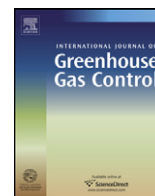




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Feasibility of storing CO₂ in the Utsira formation as part of a long term Dutch CCS strategy An evaluation based on a GIS/MARKAL toolbox

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ABSTRACT

This study provides insight into the feasibility of a CO₂ trunkline from the Netherlands to the Utsira formation in the Norwegian part of the North Sea, which is a large geological storage reservoir for CO₂. The feasibility is investigated in competition with CO₂ storage in onshore and near-offshore sinks in the Netherlands. Least-cost modelling with a MARKAL model in combination with ArcGIS was used to assess the cost-effectiveness of the trunkline as part of a Dutch greenhouse gas emission reduction strategy for the Dutch electricity sector and CO₂ intensive industry. The results show that under the condition that a CO₂ permit price increases from €25 per tCO₂ in 2010 to €60 per tCO₂ in 2030, and remains at this level up to 2050, CO₂ emissions in the Netherlands could reduce with 67% in 2050 compared to 1990, and investment in the Utsira trunkline may be cost-effective from 2020–2030 provided that Belgian and German CO₂ is transported and stored via the Netherlands as well. In this case, by 2050 more than 2.1 GtCO₂ would have been transported from the Netherlands to the Utsira formation. However, if the Utsira trunkline is not used for transportation of CO₂ from Belgium and Germany, it may become cost-effective 10 years later, and less than 1.3 GtCO₂ from the Netherlands would have been stored in the Utsira formation by 2050. On the short term, CO₂ storage in Dutch fields appears more cost-effective than in the Utsira formation, but as yet there are major uncertainties related to the timing and effective exploitation of the Dutch offshore storage opportunities.

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1. Introduction

1.1. Overview

CO₂ capture and storage (CCS) is increasingly considered a crucial technology for mitigating climate change (IPCC, 2007). An important precondition for the implementation of CCS, however, will be the realisation of a CO₂ transport and storage infrastructure. In North West Europe part of this infrastructure may be constructed in the North Sea because of the large CO₂ storage potentials that have been identified there. For example, in the Norwegian part of the North Sea, storage capacity has been estimated to be 148 GtCO₂ in aquifers, 4.4 GtCO₂ in gas fields, and 4.8 GtCO₂ in oil fields (BERR, 2007; Bøe et al., 2002). In the part of the North Sea that belongs to the United Kingdom (UK), the storage

potential has been estimated to be 14.5 GtCO₂ in aquifers, 6.0 GtCO₂ in gas fields, and 4.2 GtCO₂ in oil fields (BERR, 2007).

The geological reservoirs under the North Sea with very large CO₂ storage potentials (e.g. large reservoirs in the Bunter Sandstone formation in the UK part of the North Sea, or the Utsira formation in the Norwegian part of the North Sea) may be indispensable when large amounts of CO₂ need to be stored (Damen et al., 2009). A North Sea pipeline network could connect CO₂ sources in countries around the North Sea to such a geological storage reservoir. So far most studies of trans-boundary transport crossing the North Sea have concentrated on the use of CO₂ for enhanced oil recovery (EOR). For example, Markussen et al. (2002) looked at the use of large volumes of CO₂ from the UK, Denmark, and Norway for EOR on the North Sea continental shelf. According to them it is cost-effective to sequester around 680 MtCO₂ in the North Sea while at the same time producing an additional amount of two billion barrels of oil. More recently, a study in the UK (BERR, 2007), which examined a CO₂ infrastructure for storing CO₂ from UK and Norwegian sources in the North Sea, found that only for the

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purpose of EOR, it would be worthwhile to transport CO₂ from the UK to Norway.¹ Also in the Netherlands, a study of the Rotterdam Climate Initiative to reduce CO₂ emissions in the Rotterdam region, considered CO₂ transport to Norway only for EOR purposes (Hoog, 2008). Furthermore, the authors of the IEA GHG study, which calculated cost curves of CO₂ transport and storage for Europe (IEA GHG, 2005a), did not include the aquifers with large CO₂ storage potentials such as the Utsira formation in their analysis. However, recent broader analyses (Broek et al., 2008, 2009; Damen et al., 2009) showed that CO₂ storage in very large geological storage reservoirs, can make CO₂ trans-boundary transport for the mere purpose of CO₂ storage an interesting option as well. Yet, a decision to invest in a major trunkline across the North Sea to such a reservoir, requires additional insights into its feasibility with respect to costs and organisation.

In this paper, we, therefore, aim to assess the cost-effectiveness of CCS and CO₂ storage in a very large formation under the North Sea in competition with CCS and CO₂ storage in smaller nearby formations or in competition with other CO₂ mitigation options. We also try to identify the boundary conditions that make investments in a major CO₂ pipeline across the North Sea worthwhile, and to assess suitable routings for this pipeline. Finally, we will make a first inventory of organisational issues related to its construction.

We will investigate these issues by investigating the specific case of a CO₂ trunkline from the Netherlands to the Utsira formation. This formation has already been used for CO₂ injection from 1996 in the Sleipner project, the first commercial project to store CO₂ in a saline aquifer (Gale et al., 2001; Hermanrud et al., 2009; Torp and Gale, 2004). This formation consisting of sand and sandstone, is located east of Norway from ca 58°N to 62°N and covers an area of up to 470 km in North-South direction and up to 100 km in East-West direction, the thickness is probably not more than 250 m, and is located at a depth of 500–1500 m below the sea floor (Bøe et al., 2002) and a water depth of 80–100 m (Torp and Brown, 2004). The formation is of special interest due to its enormous theoretical CO₂ storage potential (42 GtCO₂) and its high permeability (Bøe et al., 2002). The permeability is in the order of 3500 mD, and the porosity ranges from 27% to 42% (Torp and Gale, 2004). By using a general storage efficiency of 6% for open aquifers, the pore volume that can be used for CO₂ storage is estimated to be 55 km³ (Bøe et al., 2002). Furthermore, it is overlain by the Nordland shale (Bøe et al., 2002) consisting of fine-grained clays or silty clays, through which it is unlikely that CO₂ will leak (Kemp et al., 2002).

The structure of this paper is as follows. Details about the adopted methodology and input data can be found in Section 2. Results are presented and discussed in Sections 3 and 4. In Section 5 we discuss a few organisational issues, and finally in Section 6 conclusions are drawn with respect to the feasibility of a CO₂ trunkline from the Netherlands to the Utsira formation. It should be noted that the scope of the study is limited to sources that emit more than 100 ktCO₂ in the industrial, electricity and cogeneration sector in which CO₂ capture can be applied. In this paper, a discount rate of 7% is used, and all costs are in €₂₀₀₇.

2. Methodology

2.1. Overview

To evaluate the techno-economic feasibility of a CO₂ trunkline from the Netherlands to the Utsira formation, temporal and spatial

¹ For the purpose of CO₂ storage only, they found that sufficient storage capacity is available for the UK on its own territory. Most of the UK sources which are in the region of East Midlands and South Yorkshire, are even close to the sinks (gas fields as well as saline aquifers) on the UK territory in the Southern part of the North Sea.

dimensions need to be taken into account explicitly. Therefore we use a toolbox integrating ArcGIS, a geographical information system (GIS) with elaborated spatial and routing functions, and the MARKAL (an acronym for MARKET ALlocation) tool, which can generate energy bottom-up models to calculate energy technology configurations over time (Loulou et al., 2004). More specifically, we apply the MARKAL implementation of the Dutch electricity and cogeneration sector, MARKAL-NL-UU, that was used earlier to assess possible CCS deployment trajectories in the Netherlands (Broek et al., 2008). In MARKAL-NL-UU, technologies that convert primary energy carriers (e.g. coal, gas, uranium) or renewables (e.g. wind, biomass, and solar) into final energy carriers (electricity and heat), are modelled. Furthermore, MARKAL-NL-UU includes CO₂ transport and sink technologies, and industrial technologies that produce other types of products (e.g. steel, hydrogen). The model can determine the deployment of CCS and other CO₂ mitigation measures like photovoltaic cells, wind turbines, or biomass co-firing by minimising the net present value of all system costs. Furthermore, it assesses which sources, sinks, and transport options will be used over time and to what extent. The period of analysis is 2010–2050, and a time step of 5 years is used.

The application of this toolbox provides blueprints of the development of a CO₂ infrastructure in the Netherlands taking into account CO₂ emission sources in Germany and Belgium. Insights can be obtained into possible CO₂ pipelines routings and their associated costs, and the amounts of CO₂ that can be captured in different Dutch regions and stored in Dutch sinks (onshore or near-offshore) or in the Norwegian Utsira formation. The methodology, which is described in detail by Broek et al. (2009), can be summarized in four main steps related to processing data for CO₂ sources, CO₂ sinks, and pipelines. The fourth step concerns the specification and running of MARKAL-NL-UU (see Fig. 1).

In the rest of this section, we describe the individual steps in more detail with a focus on relevant issues for assessing the specific case of an Utsira trunkline from the Netherlands.

2.2. Inventory of sources

2.2.1. CO₂ from inside the Netherlands

Under the condition of a strict climate policy, CO₂ emissions can be reduced by capturing them at large scale fossil-fuelled power plants, industrial processes generating small quantities of pure CO₂ (e.g. hydrogen, ammonia, or ethylene oxide production units) or large quantities at a single site (e.g. steel industry, refineries, or ethylene production units) (Damen et al., 2009). Therefore, the inventory of potential sites for CO₂ capture in the Netherlands in the period 2010–2050 includes the sites of the 24 large scale power plants, 15 industrial plants, and 4 probable locations for new power plants (43 sources in total). The capture units at power plants can be post-combustion units at natural gas combined cycle power plants (NGCC) or pulverised coal-fired power plants with possibly biomass co-firing (PC), post-combustion retrofit units for PCs, or pre-combustion units at integrated coal (with possibly biomass) gasification combined cycle power plants (IGCC).² Fig. 2 shows the 43 locations where CO₂ may be captured in the future, and how they are clustered into seven source regions as described in (Broek et al., 2009). Per region it is known when the existing power plants will be decommissioned.³ Consequently, MARKAL-

² Pulverised coal-fired power plants with oxyfuel combustion and CO₂ removal were not included, because they are not clearly different from PC power plants with a post-combustion CO₂ capture unit with respect to cost-effectiveness (Damen et al., 2006).

³ Based on the age of existing power plants, plans of energy companies and/or a life time of 40 years for NGCC and IGCC, and 50 years for PC. For more details on the vintage structure of the electricity sector see Damen et al. (2006).

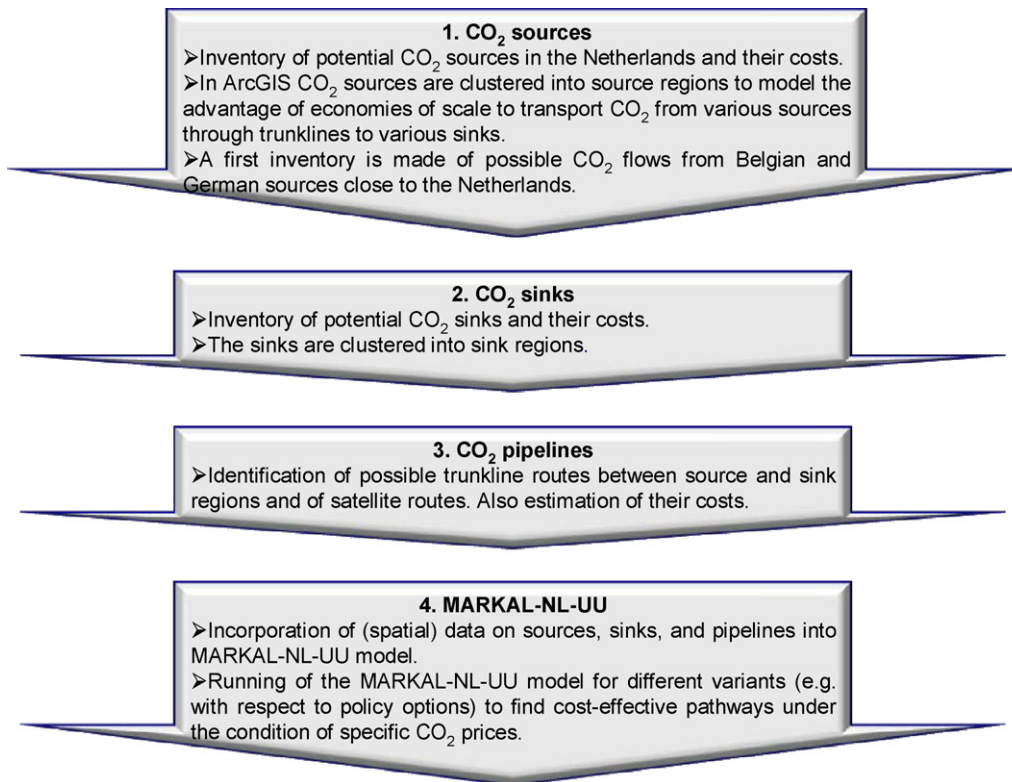


Fig. 1. Schematic representation of the methodological approach in this analysis.

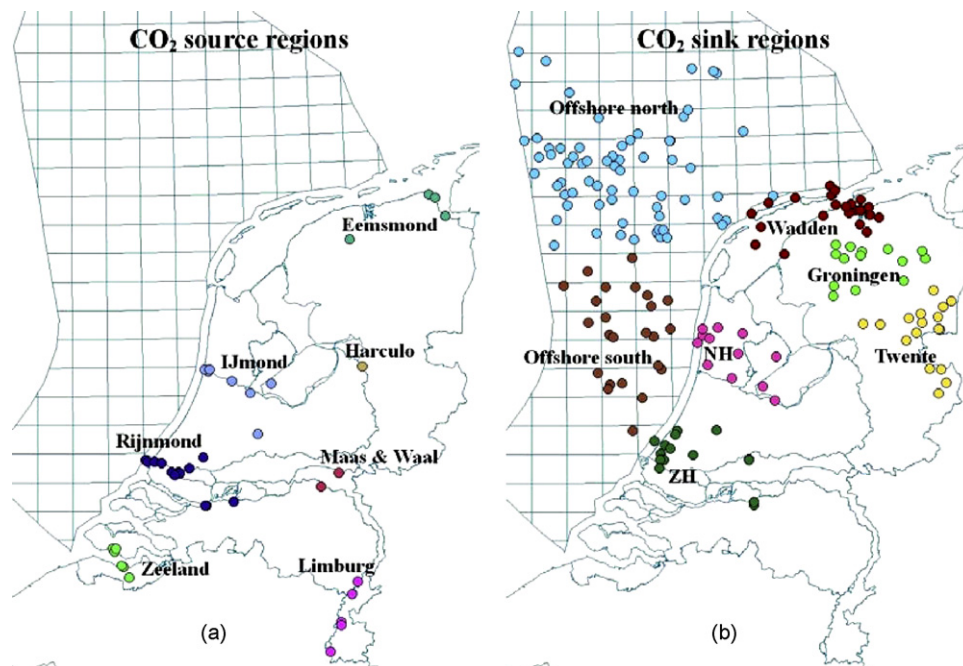


Fig. 2. Clustering of potential CO₂ source locations into source regions (a) and potential CO₂ sinks into sink regions (b). The names of the regions are specified in the maps. Note that some sources are almost at the same location, and thus cannot be distinguished from each other on the map. The Utsira formation offshore Norway is not shown.

NL-UU can calculate when in the Netherlands new power plants (see Section 2.5 for more details) are needed to meet the future electricity demand, selects the types of power plants, and selects the source regions where these new power plants will be constructed. For the industrial units, it is assumed that the industrial production continues at today's level, and the costs for

necessary replacement of these units are not included in MARKAL-NL-UU.

2.2.2. CO₂ from outside the Netherlands

In the Belgian part close to the Zeeland region, the German part close to the Eemsmond region, and the North Rhein-Westfalian

(NRW) part of Germany (close to the Limburg and Maas and Waal region), many large point sources of CO₂ exist, but nearby storage sites for these sources are limited. While the total storage potential for Germany was first estimated to be in the order of 10–40 GtCO₂ (May et al., 2005), the most recent assessment (EU Geocapacity, 2009) results in 17 GtCO₂ storage capacity (mainly in aquifers) which would be sufficient for 37 years of emissions from the existing large point sources in Germany. Unfortunately, although the large stationary sources in the Ruhr area in NRW emit nearly 50% of the German CO₂, NRW has only one aquifer with a storage capacity of some more than 100 MtCO₂ (with a 90% probability) and in total, a capacity of 348 MtCO₂ in aquifers could exist there (GD and BGR, 2005).⁴ Therefore, an enormous pipeline infrastructure would be required to store the CO₂ from NRW sources in the German sinks, which are mainly located in the North of Germany. For Belgium, the recent CO₂ storage assessment (EU Geocapacity, 2009) yields a storage capacity of only 199 MtCO₂ compared to 58 Mt of annual CO₂ emissions from large Belgian sources. For these reasons, storage outside the German and Belgian territories should be taken into consideration. Possible options would be to transport the CO₂ to Dutch sinks or via the Netherlands to the Utsira formation.

Data on the CO₂ capture potentials from CO₂ sources in NRW, were derived from recent studies of a CCS infrastructure in NRW (Viebahn et al., 2009a,b) (Fig. 3). Although NRW plans to replace most old power plants by highly efficient new ones before 2020, this is not sufficient to reach an 80%⁵ reduction of greenhouse gas emissions compared to the 1990 level by 2050 in Germany. A part of the solution could be the application of CCS. In the mentioned NRW studies, the infrastructural requirements necessary to realise such a scenario, were assessed. The maximum CO₂ flows were calculated that can be captured under the condition that the CO₂ permit price is high enough. It was investigated which power plants could be retrofitted with post-combustion CO₂ capture or replaced as thermal or IGCC power plants with CCS from 2020 in NRW. For economic reasons, only power plants were considered for retrofit with a CO₂ capture unit that will not be older than 12 years in 2020.⁶ Furthermore, the CO₂ capture potential at big industrial emitters was assessed.

Data on CO₂ capture potentials from sources in Belgium close to Zeeland and in Germany close to Eemsmond are derived from the GESTCO project (Hendriks and Egberts, 2003).⁷ It is assumed that in Belgium a pure CO₂ emission stream of 1 MtCO₂/yr can be stored from 2015, and CO₂ from the other Belgian sources after 2020. Furthermore, it is assumed that a new coal-fired power plant according to E.ON's plan (E.ON, 2007) will be built and can be equipped with a CO₂ capture unit (6 MtCO₂/yr) before 2020. Table 1 presents the resulting CO₂ capture potentials from the different foreign regions.

⁴ In the NRW area, also a maximum of 160 MtCO₂ may be stored in coal seams with enhanced coal-bed methane recovery (ECBM). However, the application of ECBM is restricted due to the low permeabilities and large depth of the coal deposits (Kronimus et al., 2008).

⁵ To reach a greenhouse gas concentration below 500 ppm CO₂-equivalent, which is needed to keep global mean surface air temperature increase around 2.0–2.4 °C, worldwide CO₂ emissions need to reduce by 50–85% compared to 2000 levels and CO₂ emissions should peak before 2015 (IPCC, 2007). Furthermore, the CO₂ emission reduction in developed countries need to be substantially more than in developing countries (IEA, 2008), up to 80% compared to 1990 level (EU Council Environment, 2005).

⁶ According to McKinsey (2008), only power plants not older than 12 years will be retrofitted from 2020, because they estimated total CCS costs to be at least 30% higher for older (same scale) plants, and possibly much more, depending on the specific case.

⁷ Sources are considered with pure CO₂ streams or emissions of more than 2 MtCO₂/yr. Furthermore, Belgian sources are included which are located at latitude >51°N and longitude <4.6°E, and German sources (close to Eemsmond) that are located at latitude >53°N and at longitude <8.8°E.

2.3. Inventory of sinks

In this study 172 Dutch sinks are considered for CO₂ storage. Only hydrocarbon fields are considered with a storage capacity >4 MtCO₂, and aquifers with a storage capacity >2 MtCO₂. Together these sinks are assumed to have an effective capacity potential of 1.8 GtCO₂ (81 sinks) onshore and 1.3 GtCO₂ (87 sinks) offshore.^{8,9} From these fields 35 are aquifers, 131 are gas fields, 5 are oil fields and 1 field contains both oil and gas. The storage potential of aquifers amount to 0.25 GtCO₂ onshore, and 0.15 GtCO₂ offshore. Apart from the Dutch fields, the large aquifer in the Utsira formation in the Norwegian part of the North Sea with an estimated capacity of 42 GtCO₂ (Bøe et al., 2002) is investigated. Clustering the sinks into sink regions (Broek et al., 2009) resulted in three onshore regions in the North East of the Netherlands, two onshore regions in the West of the Netherlands, two offshore regions in the Dutch part of the North Sea, and the Utsira formation offshore Norway (see Fig. 2). In this paper we will refer to the Dutch offshore fields as near-offshore fields because they are located between 20 and 200 km away from the Dutch coast while the Utsira formation is more than 750 km away. Finally, CO₂ storage in German or Belgian sinks is not considered as an option in this paper.

Per sink, investment, and operating, maintenance, and monitoring (O&M&M) costs are specified on the basis of depth, thickness, CO₂ storage capacity, and injectivity per well. A distinction is made between storage in onshore fields and near-offshore fields, and between hydrocarbon fields (gas and oil) and aquifers. Specific cost data are used for storage in the Norwegian Utsira formation. It is assumed that aquifers are available from the start, and gas fields become available when gas production has ceased. These dates are based on the production reports of the oil and gas exploration companies and are sometime between 2005 and 2025.¹⁰ Near-offshore CO₂ injection facilities can be installed on existing platforms, thus limiting expenditures to the costs of conversion of the platform and well workovers. However, the period in which a platform may be re-used, the *window-of-opportunity*, is limited. Once most of the resources within reach of a platform have been produced, it is often not economic to continue the production activities at this platform because of its high operating costs.¹¹ Then, when production activities cease, the platform needs to be removed as

⁸ The Slochteren field in the province Groningen has an estimated CO₂ storage capacity of about 7 GtCO₂. This gas producing field is considered unavailable for storage before 2050 and therefore it is not considered in this project (NLOG, 2007).

⁹ NOGEP A (2008) recently published a study with slightly different storage potentials due to different techno-economic thresholds. They estimated Dutch offshore storage capacity to be around 0.9 Gt. The study did not include any storage in offshore aquifers (0.14 GtCO₂). Furthermore, the NOGEP A study only included fields with more than 2.5 MtCO₂ storage capacity that were still producing, fields with temporarily ceased production, or with a Field Development Plan. Abandoned fields were left out. In addition, to ensure a reasonable injectivity, only fields, for which the product of permeability and thickness was higher than a chosen threshold value of 0.25 Darcy meter, were considered. NOGEP A, which is the association of companies holding licences to explore for, develop and produce hydrocarbons on- and off-shore in the Netherlands, has access to confidential production data to make such injectivity estimations per field.

¹⁰ The year in which gas field are released, however, shifts ahead, because gas production continues longer due to higher revenues and new production technologies (TNO, 2007). Because it is not known beforehand how much longer production will continue in specific fields, we did not take this shift into our analysis.

¹¹ For example, in Ireland, it is estimated that after 30 years of production 95% of the ultimate recoverable gas reserves has been produced from the Kinsale Head gas field, and that it approaches the end of its economic lifetime. The overhead costs of the platform are considered too high to produce small amounts of gas (CSA Group, 2008). Consequently, without any other purpose for the infrastructure in the near future, the platform needs to be decommissioned.

Table 1
CO₂ capture potential at existing CO₂ sources in Germany and Belgium for different timeframes.

Region abroad	Nearest source region in the Netherlands	Estimated CO ₂ capture potential (in MtCO ₂ /yr)			
		2015	2020	2025	2030 onwards
Belgium (around Antwerp) ^a	Zeeland	1	7	22	22
Germany (NRW) ^b	Maas and Waal		30	104	104 (from 2,040,112)
Germany (NRW) ^c	Limburg		21	21	21
Germany (Niedersachsen) ^d	Eemsmoond		3	10	11

Sources: Hendriks and Egberts (2003); Viebahn et al. (2009a,b).

^a Data on existing sources (>2MtCO₂/yr) and CO₂ pure streams are derived from (Hendriks and Egberts, 2003). Furthermore, the plan of E.ON to build a coal-fired power plant with capture of 6 MtCO₂/yr is added. It is assumed that the 1 MtCO₂ of pure CO₂ available in this area could already be stored from 2015. Around 2020, the E.ON power plant could be online, and then the other sources could be equipped with CO₂ capture.

^b Based on studies by Viebahn et al. (2009a,b), which provide insights into the timing of CCS at different power plants in the German State North Rhine-Westphalia (cluster Middle and cluster West in Fig. 3). The industrial emitters are responsible for around 20% of the CO₂ capture potentials. Only sources >1 MtCO₂ are considered.

^c Based on studies by Viebahn et al. (2009a,b). The CO₂ close to the Limburg region in the Netherlands originates from the Weisweiler power plant (see NRW NL cluster in Fig. 3).

^d Based on data about existing sources in the GESTCO database (Hendriks and Egberts, 2003). The rate by which these sources become available is similar to that in North Rhine-Westphalia close to Maas and Waal. These data exclude any plan to build new coal-fired power plants in this region because no details were available on the status of these plans.

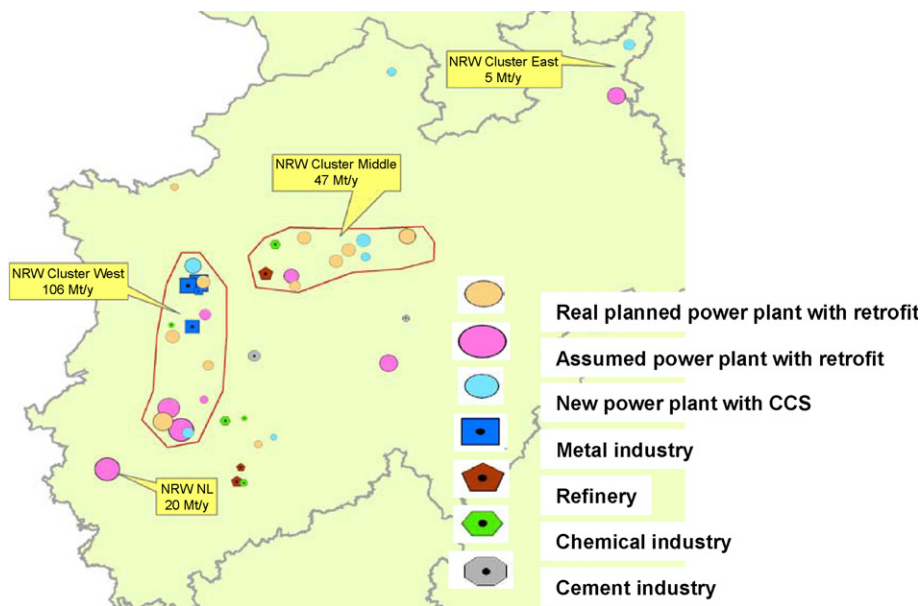


Fig. 3. Locations of CO₂ sources in North Rhine Westphalia. Assumptions on CCS made by the authors (Viebahn et al., 2009b).

required by Dutch legislation (EZ, 2002a,b) following international regulation.¹² If it is later decided to store CO₂ in these fields, new platforms and new wells would need to be constructed for the CO₂ storage activities. Also onshore, there is the possibility to re-use wells and facilities. To model the window-of-opportunity, we take care that in MARKAL-NL-UU the facilities of a sink can only be re-used if CO₂ storage starts within 5 years after the estimated year in which gas (or in some cases oil) production will cease.

The investment costs to develop a specific sink for CO₂ storage are calculated using Equation 1 and the input data for the different types of sinks in Table 2. The O&M&M costs of a sink are always based on a fixed percentage (see Table 2) of the investment costs for the development of the sink from scratch, because in the case of re-use the existing equipment also needs to be operated and maintained.

$$I = W * (C_d * H + C_w) + C_{sf} + C_{sd} \quad (1)$$

where *I* = investment costs sink (€); *W* = number of wells per sink, the number of wells depend on the storage potential of the sink and

¹² In 1998, the OSPAR decision 98/3 was adopted that prohibits to dump disused offshore installations, and/or leave them wholly or partly in place within the maritime area (OSPAR convention, 1998).

the injectivity per well for the sink; *C_d* = drilling costs (€ per meter); *C_d* = 0 if old wells can be re-used; *H* = the drilling distance being the depth of the reservoir starting at the bottom of the sea (for offshore sinks) or the ground surface (for onshore sinks) plus the thickness of the reservoir (in meter); *C_w* = fixed costs per well (in €). In case of re-use, these are the costs for the workovers of the old wells. *C_{sf}* = investment costs for the surface facilities on the injection site and investments for monitoring (e.g. purchase and emplacement of permanent monitoring equipment) (in €). *C_{sd}* = investment costs for the site development costs. E.g. site investigation costs, costs for preparation of the drilling site and costs for environmental impact assessment study. In general it is expected that for ‘empty’ gas and oil fields geological and geophysical data are available (in €).

In order to illustrate the range in costs for the different sink types, Table 2 also shows the CO₂ storage costs in € per tCO₂ for illustrative sinks.

2.4. Inventory of pipeline routes

In ArcGIS, routings of possible trunklines between the Dutch source and sink regions are identified with least-cost routing functions (see Fig. 4). The investment and operational costs of a

Table 2
Storage cost data used in this study.

	Parameter	Unit	Hydrocarbon onshore	Hydrocarbon onshore with re-use ^a	Hydrocarbon near-offshore	Hydrocarbon near-offshore with re-use ^a	Aquifer onshore	Aquifer near-offshore	Utsira formation
Input data	Drilling costs (C_d)	€ per meter	3000 ^b		5314		3000 ^b	5314	14,600 ^c
	Fixed well costs (C_w)	M€ per well		1	8.2	2		8.2	18 ^{c,d}
	Site development costs (C_{sd}) ^e	M€	3.3	3.3	3.3	3.3	25.5	25.5	4.5 ^f
	Surface facilities costs (C_{sf})	M€	1.5	0.4	61	15	1.5	61	
	O&M&M costs	% of investment ^g per year	5	5	5	5	5	5	5
	Depth + thickness reservoir (H)	m	800–4190		1979–4429		1150–3800	1550–3900	1,250
	Injection rate per well ^h	MtCO ₂ /yr	0.2–1	0.2–1	0.2–1	0.2–1	0.2–0.5	0.2–0.5	2
An example sink ⁱ	Depth + thickness reservoir	m	2500		3600		2500	3000	1,250
	Injection rate per well	MtCO ₂ /yr	1	1	1	1	1	0.5	2
	Levelised storage costs	€/tCO ₂	1.7	1.0	12.5	6.4	9.4	30.1	2.8

Sources: BERR (2007); CASTOR project (2004); Serbutoviez et al. (2007); Torp (2008); Wildenborg et al. (2008).

^a Re-use of wells and platform. The fixed costs per well are the estimated costs to convert a production well into a CO₂ injection well.

^b For the onshore wells, the fixed costs per well are included in the drilling costs (these costs assume reservoir depths of around 3000 m).

^c Costs for storage into the Utsira formation were given in €₂₀₀₈. A factor of 0.73 based on the IHS/CERA upstream capital cost index (IHS, 2008) is used to convert them to €₂₀₀₇. Costs of, for example, renting drilling rigs had risen tremendously in 2008 due to the high oil prices; in 2009 these costs are again falling rapidly (IHS, 2009).

^d Instead of injecting CO₂ from a platform into the Utsira formation, CO₂ can be injected from systems on the sea bottom (subsea completion systems). A subsea frame with subsea completion systems for 4 wells costs ca 100 million €₂₀₀₈ (18 M€₂₀₀₇ per well). These costs include costs for engineering, transport of the subsea frame to the right location, installation, and a reserve of 25% for contingency costs (non-budgeted expenses). Although the injection itself takes place at the sea bottom, the control of the injection will take place at a nearby existing platform (Torp, 2008).

^e Including monitoring investment costs in pre-operational phase.

^f Site development costs for the Utsira formation are much lower than for the Dutch near-offshore aquifers, because the Utsira formation is already used for CO₂ injection.

^g As a fixed percentage of the investment costs for the development of the sink from scratch (also in the case of re-use of equipment).

^h The injectivity rate depends on the reservoir type and the lithology of the reservoir rock.

ⁱ In the model storage costs are calculated per individual sink depending on type, CO₂ storage capacity, depth, and injection rate of the sink. However, to get an impression of the storage costs per type of sink, the levelised costs are shown for a sink with a specific depth, a typical injection rate expected for Dutch sinks, and lifetime of 25 years for the storage facilities. The calculation is based on a 7% discount rate.

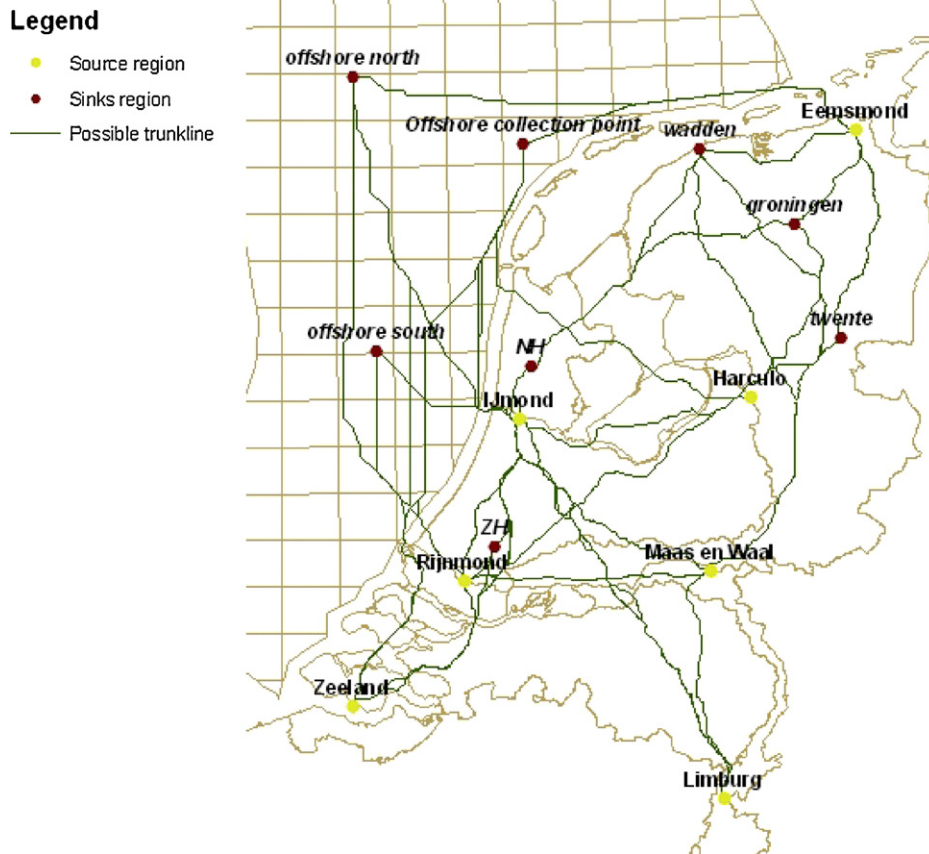


Fig. 4. Possible trunklines between source and sink regions in the Netherlands.

pipeline are influenced by terrain conditions such as land-use or roads to be crossed (Vandeginste and Piessens, 2008). Therefore, we differentiate the CO₂ pipeline construction costs per land-use type by using terrain factors, and a preference is given for following the existing hydrocarbon pipeline corridors resulting in investment costs varying between 1300 and 4300 € per meter length and per meter diameter for a specific location (Broek et al., 2009).¹³ Future land-use is taken into account via a GIS map for 2040 developed by the Netherlands Environmental Assessment Agency (MNP, 2007). We use Eq. (2) of Hendriks et al. (2003) rearranged by McCollum and Ogden (2006)¹⁴ to calculate the diameters of the CO₂ pipelines for all the trajectories and several capacities per trajectory (e.g. for a maximum of 5, 15, or 25 MtCO₂ flow per year):

$$D^5 = \frac{8 * \lambda * m^2}{\pi^2 * \rho * (\Delta P/L)} \quad (2)$$

where D = diameter pipeline (m); λ = friction coefficient (0.015); m = mass flow rate (kg/s); ρ = CO₂ density (800 kg/m³); ΔP = pressure drop (3×10^6 Pa) assuming an inlet pressure of 110 bar and a delivery pressure of 80 bar at the injection site; L = length of pipeline (m).

Finally, we select four options for a trunkline from the Netherlands to the Utsira formation taking into account the

¹³ The calculations to determine the requirements for the pipelines are based on transport of pure CO₂. In reality, the CO₂ will contain a certain level of impurities which may change the behaviour of CO₂ at a given pressure and temperature. These impurities may also have an impact on the pipeline requirements to prevent corrosion, which may affect investment costs.

¹⁴ As can be seen in the model comparison analysis by McCollum and Ogden (2006), the resulting diameters lay within the range of diameters calculated by models in other studies (Heddle et al., 2003; IEA GHG, 2002, 2005a,b; Ogden et al., 2004).

locations of CO₂ source regions and the existing Dutch landfalls (i.e. locations where pipelines are preferred to go from onshore to offshore) which are preferably used for new pipelines as well (EZVRM, 1984). Fig. 5 shows the routings found by the ArcGIS least-cost routing functions and Table 3 shows the technical and economic details of these pipelines.

2.5. MARKAL-NL-UU scenario assumptions

The role of CCS and the associated CO₂ infrastructure within the total portfolio of mitigation options for a given year can be determined in the context of a scenario. The base scenario inputs that underlie the runs of MARKAL-NL-UU are the following:

- The Dutch electricity demand will increase from 110 TWh in 2005 to 175 TWh in 2050. This value is in line with the electricity demand growth in the “strong Europe” scenario used by the Dutch planning agencies (Janssen et al., 2006).
- The permit price of CO₂ increases from 25 €/tCO₂ in 2010 to 60 €/tCO₂ in 2030, and remains at this level up to 2050.
- Nuclear power phases out in 2033 when the existing nuclear power plant in Borssele of 450 MW has to shut down (VRM, 2006).
- Input data for the development of costs and performance characteristics of the electricity generating technologies (including power plants with CCS, nuclear power plants, and renewable electricity generation technologies) and of CO₂ capture units in the industry are described in (Broek et al., 2008; Damen et al., 2009).¹⁵ In these studies, the data for new and advanced gas- and coal-fired power plant technologies (with and without CCS were

¹⁵ All cost data are updated to €₂₀₀₇ monetary units by using the CEPCI index.

adopted from (Damen et al., 2006; IEA GHG, 2003, 2004). Data from other electricity generating technologies were taken from various other studies, e.g. (EU PV Technology Platform, 2007; Junginger et al., 2005; University of Chicago, 2004).

- The Netherlands changes from an electricity importing country towards a self-sufficient electricity producing country in 2020. Import of electricity decreases from 18 TWh in 2005 to 0 TWh in 2020 because of the expected increase in electricity generation capacity in the coming years. However, the amount of electricity produced in the Netherlands may be higher than assumed in this study. According to various studies the Netherlands may even become a net exporter following the increase in production capacity until 2020 (Özdemir et al., 2008; Seebregts and Daniëls, 2008; Seebregts and Groenbergh, 2009). Also, TenneT (2008), the Dutch Transmission System Operator, has indicated that this could happen.
- The share of electricity from renewable sources in the final electricity consumption increases from 29% in 2020 to 43% in 2050.¹⁶
- The current plans to build two pulverised coal-fired power plants in the Rijnmond area (the E.ON plant of 1.1 GW, and the Electrabel plant of 0.7 GW), and one in the Eemsmond region (the RWE plant of 1.6 GW) before 2015 materialise.
- Increases in coal and gas prices up to 2030 are based on the “high growth” scenario in the World Energy Outlook by the IEA (IEA, 2007). From 2030 on, we assume that prices keep rising at similar rates until 2050. This results in a gas price increase from 5.5 €/GJ in 2010 to 11.7 €/GJ in 2050, and a coal price increase from 2.5 €/GJ in 2010 to 4 €/GJ in 2050.
- CO₂ from Belgium and/or Germany can be transported and stored via or in the Netherlands. In this study the costs for CO₂ capture from German and Belgian stationary CO₂ sources and transport to the collection point in the Netherlands (in the Zeeland, Limburg, Maas and Waal or Eemsmond region) are not included. These costs would be driven by climate policies in those countries which lie outside the modeling being done here which focuses on CCS adoption in the Netherlands. However, to explore how the export of captured CO₂ from these countries would affect the economics of using CCS in the Netherlands, we exogenously specify maximum amounts that can be captured from large stationary point sources in these two countries which might be transported to the Netherlands (see Table 1). Based on the assumption that these countries are willing to pay 7.5 €/tCO₂ to the Netherlands to transport and store their CO₂, the model decides how much CO₂ is imported into the Netherlands.
- Sinks are only allowed to be used for CO₂ storage if they can be developed into a safe and effective storage site. Therefore, they need to fulfil a number of criteria, for example, with respect to seismicity, integrity of existing wells, faults, overburden, and seals. To take this type of criteria into account, we used the indicator developed by Ramírez et al. (2009), which ranked the Dutch CO₂ storage options with respect to the required effort to manage risks (on a ranking scale of 0–100, with 0 indicating a storage site requiring the “most” effort to manage risks, and 100, the “least”). We chose a threshold value of 70 below which the sinks are not considered suitable. This criteria results in a decrease in Dutch storage capacity for onshore from 1.8 to 1.2 GtCO₂, and for near-offshore from 1.3 to 1.0 GtCO₂. In addition to

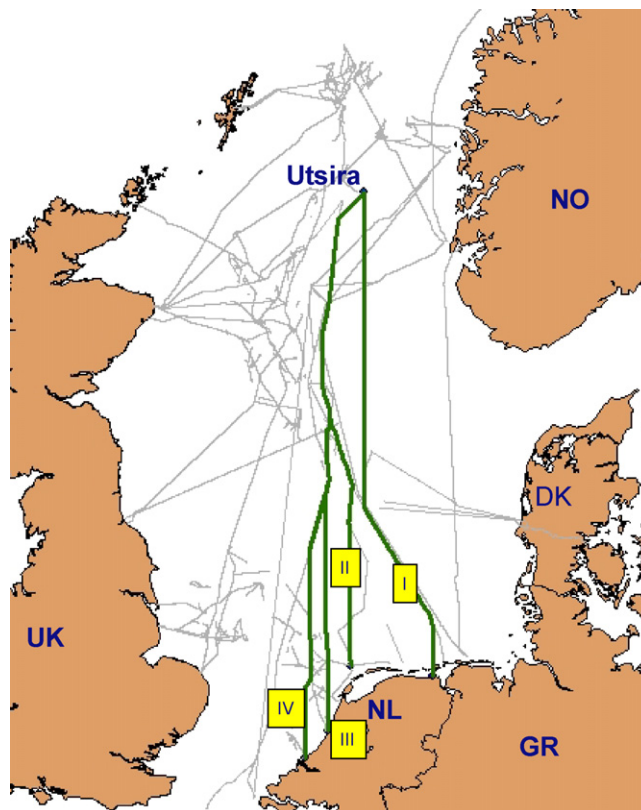


Fig. 5. Possible trajectories for a trunkline from the Netherlands to the Utsira formation (see also Table 3).

be conservative, we have disregarded all Dutch aquifers (0.4 GtCO₂), because there is little published about these formations.

In order to study the feasibility of a North Sea trunkline to the Utsira formations under different conditions, the following scenarios are studied:

1. *Base case.* This scenario is based on the base scenario assumptions above.
2. *CO₂ storage offshore only.* CO₂ can either be stored in the Dutch near-offshore sinks or in the Utsira formation offshore Norway.
3. *CO₂ flows from Dutch sources only.*
4. *CO₂ flows from Dutch sources only and CO₂ storage offshore only.* A combination of scenarios 2 and 3.
5. *Low CO₂ permit price – low electricity demand scenario.* In this scenario, the electricity demand grows less (from 110 TWh in 2005 to 137 TWh in 2050) as in the Regional Communities scenario (Janssen et al., 2006), the CO₂ permit price increases from 25 €/tCO₂ in 2010 to 45 €/tCO₂ in 2030, and remains at this level up to 2050. Germany and Belgium will pay only 5 €/tCO₂ for transport and storage of their CO₂ from the collection point in the Netherlands.

3. Results

3.1. Base case

In this section the results of the MARKAL-NL-UU runs are described for the base case. In order to meet the growing electricity demand and to offset the lower availability of wind and solar capacity, the power generation capacity more than doubles over the analysis period. Due to the assumed CO₂ permit price (43 €/tCO₂ in 2020 and 60 €/tCO₂ from 2030 onwards) and the renewable energy target, CO₂ emissions are reduced by 29% and

¹⁶ In order to stimulate the use of renewable energy, the EU has stipulated that the Netherlands must obtain 14% of the final energy consumption from renewable energy sources by 2020 (Council of European Union, 2008; EC, 2008). However, to achieve this target, the share of renewable electricity in the final electricity consumption must be higher than the overall national renewable target. E.g. Harmsen and Hoen (2008); Menkveld and van den Wijngaart (2007) mention shares of 39–41% to reach the Dutch national renewable target of 20%.

Table 3
Technical and economic details of four possible trunklines to Utsira.

Collection point	Length (in km)	Landfall	Parameter	Unit	Pipeline capacity (in MtCO ₂ /yr)			
					20	40	60	80
I. Eemsmond	750	Existing landfall in the municipality of Warffum (near Eemsmond).	Pipeline diameter ^b	in.	36	42	48	48
			Power pumping station ^c	MW	17	65	114	464
			Pressure before transport ^c	bar	100	115	120	160
			Investment ^d	M€	1250	1530	1820	2140
II. At sea North West of the Netherlands ^a	750	The landfall would be at existing locations in Rotterdam, or at the second Maasvlakte as in the RCI plan (Hoog, 2008).	Pipeline diameter	in.	36	42	48	48
			Power pumping station	MW	17	65	114	464
			Pressure before transport	bar	100	115	120	160
			Investment	M€	1250	1530	1820	2140
III. IJmond	830	Existing landfall location near IJmuiden.	Pipeline diameter	in.	36	42	48	48
			Power pumping station	MW	19	75	130	493
			Pressure before transport	bar	100	120	125	165
			Investment	M€	1380	1690	2010	2340
IV. Rijnmond	890	Existing landfall near Rotterdam or at the second Maasvlakte as in the RCI plan (Hoog, 2008).	Pipeline diameter	in.	36	42	48	48
			Power pumping station	MW	21	83	143	514
			Pressure before transport	bar	105	125	130	170
			Investment	M€	1480	1810	2160	2480

Source: Buit (2009).

^a Or onshore close to an existing landfall possibility near Den Helder at Callantssoog (starting point for a gas pipeline to the United Kingdom, the BBL pipeline).

^b A dedicated physical model has been used to determine the dimensions of the pipeline and the pumping station. The mass flow of CO₂ and the pressure specifications determine the possible diameters of the pipeline. Pipeline diameters of 30, 36, 42 and 48 in. are available. The pipeline material must be able to withstand high pressures, so the material of choice is X70 pipeline steel.

^c It is assumed that the CO₂ delivered to the collection point at the start point of the Utsira trunkline is in the dense phase (at 80 bars). At the collection point, there is a station pumping the CO₂ and thus increasing the pressure. Pressure loss along the pipeline must be limited, to keep the CO₂ at or above 80 bars. At the storage site, a pressure of 80 bars is sufficient to inject the CO₂.

^d Estimations of CO₂ transport costs are based on available data of oil and gas pipelines at the Gasunie company which is responsible for the operation and development of the Dutch natural gas transmission grid (Buit, 2009). Operating and maintenance costs of the trunkline and pumping station (excluding electricity costs for the pumping station) are estimated at 3.5% of the investment. Costs for electricity in the pumping station are assumed to be 60€/MWh.

67% compared to the 1990 level in the electricity generation sector and CO₂ intensive industry in 2020 and 2050, respectively. On average 31% of the reduction of emissions in the power sector (compared to a scenario without a CO₂ permit price or renewable targets) can be attributed to CCS. Over the whole analysis period a cumulative amount of 1.8 GtCO₂ of CO₂ from the Netherlands and 1.5 GtCO₂ from abroad will be captured and stored.

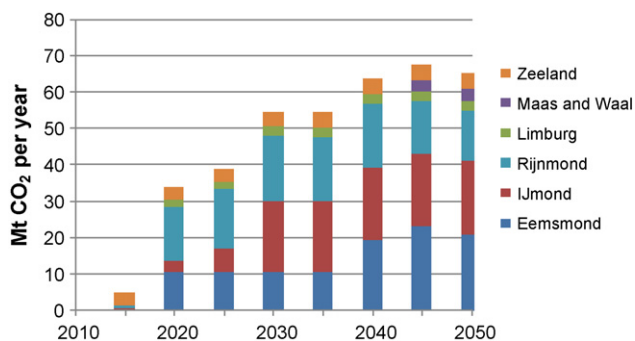


Fig. 6. Annual amount of CO₂ captured at power plants and industrial units per region in the Netherlands in the base case.

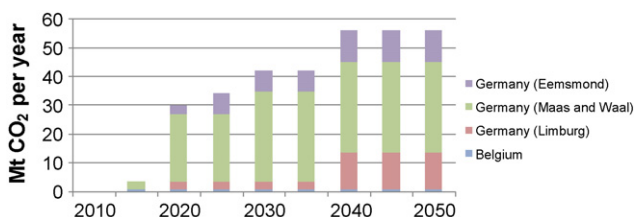


Fig. 7. Annual amount of foreign CO₂ captured at power plants and industrial units per region and transported to the Netherlands.

In 2020, the PC power plant capacity installed before 2015 (i.e. the RWE, E.ON, and Electrabel power plants) will have been retrofitted with CO₂ capture, and by 2050 a total of 6.8 GW of IGCC with CCS, and 2.9 GW of NGCC with CCS will have been constructed. Furthermore, from 2030 the share of biomass co-firing in coal-fired power plants will be 30% of fuel energy input. Finally, model results indicate that onshore wind is cost-effective from the start, and photovoltaic cells from 2050 onwards. To reach the renewable targets, also offshore wind power would be deployed up to 11 GW in 2050.

The annual amount of CO₂ captured per region in the Netherlands is presented in Fig. 6. In 2015, only CO₂ from industrial units (5 MtCO₂) is captured and stored in Dutch onshore fields. In 2020, 44% of the CO₂ is captured in the Rijnmond (15 MtCO₂) and 32% in the Eemsmond region (11 MtCO₂).¹⁷ During the rest of the analysis period, the amount of CO₂ captured grows to around 65 MtCO₂/yr. In 2050, the Eemsmond, Rijnmond and IJmond regions all generate substantial amounts of CO₂ that need to be stored (21, 14, and 20 MtCO₂/yr, respectively). IJmond is a favoured location for CO₂ capture, because in this scenario it is also the location where the CO₂ is collected for transport to Utsira.¹⁸

¹⁷ These results are in agreement with the plans of the Rotterdam Climate Initiative and the “Kern Team” Consortium in the North of the Netherlands. The Kern Team assumes that the RWE power plant, which is probably built as a CO₂ capture ready plant before 2014, may be retrofitted before 2020, and that CO₂ capture partly takes place at another plant, the NUON IGCC plant, which also is planned to be constructed.

¹⁸ In this study, only approved plans for new power plants in the Rotterdam harbour are taken into account. However, Rotterdam may increase its industrial activities and electricity generating technologies even more in the coming decades. As a consequence more CO₂ capture could be needed in this area than this study shows. For example, the physical space in the Rijnmond harbour allows for around 8000–9000 MW of power plants. Currently, electricity generation capacity in the Rotterdam harbour amounts to 3000–3500 MW, and capacity planned on the short term is around 3000 MW.

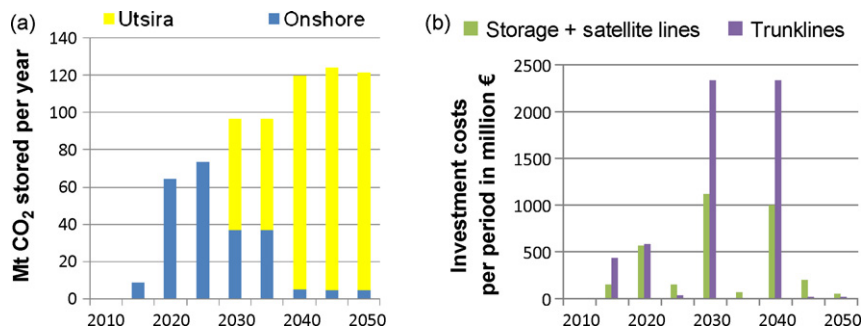


Fig. 8. Total annual amount of CO₂ stored (Dutch and foreign CO₂) in Dutch onshore sinks and the Utsira formation (a) and upfront investment costs for transport and storage in the period 2010–2050 (b).

Fig. 7 presents the total amount of CO₂ stored per year including the CO₂ from Germany and Belgium, and Fig. 8 shows that from 2030 onwards storage in the Utsira formation is considered a cost-effective option by the model (60 MtCO₂/yr is transported from the Netherlands to Utsira). From 2040, the CO₂ flow to Utsira increases to 120 MtCO₂/yr. The investment costs are distributed unevenly over the analysis period (Fig. 8): in 2015–2020, the basis of the CO₂ infrastructure in the Netherlands is laid down, in 2030 one trunkline is built to the Utsira formation, and in 2040 a second one.

Fig. 9 depicts the development of CO₂ storage over time in Dutch sinks. Note that, once most Dutch onshore sinks have been filled, CO₂ is stored in the Utsira formation. The near-offshore sinks are not selected by the model, because at the beginning of the analysis period they are not cost-effective compared to the Dutch onshore sinks. At a later stage the existing gas infrastructure (e.g. platforms) has been decommissioned, and the window-of-opportunity (see Section 2.3) for re-use of infrastructure has thus passed, making CO₂ storage in the Dutch near-offshore fields even more expensive. Furthermore, in these fields, the amount of CO₂

stored per well (over its entire lifetime) is limited due to the on average small size of the sinks and the injectivity rate never being higher than 1 MtCO₂/yr per well. On the contrary, storage in the Utsira formation is cost-effective, because there 50 MtCO₂ can be stored per well over its lifetime due to the enormous storage potential of the Utsira formation and the higher injectivity rate of 2 MtCO₂/yr per well.

Finally, Figs. 10 and 11 depict the trunklines that may be built and used around 2020 and 2040.¹⁹ CO₂ from Limburg is stored in the Twente region, from Eemsmond in the Groningen region, and from the other source regions in the Wadden region and (to a small extent) in the North Holland region.

3.2. Comparison of scenarios

Table 4 summarizes the main results for all scenarios investigated. These results are: the development of transport and storage costs (€/tCO₂), the cumulative amounts of CO₂ stored over time, the year when storage in the Utsira formation would become cost-effective, the capacity and starting point in the Netherlands of the trunkline to the Norwegian Utsira formation, and the total amount of CO₂ stored in the Utsira formation in 2050.

The results from the scenarios led to the following insights.

3.2.1. Scenarios with CO₂ storage offshore only in near-offshore sinks or the Utsira formation (scenarios 2 and 4)

- In absence of possibilities to store CO₂ onshore (Fig. 12), CO₂ from Rijnmond is transported via Eemsmond to Utsira from 2020. In fact, CO₂ from all Dutch regions except from the IJmond region is transported to Utsira via this collection point. A pre-requisite for the Utsira pipeline to be cost-effective at this stage is that it also needs to transport CO₂ from Germany.
- Storage in the near-offshore fields is mainly cost-effective when already existing wells and platforms can be re-used. In none of the scenarios more than 20 MtCO₂ is stored in near-offshore fields that had to be re-opened. Planning the offshore CO₂ infrastructure on the Dutch continental shelf is therefore important, but difficult. On the one hand it is not certain when gas production in individual fields will cease and thus, when CO₂ storage can start.²⁰ On the other hand, once gas production has ceased, the infrastructure around the gas fields need to be mothballed to keep them suitable for CO₂ storage. This mothballing activity would encounter two difficulties. First, an exemption needs to be made from the current Dutch legislation

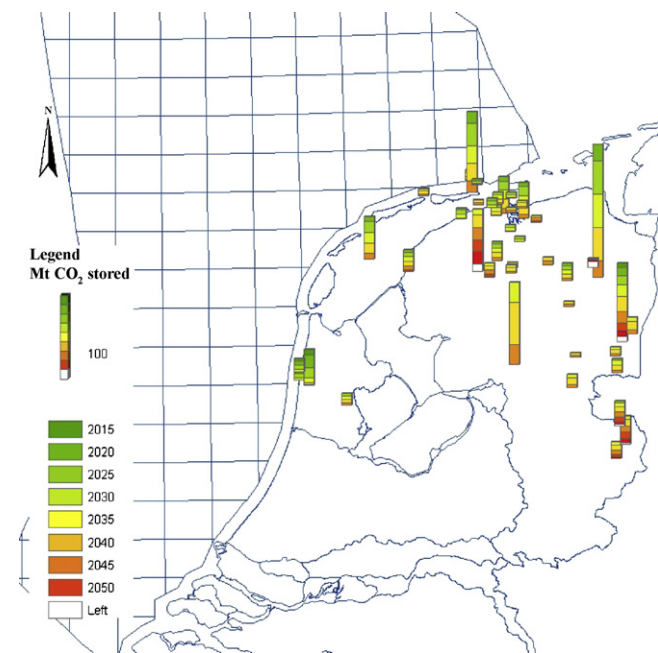


Fig. 9. CO₂ storage over the time in the base case. Each stacked bar represents a sink. The size and colours relate to, respectively, the amount and timing of the stored CO₂. A white section represents the storage capacity that is still available. Note the sinks that are not used for CO₂ storage during the analysis period, are not depicted on the map. Furthermore, the map does not show that 2.1 GtCO₂ is stored in the Utsira formation from 2030 onwards, because this formation is located around 650 km to the North of the map.

¹⁹ Model outcomes are also available for other periods (i.e. for each 5 year time step).

²⁰ For example, when gas prices rise or mining costs decrease, production from almost depleted gas fields remains profitable for a longer time period.

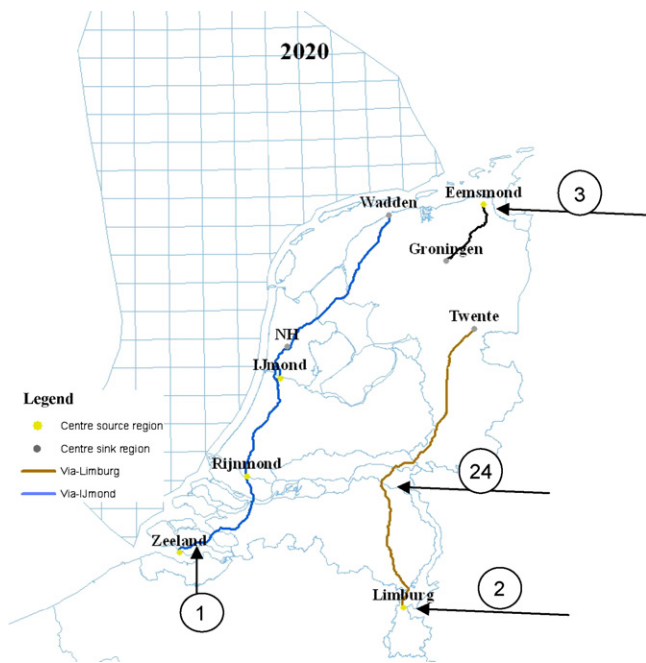


Fig. 10. CO₂ infrastructure in 2020 for the base case. The numbers represent the amount of CO₂ transported from abroad (in MtCO₂/yr).

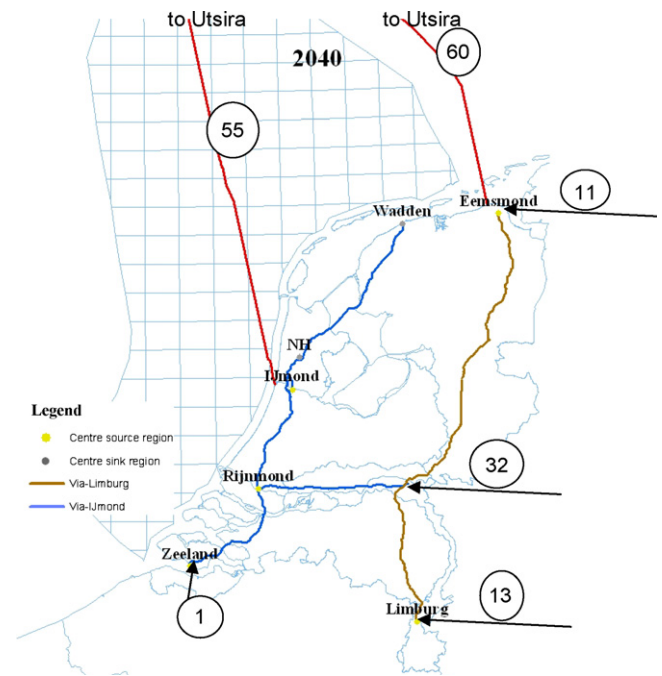


Fig. 11. CO₂ infrastructure in 2040 for the base case. The numbers represent the amount of CO₂ transported from abroad and to the Utsira formation (in MtCO₂/yr).

which requires platforms to be dismantled when production activities have been stopped (EZ, 2002a,b). Secondly, exploration companies may not be willing to pay the mothballing costs, but instead opt for abandoning the gas fields, when there is uncertainty about the supply of CO₂. Finally, an issue could be whether exploration companies will provide guarantees on the availability of storage capacity over long time periods to energy companies which need to store their CO₂. In case of the Utsira formation, this may be easier to guarantee.

3.2.2. Scenarios with CO₂ flows from Dutch sources only (scenarios 3 and 4)

- Before 2040 the Netherlands has sufficient cost-effective onshore storage options to fulfil its own storage demand and the Utsira formation is not yet needed (scenario 3). Therefore, compared to the scenario which includes CO₂ flows from Germany and Belgium (scenario 1), the construction of a pipeline to the Norwegian Utsira formation becomes cost-effective 10 years later (i.e. in 2040 instead of 2030).

- However, if due to lack of public support, the use of the Dutch fields onshore is not allowed (scenario 4), an Utsira pipeline for CO₂ from Dutch sources becomes again cost-effective 10 years earlier (in 2030). Note that in the scenario with the German and Belgian CO₂ flows and offshore storage only (scenario 2), the Utsira trunkline would already be cost-effective from 2020.
- Furthermore, in scenario 4, costs for CO₂ transport and storage are 8.3 €/tCO₂ and CCS will contribute with 21% to the CO₂ avoidance in the electricity sector in 2020 compared to 4.1 €/tCO₂ and 31%, respectively, in the scenario with onshore storage (scenario 3). The increase in costs is mainly due the higher investment and O&M&M costs needed for CO₂ storage costs in the offshore fields (see Table 2). Although CO₂ avoidance costs of CCS are mainly determined by the CO₂ capture costs, the increased transport and storage costs have an impact on the competitiveness of CCS in the short term.
- In the long term, the impact of only allowing CO₂ storage offshore on the role of CCS in the portfolio of mitigation measures in the Netherlands, is limited, if the CO₂ can be stored in the Utsira formation (or another large formation under the North Sea).

Table 4
Overview of results per scenario.

Scenario	Average transport and storage costs (€/tCO ₂)			Total amount of CO ₂ stored (MtCO ₂ until)			Origin CO ₂ (total MtCO ₂ stored until 2050)		Trunkline to Utsira			Total amount of CO ₂ stored in Utsira formation (MtCO ₂) 2050
	2020	2035	2050	2020	2035	2050	NL	Belgium/Germany	Construction period	Capacity (Mt/year)	Starting point	
1 Base case	3.5	7.0	8.5	202	1451	3212	1751	1461	2030/2040	60/60	IJmond/Eemsmond	2054
2 CO ₂ storage offshore only	8.8	8.1	8.3	139	1164	2977	1747	1230	2020/2040	60/60	Eemsmond/Rijnmond	2678
3 CO ₂ flows from Dutch sources only	4.1	4.2	8.8	121	868	1846	1846	0	2040	60	Eemsmond	750
4 CO ₂ flows from Dutch sources only and CO ₂ storage offshore only	8.3	10.6	9.2	89	697	1675	1675	0	2030	60	IJmond	1229
5 Low CO ₂ permit price – low electricity demand	4.2	5.3	10.8	126	738	1438	1236	202	2050	40	Eemsmond	100

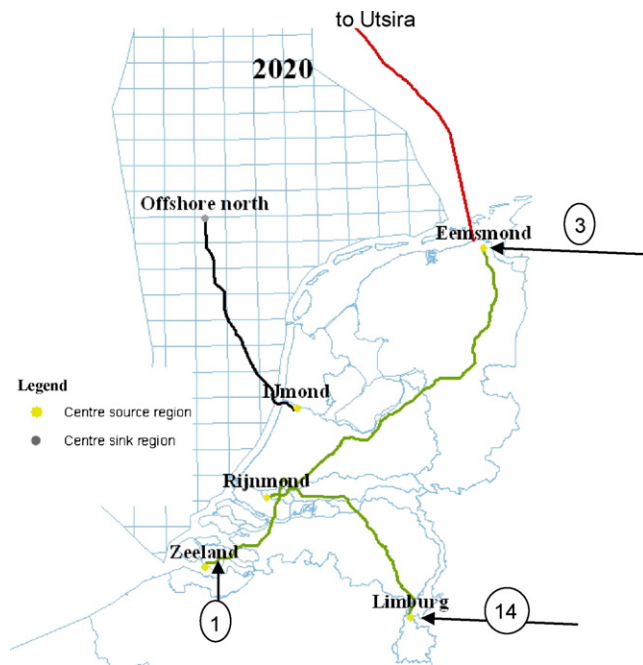


Fig. 12. CO₂ infrastructure in 2020 for CO₂ storage offshore only scenario in near-offshore fields and the Utsira formation. The numbers represent the amount of CO₂ transported from abroad (in MtCO₂/yr).

Without this possibility, there would not be enough cost-effective offshore Dutch sinks to store the CO₂ produced in the Netherlands over time and consequently the share of CCS in the portfolio would significantly decrease.

3.2.3. Low CO₂ permit price – low electricity demand scenario (scenario 5)

- The role that CCS can play in the portfolio of Dutch mitigation measures will depend mainly on the permit price of CO₂. If the only policy measure applied is the emission trading system (ETS), if the CO₂ permit price stays below 45 €/tCO₂ by 2030, and if the energy demand grows less, CCS will be implemented to a lesser extent than in the base case. Reason is that whereas in the base case coal-fired power plants, which could be equipped with CCS, were built after 2015 to meet the growing electricity demand, there is no need for them in this scenario (except for one in 2040). Furthermore, in the *base case* (scenario 1) NGCC plants were equipped with CCS, which is too expensive under the given CO₂ permit price of 45 €/tCO₂. The average contribution of CCS to the reduction of emissions in the power sector (compared to a scenario without a CO₂ permit price and renewable targets) decreases from 31% in the base case to 17% in this scenario. However, because the energy demand is also lower (119 TWh instead of 137 TWh in 2020), the total CO₂ emission in 2020 is similar to that in the base case.
- If the CO₂ permit price increases to 45 €/tCO₂ instead of 60 €/tCO₂, constructing a trunkline to Utsira appears only cost-effective around 2050. Furthermore, if Germany and Belgium pay a fee of 5 €/tCO₂ for transport and storage of their CO₂, it is hardly attractive to store their CO₂. In that case, only small flows (<3 MtCO₂/yr) from Belgium and Germany are passing through the Netherlands, and are used to fill up spare²¹ capacity in the Dutch CO₂ pipelines.²²

²¹ Note that MARKAL-NL-UU can only choose between a limited amount of pipeline capacities which may not match entirely the CO₂ flow from Dutch sources.

²² However, MARKAL-NL-UU takes care that a CO₂ flow from Germany or Belgium to the Netherlands, once started, cannot be reduced within 40 years.

3.2.4. Overall findings

The analysis of the scenarios led to a number of important findings with respect to a CO₂ trunkline from the Dutch coast to the Utsira formation:

- Investment costs for the chosen trunklines to Utsira vary between 1.8 and 2.2 billion €. The most cost-effective transport capacity for the Utsira pipeline seems to be 60 MtCO₂/yr.²³ Lower (20 or 40 MtCO₂/yr) or higher (80 MtCO₂/yr) values are not chosen in the model runs.²⁴
- From an economic and infrastructure development point of view, there is no clear preference for the location of the collection point from where CO₂ is transported to Utsira. In the three coast locations (Eemsmond, IJmond, and Rijnmond), it is possible to collect the necessary amount of around 50–60 MtCO₂/yr to make a trunkline to Utsira from these locations profitable.
- Pipelines transporting German CO₂ flows can either cross the Netherlands from East to West and then go to a starting point of a trunkline at IJmond or Rijnmond to Utsira, or they can stay east and go to the starting point at Eemsmond. The CO₂ flows from Belgium and Germany, where a maximum amount of 22 and 144 MtCO₂/yr, respectively, could be captured, help to reach 60 MtCO₂/yr flows at an earlier stage.
- In the scenarios on average 8 fields need to be used simultaneously to store 10 MtCO₂/yr in the Netherlands due to the limited storage potential of the individual sinks (on average 26 MtCO₂ onshore, and 15 MtCO₂ offshore). In the beginning of the period usually the larger fields are chosen and around 4–6 fields suffice for 10 MtCO₂/yr, at the end of the period 12–17 smaller fields may be needed to store the same amount of CO₂. In this case, it requires a good logistic plan to choose the CO₂ sinks at the right time (so that equipment can be re-used), to match the CO₂ flows from different CO₂ sources to the different CO₂ sinks, and to switch timely to new sinks. In comparison logistics of the CO₂ transport and storage would be rather easy when a trunkline to Utsira is built and all CO₂ can be stored in this one formation which is available all the time.

4. Discussion of the outcomes

In this paper the development of a Dutch CO₂ infrastructure that would include an offshore trunkline to the Utsira formation was investigated taking into account policy to mitigate CO₂ emissions. The applied model MARKAL-NL-UU in combination with ArcGIS indicates that CO₂ capture and storage in the Netherlands may increase steeply around 2020. Projections of total volume captured are in the range of 26–39 MtCO₂/yr. These figures are in line with regional plans in the Netherlands. In the Rijnmond region the “Rotterdam climate initiative” aims for an increase of CO₂ storage from 1 MtCO₂/yr in 2010 and 5 MtCO₂/yr in 2015 to 15 MtCO₂/yr in 2020 and 20 MtCO₂/yr in 2025 (Hoog, 2008). In the Eemshaven region a consortium called the “Kern team”, recently published an action plan in which they aim for around 10 MtCO₂ storage per year by 2020 (Kernteam CCS Noord-Nederland, 2009). However, this fast increase is not envisioned by other studies (Daniëls et al., 2008; Menkveld, 2007) evaluating present Dutch climate policy measures (VROM, 2007). According to these studies CO₂ storage of at most 10 MtCO₂/yr will be achieved by 2020 in the Netherlands.²⁵ The difference with the findings of this paper can be explained by the fact

²³ Note that in the base case and offshore only scenario two trunklines of 60 MtCO₂/yr are constructed.

²⁴ Nevertheless, a 40 MtCO₂/yr pipeline may also be an option depending on CO₂ permit prices, since its levelised transport costs are less than 1 €/tCO₂ more than the transport costs through a 60 MtCO₂/yr pipeline (and assuming an electricity price of 60 €/MWh for the pumping station).

²⁵ Although, it is assumed that large scale CO₂ storage is feasible before 2020, it is not argued why this remains limited to 10 MtCO₂/yr.

that MARKAL-NL-UU does not take into account political, legal, business-related, or organisational barriers that can delay the implementation of the capture units or even prevent it. The projected steep increase should, therefore, only be considered as a techno-economic potential (based on the model input data regarding costs and performance, and a discount rate of 7%). It must also be noted that the model opts for a quick growth so that transport costs are lowered by full utilisation of large trunklines at an early stage (resulting in transport costs of 1.6–3.2 €/tCO₂ in 2020, and 5.9 €/tCO₂ in the scenario in which a trunkline to Utsira is already built in 2020). A slower growth in capture capacity would lead to higher transport costs (e.g. model results show that the costs in 2015 are varying between 4.0 and 9.7 €/tCO₂ because of underutilisation of the pipelines).

Other aspects that could change the cost-effectiveness of a trunkline to Utsira over time are:

- Electricity production in the Netherlands for export has not been modeled in this study. Inclusion of electricity production for foreign use will imply greater revenues for plant operators and thus could facilitate the financing of CO₂ infrastructures.
- We departed from a fee of 7.5 €/tCO₂ for transporting CO₂ from German and Belgian parties. A higher fee (e.g. 8.5 €/tCO₂ instead of 7.5 €/tCO₂) would also help to make a trunkline to Utsira cost-effective earlier.
- Higher costs for the pumping station as a result of increased energy or capital costs (i.e. more than 60 €/MWh) would delay cost-effectiveness of a CO₂ trunk pipeline to Utsira.
- In this study, the whole portfolio of measures including CCS would result in CO₂ emission reduction of less than 70% in 2050 compared to 1990 levels in the electricity generating and CO₂ intensive industrial sectors. This may not be in line with a worldwide climate strategy to keep global mean surface air temperature increase around 2 °C. In such a strategy emission reductions of up to 80% are necessary in developed countries, and the power sector needs to be virtually decarbonised (IEA, 2008; IPCC, 2007). This strategy would increase the demand for CCS, and bring forward the need for an Utsira pipeline.
- Finally, the costs of CO₂ storage in the Utsira formation may be underestimated. Costs for possible extra wells that produce water out of the aquifer to avoid pressure build up, which could jeopardise the integrity of the sealing rock as investigated by Lindeberg et al. (2009), are not included.

Furthermore, this paper investigated the development of a CO₂ infrastructure which will favour the national strategy of the Netherlands to reduce its CO₂ emissions. As a consequence specific interests of neighbour countries are not taken into account. For instance:

- In this study, it is assumed that the Netherlands has unhindered access to storage capacity in the Utsira formation. In the scenarios up to 2.7 GtCO₂ from (and via) the Netherlands is stored in the Utsira formation by 2050 filling 6% of the total storage capacity of 42 GtCO₂ according to (Bøe et al., 2002). However, there may well be a need to store CO₂ from other countries in the Utsira formation apart from CO₂ coming from Norwegian sources (Bergmo et al., 2009). UK, on the contrary, may be less interested in storing CO₂ there, because a recent study which investigated a North Sea CCS infrastructure for the UK and Norway (BERR, 2007) stated that sufficient storage capacity is available for the UK on its own territory.²⁶
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²⁶ However, in this study, they did not consider the entire Utsira formation as an option for CO₂ storage.

MARKAL-NL-UU may choose the German and Belgian flows so that larger CO₂ pipelines with lower unit costs become profitable or to fill up spare capacity in the Dutch CO₂ pipelines. Belgium and Germany, if they decide to transport and store their CO₂ via or into the Netherlands, probably have specific requirements about the amounts of CO₂ that need to be transported. Since currently no German or Belgian strategy is known about reducing CO₂ emissions using CCS, only data on maximum possible CO₂ flows from Germany and Belgium have been applied in our study as boundaries for the model runs.

- In this paper it is assumed that Germany and Belgium pay a fee of 5–7.5 €/tCO₂ for transport from a collection point in the Netherlands and storage of their CO₂. It is not investigated whether the CO₂ permit price is attractive enough for them to capture and transport CO₂ to the collection point in the Netherlands.
- We do not consider the opposite case that Germany wants to import CO₂ from the Netherlands. For example, CO₂ from Eemsmond may be transported to Emden in Germany, which is close-by and could be a potential CO₂ collection point for CO₂ storage in the North sea.²⁷

Another point to be taken into account is that the results related to CO₂ storage in specific sinks should be viewed with care, because input assumptions on the storage potentials per sink are uncertain:

- CO₂ storage potentials in this study were based on the TNO database using publicly available data and may have been either underestimated or overestimated (TNO, 2007). More detailed data from local feasibility studies (e.g. from field operators on the ultimate recovery of hydrocarbon fields, and site characteristics) can improve the estimates of the storage potentials and associated cost-effectiveness of the individual sinks (in a positive or negative way).
- Also the storage capacity of the Utsira formation is still in debate. Lindeberg et al. (2009) state that there is no exact limit of the storage capacity in the Utsira formation, and estimate a cost-effective storage capacity range of 20–60 GtCO₂. According to them an economic optimisation of the well and infrastructure would determine the optimal filling over a very long time perspective. A higher capacity may be reached by closer well spacing. Conversely, other studies indicate that the CO₂ storage capacity may be lower than expected because of, e.g. inadmissible pressure built up when CO₂ is injected in aquifers (Meer and Yavuz, 2008).

5. Discussion of some organisational issues

From a Dutch perspective, a number of options are conceivable for setting up a CO₂ transport network. These options can include (or are a combination of) a network connecting CO₂ sources to onshore storage sites, to Dutch near-offshore hydrocarbon fields, or to a huge reservoir underneath the North Sea (in this study the Utsira formation). Some organisational implications of the different options are pointed out:

5.1. CO₂ storage onshore

Our analysis shows that storage of CO₂ onshore is preferred from an economical point of view (scenarios 1, 3, 5). In this case governmental intervention is needed to promote the realisation of a large CO₂ pipeline connecting regions with major CO₂ point sources to the North East of the Netherlands. The sizeable investment related

²⁷ Emden was considered a CO₂ collection point in a study by Holt et al. (2009), who investigated a CO₂ infrastructure for EOR in the North Sea.

to this pipeline makes it unlikely that a private company would build it on its own. The government may encourage and involve the private sector in constructing such a pipeline, for instance, by issuing a tender for a preferred trajectory such as Rijnmond–Eemmond. Private companies may design, build and operate the pipeline, while the investment will most likely need to be co-financed by industry and government. As a consequence, ownership of the pipeline may be both public and private.

Once Dutch onshore capacity has been filled up, it is probably too costly to exploit the Dutch near-offshore capacity, as pointed out in this study. In this case (after 2040) a trunkline towards Utsira would need to be ready.

5.2. CO₂ storage in Dutch near-offshore fields

Storage of CO₂ offshore near the Dutch coast or elsewhere may be preferred if the public acceptance of storage onshore would be negative, and/or because permitting procedures will be shorter (scenarios 2, 4). In this case, the government could advance full exploitation of storage capacity in near-offshore depleted hydrocarbon fields (NOGEP, 2008). The government would need to have a greater role in the selection of storage locations offshore, and take care that platforms of near-offshore depleted gas fields are kept in good condition until they can be used for CO₂ storage. It is unlikely that this would happen in absence of public intervention, since mothballing platforms would involve expenditures in the order of millions of euros. As in the case of onshore storage design, construction and operation may be done effectively by private companies, while both funding and ownership could be shared by the public and private sector. Once near-offshore capacity has been filled up, a trunkline towards Utsira (or another major storage formation) would need to be ready, and some sort of Initiative taken by North Sea countries is needed to realise such a (joint) pipeline.

5.3. CO₂ storage in the Utsira formation

Storage of CO₂ before 2030 in the Utsira formation is a possibility if CO₂ may not be stored onshore and neighbouring countries will pay for the transport of their CO₂ via the Netherlands (scenario 2). However, it could also be necessary if CO₂ may not be stored onshore, and at the same time the Dutch government prefers not to coordinate utilisation of near-offshore transport and storage capacity. In these cases immediate realisation of a CO₂ trunkline towards Utsira will be necessary. Finally, the organisational implications of CO₂ storage in the Utsira formation differ somewhat from the storage in onshore or near-offshore fields. A large number of public and private parties (e.g. CO₂ suppliers) from countries neighbouring the North Sea need to be engaged, for example, in choosing the trajectory of the pipeline towards Utsira. Thus, routings and dimensions can be chosen which are preferred from a socio-economic and strategic point of view. Next, the governments may request a tender for the construction of this pipeline, and design and construction will be in the hands of private companies. Funding, on the other hand, may need to be shared between governments and private companies, because of the sizeable investment of 1–2 billion € and uncertainty in future CO₂ permit prices. Ownership could be with the private sector from the start or public assets could be sold to a private company at some point during operation of the project. Finally, a private entity may be responsible for the operation of pipeline infrastructure. This may be the operator of the storage site, or a gas transport company.

6. Conclusions

In this research we combined the energy bottom-up model MARKAL and the geographic information system, ArcGIS, to assess

the feasibility of using the Utsira formation as part of a long-term Dutch strategy to develop a CO₂ infrastructure. We strived to determine suitable technical configurations for such a pipeline, to assess the boundary conditions making its investment worthwhile, and to make a first inventory of the organisational implications around the construction of this pipeline.

Application of the ArcGIS/MARKAL toolbox shows that an offshore pipeline to the Utsira formation as part of a regional solution (transporting CO₂ from the Netherlands, Belgium and Germany) appears a cost-effective option in the medium term (after 2020). A main condition for the pipeline to Utsira is the existence of a high CO₂ permit price (increasing from around 43 €/tCO₂ in 2020 to 60 €/tCO₂ in 2030). If the price stays below 45 €/tCO₂ by 2030 and the growth of the electricity demand is limited, CCS will be implemented less, and constructing a pipeline to Utsira is only considered cost-effective by the model from 2050 onwards.

Model results suggest that an investment in a CO₂ trunk pipeline towards the Utsira formation may even be cost-effective from 2020 onwards, provided that onshore storage capacity is not permitted or used and that Belgian and German CO₂ is transported as well. Exploitation of onshore capacity and exclusion of Belgian and German CO₂ will each push back cost-effectiveness of a trunkline to Utsira by 10 years. From a national perspective, on the short term storage in Dutch near-offshore fields is more cost-effective than in Utsira, but as yet there are major uncertainties related to the timing and effective exploitation of near-offshore CO₂ storage opportunities.

The ArcGIS/MARKAL toolbox proved to be valuable to get more insights into the boundary conditions of a CO₂ trunkline from the Netherlands to Utsira, because it matches multiple sources to multiple sinks with respect to costs, availability, and location as a function of time. Furthermore, it investigates how and when CO₂ flows from the Netherlands, Germany and Belgium could be transported and stored via a Dutch CO₂ infrastructure. Finally, by adding the spatial aspect into a typical energy system study, the toolbox can support policy makers to tackle the spatial issues relevant for CO₂ infrastructure development and the timeframes involved. The resulting maps that make the development of a CO₂ infrastructure more visible, may also be used as communication tool among stakeholders.

Nevertheless, in this research there are important caveats that need to be addressed in future work. For instance, the national strategies of Belgium and Germany to develop a CO₂ infrastructure were not taken into account. Also, the possibility to transport and store CO₂ via Germany should be considered. Finally, cost data need to be periodically updated (e.g. due to additional costs for water production wells, or impurities in the CO₂ pipelines) and checked by industrial partners in order to assure that modelling results are close to real developments.

Prioritisation of CO₂ storage in onshore fields, near-offshore fields, and/or in the Utsira formation is an important aspect for the optimal design of a Dutch CO₂ infrastructure. Furthermore, suboptimal use of public resources available for developing CO₂ transport networks, can and need to be avoided while fast deployment of CCS is facilitated. The type of public responsibility during the development of CO₂ networks would mainly depend on the storage location. For onshore storage, greater public involvement is required in the permitting process for CO₂ storage sites and pipeline trajectories, especially if CO₂ storage is perceived unfavourably by the local public. Furthermore, pipeline trajectories onshore may be defined in generic terms, while private companies can design the precise layout after a tender procedure. For storage near-offshore, greater public involvement is required in order to fully exploit the near-offshore storage capacity since CO₂ storage in these fields is only cost-effective when gas and oil production platforms are preserved for CO₂ storage. Finally, CO₂

storage in the Utsira formation (or another large formation under the North Sea) would require a major consortium of public and private parties near the North Sea to render this option cost-effective, and to decide on a preferred trajectory by all stakeholders involved.

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References

- Bergmo, P.E.S., Grimstad, A., Lindeberg, E., Riis, F., Johansen, W.T., 2009. Exploring geological storage sites for CO₂ from Norwegian gas power plants: Utsira South. *Energy Procedia* 1 (1), 2953–2959.
- BERR, 2007. Development of a CO₂ transport and storage network in the North Sea. Report to the North Sea Basin Task Force, Department for Business, Energy & Regulatory Reform in association with Element Energy Ltd. with Pöyry Energy and the British Geological Survey, UK.
- Boe, R., Magnus, C., Osmundsen, P.T., Rindstad, B.I., 2002. Geological storage of CO₂ from combustion of fossil fuel. Summary Report of the GESTCO Project, 2002.010. Geological Survey of Norway, Trondheim.
- Broek, M.v.d., E. Brederode, A. Ramirez, L. Kramers, M.V.D. Kuip, T. Wildenborg, W. Turkenburg, A. Faaij, 2009. Combining GIS and MARKAL to design a CO₂ infrastructure in line with the development of the energy supply system. Case of the Netherlands, forthcoming.
- Broek, M.v.d., Faaij, A., Turkenburg, W., 2008. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. *International Journal of Greenhouse Gas Control* 2, 105–129.
- Buit, L., 2009. Personal communication with L. Buit of Gasunie about cost and performance data of pipelines from the Netherlands to the Utsira formation. CASTOR project, 2004. European Castor project on the capture and geological storage of CO₂, <http://www.co2castor.com> (October 2007).
- Council of European Union, 2008. Presidency Conclusions of Brussels European Council of 11 and 12 December 2008.
- CSA Group, 2008. Assessment of the potential for geological storage of CO₂ for the island of Ireland. Report prepared for Sustainable Energy Ireland, Environmental Protection Agency, Geological Survey of Northern Ireland, Geological Survey of Ireland.
- Damen, K., Faaij, A., Turkenburg, W., 2009. Pathways towards a large-scale implementation of CO₂ capture and storage: a case study for the Netherlands. *International Journal of Greenhouse Gas Control* 3, 217–236.
- Damen, K., Troost, M.v., Faaij, A., Turkenburg, W., 2006. A comparison of electricity and hydrogen production systems with CO₂ capture and storage. Part A. Review and selection of promising conversion and capture technologies. *Progress in Energy and Combustion Science* 32 (2), 215–246.
- Daniëls, B.W., Seebregts, A.J., Kroon, P., 2008. Trend analysis air pollution. The effects of the Dutch climate programme. In: *Clean and Efficient on the Emissions of Air Pollutants*, ECN, Petten (in Dutch), ECN-E-08-002.
- E.ON, 2007. E.ON plans hard coal fired power station in Antwerp harbour area (press release), http://www.eon-kraftwerke.com/pages/ekw_en/Media/Press_Releases/Latest_Press_Releases/Pressemitteilung.htm?id=658369 (October 2008).
- EC, 2008. Proposal for a directive of the European parliament and of the council on the promotion of the use of energy from renewable sources. Commission of the European communities.
- EU Council Environment, 2005. Press Release, 2647th Council Meeting Environment Brussels, March 10, 2005.
- EU Geocapacity, 2009. Assessing European capacity for geological storage of carbon dioxide. D42 Geocapacity final report. <http://www.geology.cz/geocapacity/publications>, Project no. SES6-518318.
- EU PV Technology Platform, 2007. A Strategic Research Agenda for Photovoltaic Solar Energy Technology Research and Development in Support of Realizing the Vision for Photovoltaic Technology. European Photovoltaic Technology Platform, Brussels.
- EZ, 2002a. Mining Act, Act of 31st of October 2002. Rules related to the exploration for and production of mining resources and other activities affiliated to mining activities (in Dutch).
- EZ, 2002b. Mining Decree, Decree of 6th of December 2002 related to rules for the enforcement of the Mining Act (in Dutch).
- EZ, VROM, V&W, 1984. Dutch policy plan pipelines (in Dutch), extended up to 2008 Netherlands Ministries of Economic Affairs, of Housing, Spatial Planning, and Environment, and of Transport, Public Works, and Water Management.
- Gale, J., Christensen, N.P., Cutler, A., Torp, T.A., 2001. Demonstrating the potential for geological storage of CO₂: the Sleipner and GESTCO projects. *Environmental Geosciences* 8 (3), 160–165.
- GD, BGR, 2005. Kurzstudie CO₂-Speicherpotenzial in NRW (not publicly available yet). GD (Geologischer Dienst Nordrhein-Westfalen); BGR (Bundesanstalt für Geowissenschaften und Rohstoffe), Krefeld/Hannover.
- Harmsen, R., Hoen, V., 2008. Provincial Ambitions Renewable Energy Generation and CO₂ Storage in Relation to the Energy Policy “Clean and Economical”. Ecofys, Utrecht (in Dutch).
- Heddl, G., Herzog, H., Klett, M., 2003. The Economics of CO₂ Storage, MIT LFE 2003-003 RP. MIT, Cambridge.
- Hendriks, C., Egberts, P., 2003. Carbon Dioxide Sequestration Systems: Economic Evaluation and Case Studies. GESTCO Technical Report. Ecofys and TNO-NITG, Utrecht, The Netherlands.
- Hendriks, C., Wildenborg, T., Feron, P., Graus, W., Brandsma, R., 2003. EC-CASE Carbon Dioxide Sequestration, M70066. Ecofys, TNO, Utrecht.
- Hermanrud, C., Andresen, T., Eiken, O., Hansen, H., Janbu, A., Lippard, J., Bolås, H.N., Simmenes, T.H., Teige, G.M.G., Østmo, S., 2009. Storage of CO₂ in saline aquifers—lessons learned from 10 years of injection into the Utsira Formation in the Sleipner area. *Energy Procedia* 1 (1), 1997–2004.
- Holt, T., Lindeberg, E., Wessel-Berg, D., 2009. EOR and CO₂ disposal—economic and capacity potential in the North Sea. *Energy Procedia* 1 (1), 4159–4166.
- Hoog, M.d., 2008. Rotterdam Climate Initiative: CO₂ Capture, Transport, and Storage in Rijnmond. DCMR milieudienst Rijnmond, Rotterdam (in Dutch).
- IEA, 2007. World Energy Outlook 2007. International Energy Agency, Paris.
- IEA, 2008. Energy Technology Perspectives 2008. IEA, Paris.
- IEA GHG, 2002. Transmission of CO₂ and Energy, PH4-6. International Energy Agency Greenhouse Gas R&D Programme, Cheltenham.
- IEA GHG, 2003. Potential for improvement in gasification combined cycle power generation with CO₂ capture, PH4/19, Cheltenham.
- IEA GHG, 2004. Improvement in power generation with post-combustion capture of CO₂, PH4-33, Cheltenham.
- IEA GHG, 2005a. Building the cost curves for CO₂ storage: European sector, 2005/2. International Energy Agency Greenhouse Gas R&D Programme, Cheltenham.
- IEA GHG, 2005b. Building the cost curves for CO₂ storage: North America, 2005/3, Cheltenham.
- IHS, 2008. IHS Indexes, IHS/CERA Upstream Capital Cost Index (UCCI). In: <http://ihsindexes.com/ucci-graph.htm> (January 8, 2009).
- IHS, 2009. Graph IHS/CERA Upstream Capital Cost Index. .
- IPCC, 2007. Climate Change 2007: Mitigation of Climate Change. Summary for Policymakers. .
- Janssen, L., Okker, V., Schuur, J., 2006. Welfare and environmental quality report for the Netherlands in 2040 (in Dutch), Netherlands bureau for economic analysis, Netherlands environmental assessment agency, and Netherlands Institute for Spatial Research, The Hague and Bilthoven.
- Junginger, M., Faaij, A., Turkenburg, W.C., 2005. Global experience curves for wind farms. *Energy Policy* 33, 133–150.
- Kemp, S.J., Pearce, J.M., Steadman, E.J., 2002. Mineralogical, geochemical and petrographical characterisation of Nordland Shale cores from well 15/9-A-11, Sleipner field, northern North Sea Sustainable Energy and Geophysical Surveys Programme, Commissioned Report CR/02/313, British Geological Survey, Keyworth, Nottingham.
- Kernteam CCS Noord-Nederland, 2009. Carbon Capture and Storage, Action Plan North Netherlands. 978-90-79147-05-2 (in Dutch).
- Kronimus, A., Busch, A., Alles, S., Juch, D., Jurisch, A., Littke, R., 2008. A preliminary evaluation of the CO₂ storage potential in unminable coal seams of the Münster Cretaceous Basin, Germany. *International Journal of Greenhouse Gas Control* 2 (3), 329–341.
- Lindeberg, E., Vuillaume, J., Ghaderi, A., 2009. Determination of the CO₂ storage capacity of the Utsira formation. *Energy Procedia* 1 (1), 2777–2784.
- Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL Family of Models. ETSAP, Paris.
- Markussen, P., Austell, J.M., Husted, C.-W., 2002. A CO₂-infrastructure for EOR in the North Sea (CENS): macroeconomic implications for host countries. In: 6th International conference on Greenhouse Gas Control Technologies, Kyoto.
- May, F., Müller, C., Bernstone, C., Rubin, E.S., Keith, D.W., Gilboy, C.F., Wilson, M., Morris, T., Gale, J., Thambimuthu, K., 2005. Assessment of the CO₂ storage potential in deep saline aquifers (in Germany). In: *Greenhouse Gas Control Technologies 7*, Proceedings of the 7th International Conference on Greenhouse Gas Control Technologies. Elsevier Science Ltd., Vancouver, Canada, doi:10.1016/B978-008044704-9/50256-1.
- McCollum, D., Ogdén, J.M., 2006. Techno-economic Models for Carbon Dioxide Compression, Transport, and Storage & Comparing Techno-economic Models for Pipeline Transport of Carbon Dioxide, UCD-ITS-RR-06-14. Institute of Transportation Studies, University of California, Davis.
- McKinsey&Company, 2008. Carbon Capture and Storage: Assessing the Economics. McKinsey&Company.

- Meer, B.v.d., Yavuz, F., 2008. CO₂ storage capacity calculations for the Dutch subsurface. *Energy Procedia* 1 (1), 2615–2622.
- Menkveld, M. (Ed.), 2007. Evaluation Work Programme Clean and Economical. ECN, MNP, Petten (in Dutch), ECN-E-07-067.
- Menkveld, M., van den Wijngaart, R.A. (Eds.), 2007. Exploration Potential and Costs of Climate and Energy Measures for the Energy Policy “Clean and Economical”. ECN, MNP, Petten (in Dutch), ECN-E-07-032.
- MNP, 2007. The Netherlands Later. Second Sustainability Outlook. Part Physical Dutch Environment. (in Dutch), 500127001/2007.
- NLOG, 2007. The winnings schemes of all hydrocarbon fields. <http://www.nlog.nl/dinoLks/requestData/nlogp/olgField/listing.jsp?menu=res> (accessed December 2007).
- NOGEP, Ministry of Economic Affairs, 2008. Potential for CO₂ Storage in Depleted Gas Fields at the Dutch Continental Shelf. Phase 1: Technical Assessment. DHV, TNO.
- Ogden, J.M., Yang, C., Johnson, N., Ni, J., Johnson, J., 2004. Conceptual design of optimized fossil energy systems with capture and sequestration of carbon dioxide. Report to the U.S. Department of Energy National Energy Technology Laboratory, University of California, Davis, CA.
- OSPAR convention, 1998. The Convention for the Protection of the marine Environment of the North-East Atlantic. .
- Özdemir, Ö., Scheepers, M., Seebregts, A., 2008. Future electricity prices. Wholesale market prices in and exchanges between Northwest European electricity markets, ECN-E-08-044. Energy Research Centre of the Netherlands, Petten.
- Ramírez, A., Hagedoorn, S., Kramers, L., Wildenborg, T., Hendriks, C., 2009. Screening CO₂ storage options in the Netherlands. *Energy Procedia* 1 (1), 2801–2808.
- Seebregts, A.J., Daniëls, B.W., 2008. The Netherlands, export country of electricity? New developments electricity power plants and effect policy “Clean and economic”. ECN, Petten (in Dutch), ECN-E-08-026.
- Seebregts, A.J., Groenenberg, H., 2009. Implications of CCS for the Northwest European electricity market and for CO₂ emissions in the Netherlands. In: Presented at ‘Climate Change: Global Risks, Challenges and Decisions’, Copenhagen, March 10–12, 2009.
- Serbutoviez, S., Coussy, P., Lokhorst, A., Keppel, F., Kramers, L., Kuip, M.D.C.v.d., Egberts, P.J.P., 2007. Economic Analysis Tool CASTOR, Deliverable 1.1.3B. .
- Tenne, 2008. Vision 2030 (in Dutch), Arnhem.
- TNO, 2007. Options for CO₂ storage in the Netherlands—time dependent storage capacity, hazard aspects, and regulations, 2007-U-R0564/B, TNO Built Environment and Geosciences, Utrecht.
- Torp, T., 2008. Personal communication about Costs for CO₂ storage in the Utsira formation (October 2008).
- Torp, T., Brown, K., 2004. CO₂ underground storage costs as experienced at Sleipner and Weyburn. In: 7th International Journal of Greenhouse Gas Control, Vancouver.
- Torp, T.A., Gale, J., 2004. Demonstrating storage of CO₂ in geological reservoirs: the Sleipner and SACS projects. *Energy* 29 (9–10), 1361–1369.
- University of Chicago, 2004. The economic future of nuclear power directed by G. Tolley and D. Jones. University of Chicago, Chicago.
- Vandeginste, V., Piessens, K., 2008. Pipeline design for a least-cost router application for CO₂ transport in the CO₂ sequestration cycle. *International Journal of Greenhouse Gas Control* 2 (4), 571–581.
- Viebahn, P., Esken, A., Fishedick, M., 2009a. Energiewirtschaftliche, strukturelle und industriepolitische Analyse der Nachrüstung von Kohlekraftwerken mit einer CO₂-Rückhaltung in Nordrhein-Westfalen. Final Report (in German). http://www.wupperinst.org/de/projekte/proj/index.html?&projekt_id=203&bid=136, Wuppertal.
- Viebahn, P., Esken, A., Fishedick, M., 2009b. Energy-economic and structural, and industrial policy analysis of re-fitting coal fired power plants with CO₂-capture in North Rhine-Westphalia/Germany. *Energy Procedia* 1 (1), 4023–4030.
- VROM, 2006. Agreement Nuclear Power Plant Borssele. (in Dutch).
- VROM, 2007. New energy for the climate, working programme clean and economical. Projectgroup clean and economic of Council of Ministers (in Dutch).
- Wildenborg, A.F.B., Neele, F.P., Kramers, L., 2008. Supplement on Report 1.1.3B—Economic Analysis Tool: Deliverable 1.1.5B CASTOR (not publicly available) .