3.4 Gt max case). Table 4-3 list the estimated storage capacity for Norwegian oil and gas fields from the NPD CO_2 storage atlas. The Troll field is assumed to produce after 2050 and a storage capacity is estimated together with the Sognefjord delta sandstones to be 14 Gt CO_2.

Table 4-3 NPD estimates of storage capacity in Norwegian fields (from the Storage Atlas).

Oil and Gas Fields	North Sea	Norwegian Sea	Barents Sea
	Storage capacity (Gt)	Storage capacity (Gt)	Storage capacity (Gt)
Abandoned fields	3		
Fields in prod. 2030	4	0.9	
Fields in prod. 2050	6	0.2	0.2
Sognefjord delta incl Troll	14		

Denmark

In 1996 the Joule II report estimated the CO_2 storage capacity to be 592 Mt. Later the CO_2 storage capacity in Danish oil and gas fields was assessed as part of the GESTCO (2004) and GeoCapacity (2009) projects. In GeoCapacity the assessment methodology has not been changed but new estimates have been calculated using the latest available information and the assessment was updated together with additional data from 6 fields that were previously not included. Only fields on stream prior to January 1st 2001 were considered, in total 17 fields and they are all still producing. The assessment methodology is based on the latest available information published by the Danish Energy Authorities being the annual report on oil and gas production for 2005 as later annual reports does not include tables of reserves on a field by field basis.

The storage capacity of the Danish hydrocarbon fields has been estimated using the formula from the GESTCO project (Schuppers et al., 2003) assuming a 1:1 volumetric replacement ratio between hydrocarbons and CO_2:

$$M_{CO2} = \rho_{CO2r} \times UR_p \times B$$

where:

M_{CO2}: hydrocarbon field storage capacity

ρ_{CO2r}: CO_2 density at reservoir conditions (best estimate)

UR_p: proven ultimate recoverable oil or gas

B: oil or gas formation volume factor

The CO_2 density varies with depth as a function of pressure and temperature and has been estimated using the PVTsim software (Calsep, 2001).

UR_p is the sum of the cumulative production and the proven reserves and is given as the sum of produced volumes and the low estimate for reserves for each field as published by the Danish Energy Authorities for 2005 (Danish Energy Authority, 2006).

CO_2 replacement of oil and gas, respectively, has been calculated separately. The formation volume factor for oil varies regionally depending on the oil type and a fixed formation volume factor of 1.2 has been used for the oil replacement. The formation volume factor used for gas varies with depth as a function of pressure and temperature.

The total estimated CO_2 storage capacity for the Danish hydrocarbon fields amounts to 810 Mt as seen in Table 4-4.

Table 4-4 The estimated storage capacity for the Danish oil and gas fields (GESTCO/GeoCapacity).

Field Name	Lithology	Main production	Start of prod.	Total estimated CO_2 storage capacity (Mt)
Lulita	Sandstone	Oil	1998	0.8
Rolf	Chalk	Oil	1986	3.13
Harald West	Sandstone	Gas	1997	0
Svend	Chalk	Oil	1996	8.53
South Arne	Chalk	Oil	1999	52.01
Tyra	Chalk	Gas	1984	211.05
Dagmar	Chalk	Oil	1991	0.78
Gorm	Chalk	Oil	1981	73.49
Dan	Chalk	Oil	1997	174.09
Kraka	Chalk	Oil	1991	11
Regnar	Chalk	Oil	1993	0.78
Valdemar	Chalk	Oil	1993	23.92
Roar	Chalk	Gas	1996	48.47
Halfdan	Chalk	Oil	2000	83.52
Skjold	Chalk	Oil	1982	43.96
Harald East	Chalk	Gas	1997	66.83
Siri	Sandstone	Oil	1999	7.85
Total estimated CO_2 storage capacity for all Danish hydrocarbon fields (Mt)				**810.21**

5. CO_2 EOR/EGR

Norway

Injecting CO_2 for enhanced oil or gas recovery can give an added value for CO_2 which can help to establish an infrastructure for large scale CO_2 storage in the Nordic countries. Several studies have been performed to investigate the potential for CO_2 EOR in the North Sea but no project or pilot have been started due to high estimated costs and lack of steady and large amounts of CO_2. A study by NPD in 2005 (NPD, 2005) indicated a CO_2 EOR in the order of 3 to 7 % giving an estimated added production potential from 20 fields to between 150 and 300 MSm^3 of oil. The potential is based on estimation of 20 fields listed in Table 5-1 below assessed to have suitable reservoir properties for CO_2 injection.

Table 5-1 Twenty fields assessed by NPD to have suitable reservoir properties for CO_2 injection.

Southern North Sea	Troll, Oseberg Area	Tampen Area	Norwegian Sea
Ekofisk	Brage	Gullfaks Gullfaks Sør	Draugen
Eldfisk	Oseberg Sør	(Rimfaks)	Heidrun (excl. Åre)
Gyda	Oseberg Øst	Snorre	Norne Åsgard (Smørbukk
Ula	Veslefrikk	Statfjord Nord	Sør)
Valhall		Sygna	
		Vigdis	
		Tordis (excl. Borg)	

In the Norwegian Sea a joint study by Statoil and Shell to develop a large-scale CO_2 EOR project on Draugen and Heidrun were performed in 2006. The main conclusion from the study was that the cost were too high and amount of available CO_2 (2.5 Mt/a from a planned gas power plant at Tjeldbergodden) too small to get a good increase of the recovery. No EOR estimate was published for Draugen but the potential for Heidrun was estimated to 2.6% (NPD Storage Atlas). Other studies of CO_2 EOR on Norwegian fields have been performed on Gullfaks (Agustsson and Grinestaff, 2004) and Ekofisk (Jensen *et al.*, 2000).

The only full field study of CO_2 injection for EOR has been performed on the Gullfaks Field by Statoil. The study estimates that with an annual CO_2 injection rate of 5 Mt the extra recovery would be 36 MSm^3 oil. This would represent an approximately 5% increase in recovery. In the same study simulations on sector models indicated between 5 and 15 % increased recovery by CO_2 injection.

An EOR screening of the Ekofisk Field performed by Phillips Petroleum Company in 2000 included a scenario with CO_2 EOR. The estimated increase in recovery was found to be 5.6 % giving an increased oil production of approximately 57 MSm^3 oil. Main objections to injecting CO_2 for EOR on Ekofisk were the lack of a large and steady supply of CO_2 and the possible effect of CO_2 saturated water on the chalk mechanical properties. Laboratory tests introducing CO_2 saturated water to Ekofisk chalk samples resulted in immediate and vigorous dissolution of the chalk. Further studies would therefore be required to assess this effect.

A study of CO_2 injection in Brage performed by Norsk Hydro in 2003 (operator at the time) was referred to in Mathiassen (Mathiassen, 2003) to give an additional oil of 4.4% of STOOIP.

Denmark

The Danish oil production peaked in 2004, which brings focus on how to prolong production from mature fields and increase the overall recovery factor. Production from the Danish North Sea oil fields has reached a stage where secondary recovery methods (mainly water injection) are the main drivers of today's oil production. When these secondary recovery methods are no longer profitable, there may still be 70% of the discovered oil left in the fields (Danish Energy Agency website, 2014).

The major operator in the Danish sector, Maersk Oil, is in the process of finding a number of commercial partners, identifying suitable locations for storing CO_2 in its Danish North Sea fields and running technical tests. As oil fields mature in the Danish North Sea, such additional recovery using CO_2 as the agent in EOR means that Maersk Oil can extend the lifespan of the operation and continue production. The potential for CO_2 storage in the Danish North Sea has been estimated to be more than 600 million tonnes, according to a 2003 study by the European Commission-funded GESTCO project (MAERSK Oil website, 2014).

As Halfdan, Tyra, Dan, Valdemar and South Arne are accounting for 80% of the total Danish oil and gas production these fields are considered the most attractive candidates for EOR. The North Sea reservoirs fit many of the criteria for miscible EOR application. They are deep enough to permit the high pressures required to attain miscibility and often contain sufficiently light and low viscosity oils, both characteristics that are ideal for miscible EOR. (Lake and Walsh, 2008).

For the subsurface part (not including the wells) the Danish fields constitute a wide range of fields with possibilities for CO_2 EOR, i.e.:

- The depth window for many of the reservoirs is favourable.
- The porosity is preserved.
- Injectivity is attainable, with or without fracturing.
- Controlled well patterns for high sweep efficiency.
- Structural closures with efficient seals.
- Effective reservoir evaluation.

Laboratory experiments with water and CO_2 flooding of reservoir chalk samples from the Danish North Sea has given some very promising results. The experiment used samples from the Tor (Upper Cretaceous) and Ekofisk (Palaeocene) Formations and was conducted under reservoir conditions. One of the conclusions was that especially the Ekofisk chalk, which is non-economic for water flooding, seems to have a significant potential for CO_2 EOR (Olsen, 2011).

6. Large scale CO_2 EOR, infrastructure projects and generic models

Studies using CO_2 from industrial sources for large scale CO_2-EOR on North Sea oil fields have been performed at SINTEF Petroleum Research (Holt and Lindeberg, 1992, 1993 and 1994, 2004). This has lead to development of a techno-economic model for CO_2 injection into North Sea oil reservoirs and aquifers using a large scale infrastructure for transport (Holt *et al.* 2009). The techno-economic model estimates an EOR potential in the range 8.5 to 9.0 % of the hydrocarbon pore volume originally in place (658 to 696 Sm3 in the North Sea). The total amount of CO_2 stored in oil reservoirs and aquifers was estimated to 7.2 Gt of which 31 % was stored in the oil reservoirs (2.2 Gt). In order to estimate the EOR potential for the North Sea oil fields a conceptual reservoir model representative of North Sea sandstone reservoirs were developed (CO_2 EOR module) on which a series of simulations with a varying set of parameters were performed. Based on these a proxy function has been constructed giving the EOR potential as function of a set of characteristic properties for the field. Figure 6-1 show the EOR profile for 18 Norwegian fields in the North Sea after 50 years of CO_2 injection and Table 3-1 lists the total EOR potential and amount of stored CO_2.

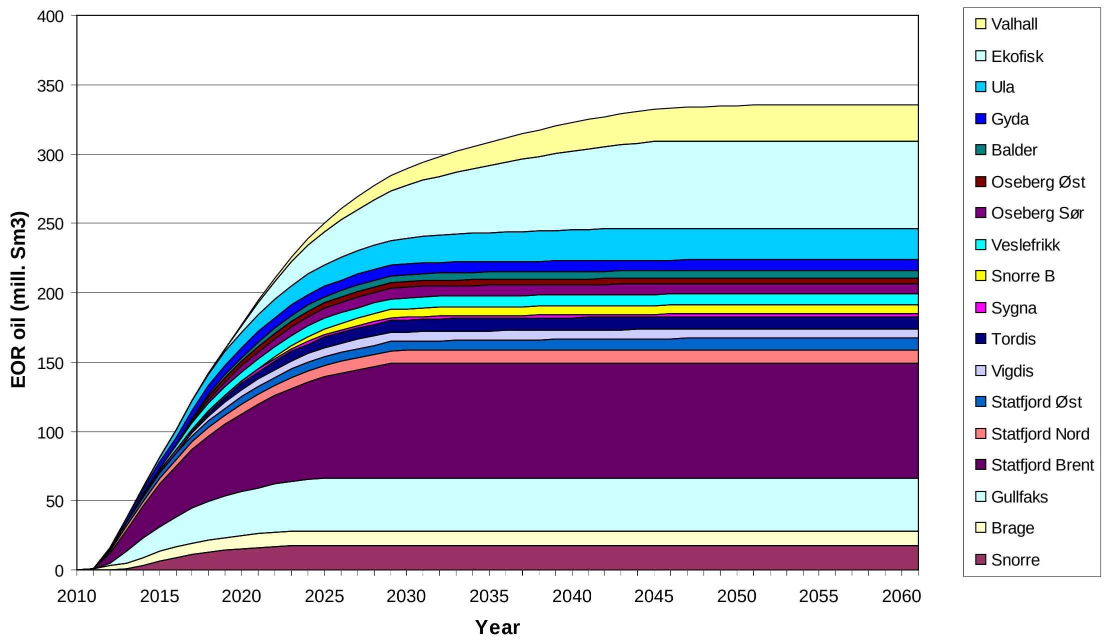

Figure 6-1 EOR profile for the 18 Norwegian Fields from the WAG EOR module developed at SINTEF Petroleum for the techno economic modelling.

Table 6-1 Total oil recovery, total oil recovery factor, CO_2 EOR potential, CO_2 EOR factor and stored CO_2 in the 18 Norwegian oil fields, from Holt *et al.*, 2009.

Total oil	2269.0	million Sm^3
Oil rec. factor	53.7	% HCPV
EOR oil	335.4	million Sm^3
EOR oil	7.9	% HCPV
Stored CO_2	1152.7	million tonnes

The generic CO_2 EOR module was modified further by SINTEF in the EU-funded ECCO project (European value chain for CO_2) to account for three main geological depositional environments; shallow marine, fluvial and turbidite deposits (Akervoll and Bergmo, 2010). The geometry of the North Sea conceptual reservoir model, the grid, the depth and the well positions are shown in Figure 6-2. The areal extent of the model is 1450 m by 790 m. The thickness of the reservoir model is 46 ± 1.2 m. The reservoir model is penetrated by two wells, one injector located down-flank (I1, water and CO2) and one producer (P1) at the crest or top of the model. The geometrical model setup is used for all three depositional environments.

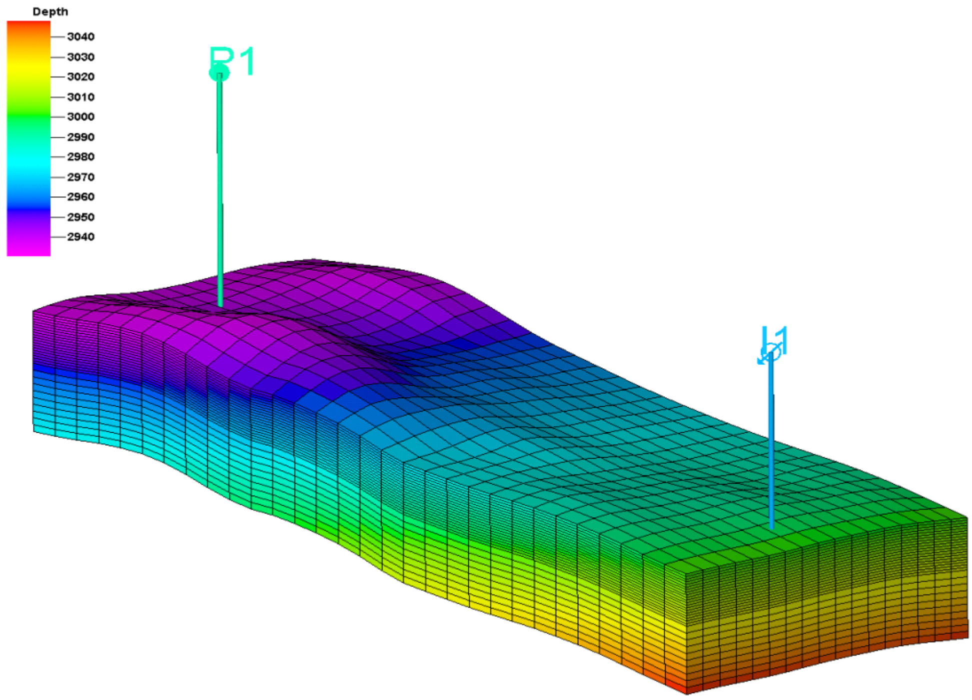

Figure 6-2: Geometry, grid, depth and well positions of the conceptual model for investigating CO_2-EOR in North Sea. Colours indicate depth. Tilt of the model is 5° and the illustration is exaggerated in z direction by a factor 5.

In addition to continued water injection (base case) the parameter variation and number of simulation for each geological representation is listed in Table 6-2. The value span of each parameter in the table relate to the occurrence of equivalent parameters found among potential North Sea oil reservoirs.

Table 6-2: Overview of reservoir simulation cases with parameter sensitivities.

Parameter	Values	Units	# of cases
Model dip	2, 5, 10	Degrees	3
Injection rate	300, 600, 1200	Rm^3/day	9
Saturation end point	0.1, 0.2, 0.3	Fraction	27
k_v/k_h*	0.01, 1	Fraction	54
Gas-oil ratio	40, 120, 159	Sm^3/Sm^3	162
Onset of CO_2	0.6, 1.2	PV injected	324
WAG cycle length	3, 12	Months	648

*Heterogeneity factor: k_v/k_h is modified by multiplying the vertical permeability (k_v) with a factor 0.01 and 1.0.

An example of the shape of a typical oil production rate from the conceptual model is shown in Figure 6-3 for continued water injection and WAG. The case shown below is for a shallow marine model with low k_v/k_h giving a very good response on the CO_2 injection, the rates have been normalized to one.

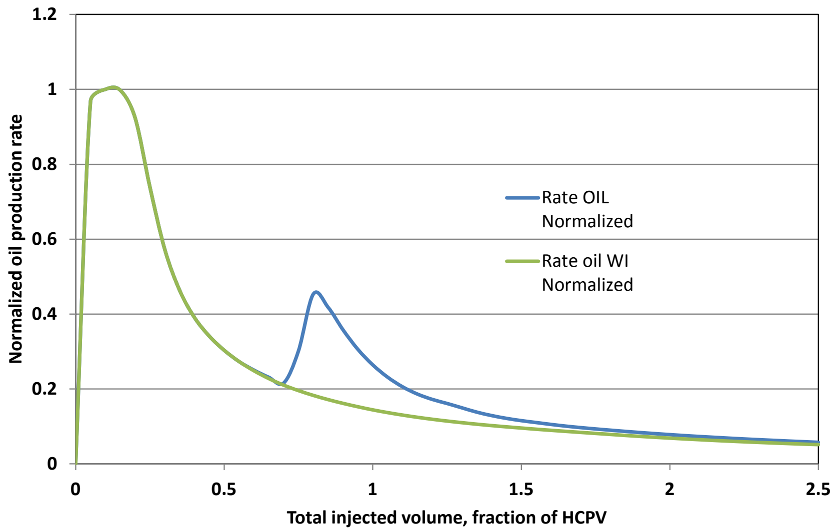

Figure 6-3 Example of oil recovery rate (normalized) for a water injection case (WI) and a WAG injection case. WAG injection starts after injecting 0.6 HCPV water.

The conceptual reservoir model is relatively small with no-flow boundary conditions and water injection from the start which can result in very high recovery. Applying the EOR results from the conceptual models directly on fields can thus give too optimistic recoveries and a scaling of the sweep efficiency of the injected CO_2 and a fitting of the dimensionless production profile is necessary. A first attempt at applying the CO_2-EOR module results on actual oil fields in the North Sea has been performed giving a range of EOR between 2.4% and 7.4% for CO_2-WAG injection in Brage, Draugen, Gyda and Ula. (Bergmo and Akervoll, 2010).

7. Summary

Hydrocarbon fields are good candidates for CO_2 storage due to their already proven sealing capacities. CO_2 EOR represents an added value which can help bridging the technology and infrastructure required for large scale CO_2 storage in saline aquifers. A wealth of data for oil and gas fields is available at NPD in Norway and to some extent at GEUS and from the Danish Energy Agency in Denmark.

Storage capacity in the Danish oil and gas fields (from GESTCO/GeoCapacity) is estimated to 810 Mt. For the Norwegian oil and gas fields the JOULE II report (Holloway *et al.*, 1996) estimates a total CO_2 storage capacity in gas fields to be 7.2 Gt and in oil fields to be 3.5 Gt. A more recent estimate by NPD in the CO_2 Storage Atlas is 14.3 Gt for Norwegian oil and gas fields (not including Troll).

CO_2 EOR potential on Norwegian oil fields have been studied by several. A study by NPD indicated a CO_2 EOR in the order of 3 to 7 % giving an estimate of extra oil from 20 selected fields between 150 and 300 Sm^3. Other studies refer to recoveries in the same range on selected fields.

Studies at SINTEF Petroleum using generic reservoir models for CO_2 EOR of already water flooded oil reservoirs indicate an EOR potential between 8.5 and 9 % (of initial oil in place). Further development of the generic modelling approach gave an EOR range between 2.4 and 7.4 % for CO_2-WAG applied to the Brage, Draugen, Gyda and Ula oil fields.

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9. Appendix

List of oil and gas fields in the NPD online database.

Felt navn	Oppr. utvinnbar olje [mill Sm3]	Oppr. utvinnbar gass [mrd Sm3]	Oppr. utvinnbar NGL [mill tonn]	Oppr. utvinnbar kondensat [mill Sm3]	Oppr. utvinnbar ekv. [mill Sm3 o.e]	Gjenv. olje [mill Sm3]	Gjenv. gass [mrd Sm3]	Gjenv. NGL [mill tonn]	Gjenv. kondensat [mill Sm3]	Gjenv. olje ekv. [mill Sm3 o.e]	Reservene oppdatert dato	NPDID for felt	Dato synkronisert OD
ALBUSKJELL	7.40	15.60	1.00	0.00	24.90	0.00	0.00	0.00	0.00	0.00	31.12.2012	43437	10.02.2014
ALVE	1.90	5.70	1.10	0.00	9.69	0.80	2.70	0.60	0.00	4.64	31.12.2012	4444332	10.02.2014
ALVHEIM	37.20	6.80	0.00	0.00	44.00	17.50	4.70	0.00	0.00	22.20	31.12.2012	2845712	10.02.2014
ATLA	0.30	1.40	0.00	0.00	1.70	0.30	1.30	0.00	0.00	1.60	31.12.2012	21106284	10.02.2014
BALDER	72.10	2.00	0.00	0.00	74.10	16.20	0.60	0.00	0.00	16.80	31.12.2012	43562	10.02.2014
BLANE	0.80	0.00	0.00	0.00	0.80	0.30	0.00	0.00	0.00	0.30	31.12.2012	3437650	10.02.2014
BRAGE	59.30	4.50	1.50	0.00	66.65	4.00	1.20	0.30	0.00	5.77	31.12.2012	43651	10.02.2014
BRYNHILD	3.60	0.00	0.00	0.00	3.60	3.60	0.00	0.00	0.00	3.60	31.12.2012	21123063	10.02.2014
BØYLA	3.40	0.30	0.00	0.00	3.70	3.40	0.30	0.00	0.00	3.70	31.12.2012	22492497	10.02.2014
COD	2.90	7.30	0.50	0.00	11.15	0.00	0.00	0.00	0.00	0.00	31.12.2012	43785	10.02.2014
DRAUGEN	146.70	1.60	2.80	0.00	153.62	14.90	0.10	0.40	0.00	15.76	31.12.2012	43758	10.02.2014
EDDA	4.80	2.00	0.20	0.00	7.18	0.00	0.00	0.00	0.00	0.00	31.12.2012	43541	10.02.2014
EDVARD GRIEG	26.20	1.80	0.60	0.00	29.14	26.20	1.80	0.60	0.00	29.14	31.12.2012	21675433	10.02.2014
EKOFISK	569.20	164.50	15.20	0.00	762.58	129.80	22.80	2.20	0.00	156.78	31.12.2012	43506	10.02.2014
ELDFISK	137.90	44.80	4.10	0.00	190.49	37.30	5.40	0.20	0.00	43.08	31.12.2012	43527	10.02.2014
EMBLA	11.90	7.50	0.70	0.00	20.73	1.50	3.60	0.30	0.00	5.67	31.12.2012	43534	10.02.2014
ENOCH	0.40	0.00	0.00	0.00	0.40	0.10	0.00	0.00	0.00	0.10	31.12.2012	3437659	10.02.2014
FRAM	30.70	8.80	0.60	0.00	40.64	5.90	6.30	0.40	0.00	12.96	31.12.2012	1578840	10.02.2014
FRIGG	0.00	116.20	0.00	0.50	116.70	0.00	0.00	0.00	0.00	0.00	31.12.2012	43555	10.02.2014
FRØY	5.60	1.60	0.00	0.10	7.30	0.00	0.00	0.00	0.00	0.00	31.12.2012	43597	10.02.2014
GAUPE	0.20	0.50	0.00	0.00	0.70	0.10	0.30	0.00	0.00	0.40	31.12.2012	18161341	10.02.2014
GIMLE	3.00	1.40	0.30	0.00	4.97	0.40	1.00	0.20	0.00	1.78	31.12.2012	4005142	10.02.2014
GJØA	11.60	32.70	8.70	0.00	60.83	6.40	27.80	7.60	0.00	48.64	31.12.2012	4467574	10.02.2014
GLITNE	8.90	0.00	0.00	0.00	8.90	0.00	0.00	0.00	0.00	0.00	31.12.2012	1272071	10.02.2014
GOLIAT	30.20	7.30	0.30	0.00	38.07	30.20	7.30	0.30	0.00	38.07	31.12.2012	5774394	10.02.2014
GRANE	124.60	0.00	0.00	0.00	124.60	36.10	0.00	0.00	0.00	36.10	31.12.2012	1035937	10.02.2014
GUDRUN	11.70	6.40	1.30	0.00	20.57	11.70	6.40	1.30	0.00	20.57	31.12.2012	18116481	10.02.2014
GULLFAKS	365.50	23.10	2.80	0.00	393.92	11.60	0.00	0.00	0.00	11.60	31.12.2012	43686	10.02.2014
GULLFAKS SØR	58.80	65.10	9.20	0.00	141.38	16.60	32.10	5.00	0.00	58.20	31.12.2012	43699	10.02.2014
GUNGNE	0.00	15.20	2.20	4.70	24.08	0.00	1.30	0.30	0.40	2.27	31.12.2012	43464	10.02.2014
GYDA	36.50	6.70	2.00	0.00	47.00	0.90	0.50	0.10	0.00	1.59	31.12.2012	43492	10.02.2014
HEIDRUN	182.10	46.50	2.20	0.00	232.78	40.10	31.30	1.70	0.00	74.63	31.12.2012	43771	10.02.2014
HEIMDAL	8.20	46.90	0.00	0.00	55.10	1.60	1.70	0.00	0.00	3.30	31.12.2012	43590	10.02.2014
HOD	10.40	1.80	0.40	0.00	12.96	0.90	0.20	0.10	0.00	1.29	31.12.2012	43485	10.02.2014
HULDRA	5.10	17.50	0.10	0.00	22.79	0.00	0.70	0.00	0.00	0.70	31.12.2012	97002	10.02.2014
HYME	3.20	0.50	0.20	0.00	4.08	3.20	0.50	0.20	0.00	4.08	31.12.2012	20474183	10.02.2014
ISLAY	0.00	0.10	0.00	0.00	0.10	0.00	0.10	0.00	0.00	0.10	31.12.2012	21105675	10.02.2014
JETTE	1.50	0.10	0.00	0.00	1.60	1.50	0.10	0.00	0.00	1.60	31.12.2012	21613906	10.02.2014
JOTUN	23.40	1.10	0.00	0.00	24.50	0.70	0.20	0.00	0.00	0.90	31.12.2012	43604	10.02.2014
KNARR	11.90	0.30	0.80	0.00	13.72	11.90	0.30	0.80	0.00	13.72	31.12.2012	20460988	10.02.2014
KRISTIN	22.90	28.70	6.30	2.10	65.67	6.00	9.70	2.30	0.00	20.07	31.12.2012	1854729	10.02.2014
KVITEBJØRN	27.30	89.10	11.50	0.00	138.25	9.80	49.80	8.10	0.00	74.99	31.12.2012	1036101	10.02.2014
LILLE-FRIGG	1.30	2.20	0.00	0.00	3.50	0.00	0.00	0.00	0.00	0.00	31.12.2012	43583	10.02.2014
MARTIN LINGE	6.00	19.70	0.70	3.00	30.03	6.00	19.70	0.70	3.00	30.03	31.12.2012	21675447	10.02.2014
MARULK	0.70	8.40	0.90	0.00	10.81	0.60	7.80	0.90	0.00	10.11	31.12.2012	18212090	10.02.2014
MIKKEL	6.60	31.40	8.60	2.20	56.54	3.30	15.80	4.40	0.00	27.46	31.12.2012	1630514	10.02.2014
MIME	0.40	0.10	0.00	0.00	0.50	0.00	0.00	0.00	0.00	0.00	31.12.2012	43792	10.02.2014
MORVIN	9.30	4.50	1.10	0.00	15.89	5.60	4.50	1.10	0.00	12.19	31.12.2012	4966234	10.02.2014
MURCHISON	13.90	0.40	0.00	0.00	14.30	0.00	0.00	0.00	0.00	0.00	31.12.2012	43665	10.02.2014
NJORD	28.50	17.20	3.90	0.00	53.11	3.00	9.40	2.10	0.00	16.39	31.12.2012	43751	10.02.2014
NORDØST FRIGG	0.00	11.60	0.00	0.10	11.70	0.00	0.00	0.00	0.00	0.00	31.12.2012	43568	10.02.2014
NORNE	90.80	12.00	1.60	0.00	105.84	3.80	5.40	0.80	0.00	10.72	31.12.2012	43778	10.02.2014
ODIN	0.00	27.30	0.00	0.20	27.50	0.00	0.00	0.00	0.00	0.00	31.12.2012	43610	10.02.2014
ORMEN LANGE	0.00	306.30	0.00	16.70	323.00	0.00	207.70	0.00	9.10	216.80	31.12.2012	2762452	10.02.2014
OSEBERG	384.60	104.10	12.10	0.00	511.69	22.70	69.20	3.80	0.00	99.12	31.12.2012	43625	10.02.2014
OSEBERG SØR	61.00	16.00	1.60	0.00	80.04	17.20	8.00	1.60	0.00	28.24	31.12.2012	43645	10.02.2014
OSEBERG ØST	26.70	0.40	0.30	0.00	27.67	7.90	0.10	0.30	0.00	8.57	31.12.2012	43639	10.02.2014
OSELVAR	4.60	3.90	0.00	0.00	8.50	4.50	3.90	0.00	0.00	8.40	31.12.2012	5506919	10.02.2014
REV	0.70	2.70	0.10	0.00	3.59	0.00	0.00	0.00	0.00	0.00	31.12.2012	4467554	10.02.2014
RINGHORNE ØST	15.50	0.40	0.00	0.00	15.90	6.30	0.10	0.00	0.00	6.40	31.12.2012	3505505	10.02.2014
SIGYN	0.00	6.90	2.60	6.40	18.24	0.00	0.70	0.20	0.60	1.68	31.12.2012	1630100	10.02.2014
SKARV	15.50	43.40	5.60	0.00	69.54	15.50	43.40	5.60	0.00	69.54	31.12.2012	4704482	10.02.2014
SKIRNE	2.20	10.20	0.00	0.00	12.40	0.50	1.30	0.00	0.00	1.80	31.12.2012	2138816	10.02.2014
SKULD	13.40	0.60	0.10	0.00	14.19	13.40	0.60	0.10	0.00	14.19	31.12.2012	21350124	10.02.2014
SLEIPNER VEST	0.00	133.30	9.50	32.90	184.25	0.00	19.80	1.50	4.50	27.15	31.12.2012	43457	10.02.2014
SLEIPNER ØST	0.00	67.80	13.50	27.00	120.45	0.00	1.50	0.40	0.20	2.46	31.12.2012	43478	10.02.2014
SNORRE	249.90	6.60	4.70	0.00	265.43	64.10	0.30	0.10	0.00	64.59	31.12.2012	43718	10.02.2014
SNØHVIT	0.00	176.70	6.40	22.60	211.46	0.00	156.90	5.40	19.00	186.16	31.12.2012	2053062	10.02.2014
STATFJORD	570.40	77.40	23.00	1.10	692.60	4.30	11.40	6.10	0.60	27.89	31.12.2012	43658	10.02.2014
STATFJORD NORD	39.50	2.10	1.10	0.00	43.69	3.00	0.00	0.30	0.00	3.57	31.12.2012	43679	10.02.2014
STATFJORD ØST	36.80	4.00	2.10	0.00	44.79	0.70	0.10	0.80	0.00	2.32	31.12.2012	43672	10.02.2014
SVALIN	12.10	0.00	0.00	0.00	12.10	12.10	0.00	0.00	0.00	12.10	31.12.2012	22507971	10.02.2014
SYGNA	11.00	0.00	0.00	0.00	11.00	1.10	0.00	0.00	0.00	1.10	31.12.2012	104718	10.02.2014
TAMBAR	9.50	2.00	0.50	0.00	12.45	0.60	0.00	0.20	0.00	0.98	31.12.2012	1028599	10.02.2014
TAMBAR ØST	0.30	0.00	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	31.12.2012	4999528	10.02.2014
TOMMELITEN GAMMA	3.90	9.70	0.50	0.00	14.55	0.00	0.00	0.00	0.00	0.00	31.12.2012	43444	10.02.2014
TOR	24.30	10.90	1.20	0.00	37.48	0.40	0.10	0.00	0.00	0.50	31.12.2012	43520	10.02.2014
TORDIS	61.20	4.60	1.80	0.00	69.22	6.00	0.40	0.20	0.00	6.78	31.12.2012	43725	10.02.2014
TROLL	263.80	1432.80	27.50	1.50	1750.35	36.00	984.90	21.10	(2.80)	1058.19	31.12.2012	46437	10.02.2014
TRYM	1.50	4.30	0.00	0.00	5.80	0.80	3.20	0.00	0.00	4.00	31.12.2012	18081500	10.02.2014
TUNE	3.30	18.30	0.20	0.00	21.98	0.00	0.00	0.00	0.00	0.00	31.12.2012	853376	10.02.2014
TYRIHANS	32.40	41.70	10.90	0.00	94.81	16.50	40.90	10.70	0.00	77.73	31.12.2012	3960848	10.02.2014
ULA	87.90	3.90	4.00	0.00	99.40	15.70	0.00	1.40	0.00	18.36	31.12.2012	43800	10.02.2014
URD	7.00	0.20	0.00	0.00	7.20	2.00	0.00	0.00	0.00	2.00	31.12.2012	2834734	10.02.2014
VALE	2.40	2.30	0.00	0.00	4.70	1.10	1.30	0.00	0.00	2.40	31.12.2012	1578893	10.02.2014
VALEMON	4.90	26.10	1.30	0.00	33.47	4.90	26.10	1.30	0.00	33.47	31.12.2012	20460969	10.02.2014
VALHALL	147.40	27.50	5.50	0.00	185.35	41.50	6.90	2.20	0.00	52.58	31.12.2012	43548	10.02.2014
VARG	16.40	1.10	1.00	0.00	19.40	1.40	1.10	1.00	0.00	4.40	31.12.2012	43451	10.02.2014
VEGA	6.60	14.00	2.40	0.00	25.16	5.10	12.20	2.00	0.00	21.10	31.12.2012	4467595	10.02.2014
VESLEFRIKK	54.10	5.70	2.00	0.00	63.60	1.80	3.30	0.70	0.00	6.43	31.12.2012	43618	10.02.2014
VEST EKOFISK	12.20	26.00	1.40	0.00	40.86	0.00	0.00	0.00	0.00	0.00	31.12.2012	43513	10.02.2014
VIGDIS	66.60	1.90	1.20	0.00	70.78	15.00	0.20	0.30	0.00	15.77	31.12.2012	43732	10.02.2014
VILJE	13.60	0.00	0.00	0.00	13.60	6.20	0.00	0.00	0.00	6.20	31.12.2012	3392471	10.02.2014
VISUND	33.90	51.30	6.40	0.00	97.36	11.50	44.30	6.00	0.00	67.20	31.12.2012	43745	10.02.2014
VISUND SØR	2.70	7.30	0.90	0.00	11.71	2.70	7.30	0.90	0.00	11.71	31.12.2012	20461008	10.02.2014
VOLUND	8.60	0.90	0.00	0.00	9.50	4.00	0.50	0.00	0.00	4.50	31.12.2012	4380167	10.02.2014
VOLVE	8.70	0.80	0.20	0.10	9.98	1.00	0.10	0.00	0.00	1.10	31.12.2012	3420717	10.02.2014
YME	22.00	0.00	0.00	0.00	22.00	14.10	0.00	0.00	0.00	14.10	31.12.2012	43807	10.02.2014
YTTERGRYTA	0.30	2.20	0.40	0.00	3.26	0.00	1.00	0.20	0.00	1.38	31.12.2012	4973114	10.02.2014
ØST FRIGG	0.00	9.20	0.00	0.10	9.30	0.00	0.00	0.00	0.00	0.00	31.12.2012	43576	10.02.2014
ÅSGARD	100.40	207.70	39.40	17.10	400.06	18.60	84.10	16.80	0.00	134.62	31.12.2012	43765	10.02.2014

Figure 9-1 Overview of oil and gas fields in the NPD FactPages database with updated produced and remaining resources.