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TNO report

TNO-034-UT-2009-02024

Inventory of potential locations for demonstration project CO2-storage

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Project number	034.20777/01.03
Classification report	
Title	Confidentieel
Abstract	Confidentieel
Report text	Confidentieel
Appendices	Confidentieel
Number of pages	34 (incl. appendices)
Number of appendices	

Samenvatting

Op verzoek van de Interdepartementale Projectorganisatie CCS (poCCS) heeft TNO-AdviesGroep Economische Zaken (AGE) onderzocht, of er vanuit de geotechniek alternatieven zijn voor Barendrecht als locatie van een kleinschalig project voor CO_2-opslag. TNO heeft zich hierbij gebaseerd op de nu beschikbare gegevens en deze vanuit geotechnisch oogpunt beoordeeld, zonder een afweging te maken of er voor een veld of veldcombinatie een realistische business case voor een opslagproject te maken is en of er daarbij een goede ‘match’ mogelijk is van een CO_2-bron en een opslaglocatie. Evenmin heeft TNO in kaart gebracht hoeveel tijd nodig is om een opslagproject uit te ontwikkelen en in procedure te brengen. Dit zijn wel elementen die in een afweging van belang zijn omdat deze bepalen of sprake is van een reëel en tijdig uitvoerbaar alternatief.

Het onderzoek heeft een basale selectie van een grote groep gasvelden gedaan op grond van de volgende twee criteria:

- beschikbaar uiterlijk in 2012
- capaciteit tussen 0,5 en 10 Mt CO_2

Bekeken is ook of het van onderscheidend belang is om de afstand tot een bestaande bron van zuivere CO_2 mee te nemen in het selectiecriteria. Niet alleen de financiële kosten van de aanleg en beheer van een pijpleiding, maar juist ook de energiekosten daarvan bij een relatief klein project zijn hierbij bekeken. Energiekosten, investeringskosten en operationele kosten blijken sterk afstandsgerelateerd te zijn: elke aanvullende 50 km transportleiding levert significant aanvullende kosten op. Teneinde de kring rondom de bestaande bron voor dit onderzoek zo groot mogelijk te houden, is een afstand van 150 km tot een bestaande bron van zuivere CO_2 als selectiecriterium toegepast, hoewel uit bedrijfseconomisch oogpunt een afstand van 100 km eerder realistisch zou zijn.

Dit proces leverde een uiteindelijke selectie op van 12 gasvelden, waaronder het Barendrecht-veld. Van deze selectie van 12 velden liggen er 4 onshore (onder het Nederlands territoir, exclusief de Noordzeekustzone) en 8 offshore (onder het Nederlandse deel van het continentaal plat, inclusief de Noordzeeksutzone).

Deze 12 velden zijn vervolgens geëvalueerd op basis van criteria uit de AMESCO studie. De AMESCO-studie is een zogeheten ‘generiek milieu-effectenrapport’. Het heeft de criteria verkend die vanuit het oogpunt van veiligheid en milieu-effecten belangrijk zijn om in een vervolgfase in detail te bekijken als er voor een concreet leeg gasveld de geschiktheid voor CO_2-opslag moet worden bepaald.

Veldnaam	Opslag capaciteit	AMESCO score	AMESCO reden	Monitoring potentieel / toegankelijkheid	Mogelijkheid om een klein veld te combineren met een groot veld
	Mt CO_2				
P15-E (offshore)	0.5			1 well only	yes
Sprang	0.7	poor	poor injectivity	1 well only	
Castricum Zee (offshore)	0.7	'good minus'	1 abandoned well	1 well only (long reach well) under protected area	
P15-C (offshore)	0.7			1 well only	yes
Barendrecht	0.8	poor	under built area		yes
Loon op Zand	1.1	poor	poor injectivity	1 well only	
L13-FH (offshore)	1.7			1 well only (subsea completion)	
P06-South (offshore)	1.9				yes
P15-12 (offshore)	1.9			1 well only (subsea completion)	
P06-D (offshore)	4.6			1 well only	
Schermer	6.1	medium	1 old abandoned well	under protected area	
Q08-A (offshore)	7.8				

Twee velden (Sprang en Loon op Zand) scoren laag vanwege lage injectiviteit (hetgeen impliceert dat voor het injecteren van CO_2 hogere drukken nodig zijn dan bij velden met een hoge injectieviteit). Twee andere velden (Castricum-Zee en Schermer) zijn minder geschikt vanwege het feit, dat zich in beide velden een reeds met cement gedichte put bevindt. Op het AMESCO-criterium "gebruik bovengrond" scoort het Barendrecht-veld ongunstig, omdat het is gelegen onder bebouwd gebied.

Vervolgens heeft TNO-AGE gelet op de toegankelijkheid van een gasveld voor monitoring, zowel via putten als (eventueel) vanaf oppervlak. Dit wordt essentieel geacht voor een demonstratieproject. Vier velden (Castricum-Zee, L13-FH, P15-12 en Schermer) worden als minder tot niet geschikte kandidaten bestempeld vanwege onvoldoende toegankelijkheid voor monitoring.

Tenslotte is geëvalueerd, als sprake is van een veld dat kleiner is dan 2 Mt CO_2, of er mogelijkheden zijn voor het combineren van zo'n klein veld voor kleinschalige opslag met een groter veld (capaciteit tot 10 Mt) als opvolger. De CO_2-effectiviteit van de aanleg van infrastructuur (leidingen en installaties) voor een relatief klein veld moeten immers in verhouding staan tot de benutting van deze infrastructuur.

Uit die evaluatie komen vier mogelijke combinaties naar voren die dit voordeel hebben:

- Barendrecht en Barendrecht-Ziedewij;
- Castricum-Zee en Q8-A;
- P15-E of P15-C met een groter veld in de blokken P15 en P18 ;
- P6-South met P6-D.

De haalbaarheid van de drie offshore combinaties hangt daarbij sterk af van het antwoord op de vraag, hoe dit zich verhoudt tot het recent door het Rotterdam Climate Initiative gepresenteerde plan, dat voorziet in gefaseerde opslag van CO_2 in Q8-A (vanaf 2013), de blokken P15 en P18 (vanaf 2015) en blok P6 (vanaf 2017).

TNO AGE concludeert dat van de 12 geselecteerde locaties die potentieel geschikt zijn voor een kleinschalig demonstratieproject voor CO_2 opslag, het Barendrecht en P06-South veld geen (geo-)technische minpunten hebben met betrekking tot de toegepaste criteria. De overige 10 velden scoren minder volgens de toegepaste AMESCO en/of de additionele criteria.

Contents

1 Introduction

Task
The *Interdepartementale Projectorganisatie CCS* ('poCCS') has requested TNO-AGE to investigate the site selection for demonstration of CO_2-sequestration in the Netherlands. The task has been described by poCCS in a document dated July 30, 2009 (ref. CCS/9135285), that is attached to this report (Appendix 1).

Purpose
The purpose of the investigation is to:
- provide insight into the considerations leading to a list of sites, that are most suitable for a demonstration project for CO_2-sequestration in the Netherlands (with the already submitted Barendrecht project proposal as a reference);
- provide input for the policy making at national level in the framework of the 'Rijksinpassingplan' for this project.

Position and expertise of TNO-AGE
TNO-AGE is an advisory group to the Ministry of Economic Affairs (MEA) on matters concerning exploration, production and storage activities in the Dutch subsurface. TNO-AGE is also the national custodian for all subsurface related data and information, which licence holders have to submit pursuant to the Dutch Mining Law. On behalf of the MEA, TNO-AGE publishes its assessments of the exploration, production and subsurface storage potential in the Netherlands on an annual basis (ref. 1).

2 Details of the task

Sources
The poCCS has requested to focus on the Shell Pernis hydrogen plant. But in view of the 'Rijksinpassingsplan', other possible sources in the Netherlands of pure and readily available CO_2, together with the associated sinks, were to be investigated as well.
The poCCS has provided the list of existing sources of pure CO_2 (i.e. the CO_2 stream that does not need to undergo a CO_2 capture process) shown in Table 1. Shell Pernis, Yara (Sluiskil, Zeeland) and DSM Agro (Sittard, Limburg) are the only sources with more than the required 0.2 Mt/year of available CO_2. DSM Agro already is planned to be the source for a local storage project. Therefore, within the framework of this study the Yara source is the only possible alternative for Shell Pernis.

Source	Location	Available pure CO_2 (Mt/year)
Abengoa	Rotterdam	0.12
DSM Agro	Sittard	0.7
Esso	Rotterdam	0.1
Shell	Pernis	0.62
Yara	Sluiskil	1.15

Table 1** **Existing sources of pure CO_2 (i.e. the CO2 stream that does not need to undergo a CO2 capture process) ***in the Netherlands (draft figures as estimated by the ministries of VROM and EZ)***

Transport
The poCCS document (App.1) does not specify the way(s) of transport of CO_2.
For this study we have assumed transport by pipeline. This is the most likely way of transportation for future large scale CCS.
Transport has been assumed to be in the gaseous phase. It seems unlikely, that rates in the order of 0.2 Mt/year could justify transport in liquid phase. Note that large scale transport will probably be in the liquid phase

Sinks
In the poCCS document (App. 1) a stepwise approach was envisaged. At the onset of the project it was decided by the poCCS that the CO_2 efficiency as mentioned in the poCCS document should rather be called cost effectiveness was to be expressed in distance between the storage location and the source. Increasing distances imply very high additional costs for pipelines, compression and operations (a.o. energy). Although from a business point of view a maximum distance between 50 and 100 km would be more realistic, poCCS' has decided on a search radius of 150 km not to narrow down the first stage selection too much.

<u>Step 1:</u> Consider all gas fields onshore and offshore the Netherlands as potential storage site candidates.

<u>Step 2:</u> Select gas fields based on (at least):
- availability for CO_2-storage: by the end of 2012 at the very latest;
- storage capacity: (a combination of) fields with a storage capacity between 0.5 and 10 Mt CO_2;

- Cost effectiveness: is determined by the distance between source and sink, related to the costs of the demonstration project. The maximum distance was set at 150km.

Step 3: Evaluate the fields resulting from of Step 2 for suitability and safety on the basis of:

- AMESCO reservoir characteristics as laid down in ref. 2;
- additional criteria, deemed necessary by TNO-AGE to determine suitability.

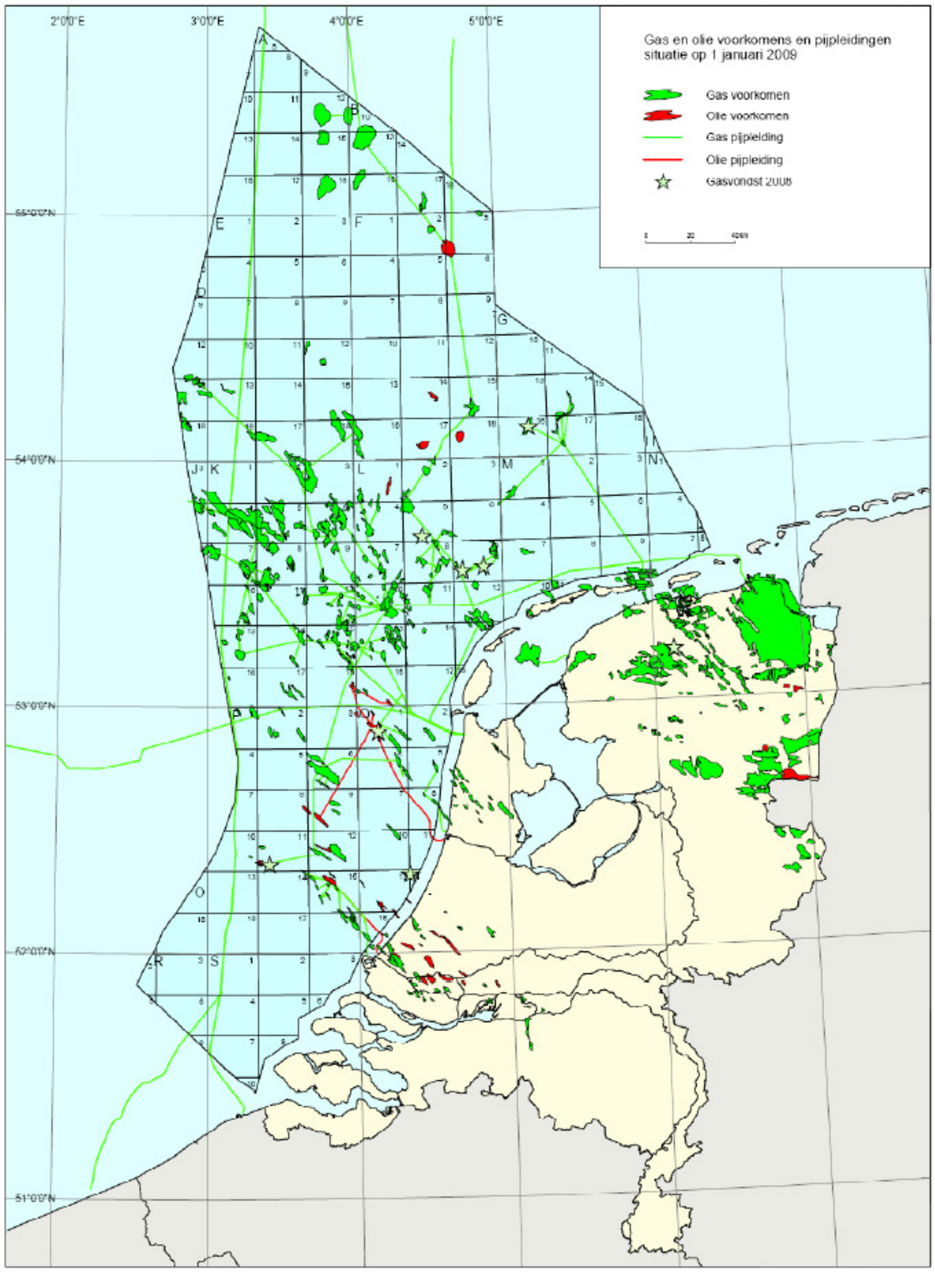

Figure 1 Gas and oil fields in the Netherlands (ref. 1).

3 Step 1: The portfolio of possible storages

Preference for depleted gas fields

The poCCS considers (depleted) gas fields the most suitable storage option because of their intrinsic safety (App. 1). TNO-AGE does support this choice for the purpose of this study for the following additional reasons:

- the technical lead time for converting a depleted gas field into a CO_2 store is short relative to other geological storage options: from their production history, much is known of the injection, storage and containment capacities of gas fields;
- the geographical footprint per unit mass of CO_2 stored is less than for any other subsurface storage option, which is an advantage for monitoring and managing the storage site;

In time, other geological storage options may prove their practical potential.

The portfolio of gas fields in the Netherlands

The starting point for this inventory therefore has been the portfolio of all onshore and offshore gas fields in the Netherlands known to date. Figure 1 shows the locations of all gas fields in the Netherlands (ref. 1). A total of 420 gas fields have been discovered as of Jan 1, 2009. Of these, 175 gas fields have not been considered candidates for the purpose of this study:

- 125 fields have not been developed as yet;
- 46 fields have already been abandoned, i.e. all wells plugged and infrastructure removed;
- 4 fields are in use as underground natural gas storage, or in an area, where a natural gas storage licence has been applied for.

The remaining 245 gas fields are currently producing or have been temporarily closed in. These fields have been used as input for the screening Step 2.

4 Step 2: Screening

4.1 Search profile

From the information provided by the poCCS (see chapter 2), TNO-AGE has constructed a screening profile for the 245 fields resulting from Step 1. The considerations and results of applying that search profile are presented below.

Availability

A candidate gas field has to be available for CO_2 storage by the end of 2012 at the very latest. The availability of a gas field for CO_2 storage implies that natural gas production must have ceased and the operator considers further gas production not commercially viable. This date can only be deduced from the present day operators forecast on annual expected production. This information is supplied to the Minister of Economic Affairs in accordance with the Mining Decree (ex article 113) on an annual basis by the licensees for gas production. This confidential information is available in the TNO-AGE database.

One has to bear in mind, that these expected production profiles are the view of the current operator based on the technical performance of the gas fields and on current field economics. Neither of these is constant over time. This implies that in the future there may be developments, which may alter the expected date on which production will cease. Given the intention of operators to optimally extract gas, the tendency is that production life times will get longer.

For this study we have relied on the 2009 versions of these annual reports submitted by the operators.

Figure 2 shows the subset of the 245 gas fields resulting from Step 1, that operators expect to be depleted before the end of 2012.The majority of these fields are located at a straight line distance of more than 150 km from the Pernis plant (and even more from the Yara plant), in the northern Netherlands and in the central offshore. Again it is stressed, that the year of availability may very well turn out to be later than 2012, given the production licence conditions and the commercial interest of the licence operators to optimally extract gas from the fields.

Storage capacity

The poCCS has defined a range for the storage capacity between 0.5 and 10 Mt CO_2.

The tender document for the demonstration project did require, amongst others, a minimum yearly injection rate of 0.2 Mt CO_2 (ref. 3). The duration for the financial contribution from government was set at 10 years, thus making a minimum cumulative amount of 2 Mt CO_2 to be injected under the tender conditions.

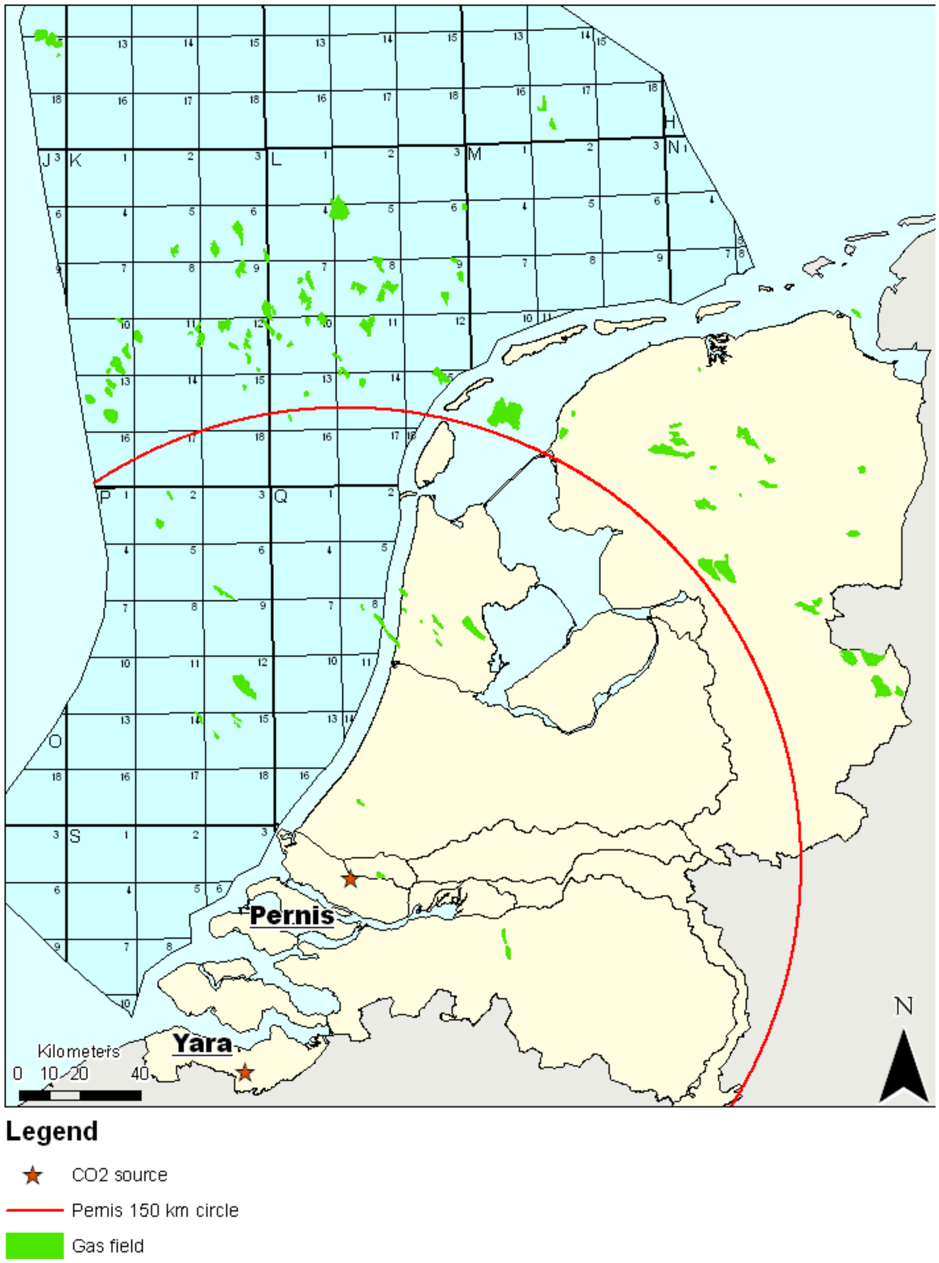

Figure 2 ***The subset of gas fields resulting from Step 1, that operators expect to be depleted before the end of 2012.***

Given the fact, that injection is supposed to start at the beginning of 2013 at the very latest and substantial learning has to be obtained from the project by 2015 (when larger projects are deemed to start), a minimum storage capacity in the order of 0.5 Mt indeed is appropriate. The learning curve of a demonstration project preferably should include all the stages of storage, from initial injection into a depleted gas field until the maximum allowed pressure will be reached, when injection will cease and the storage site may be closed and further monitored.

Even with a source with the size of Yara (max. 1.15 Mt/yr) a gas field with a storage capacity of more than 10 Mt would only be partially filled in 3 years (less than 33%). The rationale to allow 10 Mt fields to screen in this Step 2 is, that this will provide a wide selection of fields. Narrowing down this selection will occur applying other criteria in later stages of the process.

In Step 2, we have used the range for the storage capacity indicated by the poCCS (i.e. between 0.5 and 10 Mt) as a screening criterion.

In Step 3 a closer look will be presented on the possibilities to combine smaller and larger fields.

We have estimated the CO_2 storage capacity of a gas field by stating, that 1 bcm of natural gas produced will allow 2.5 Mt CO_2 to be injected.

It is noted that, depending on initial reservoir pressure and temperature, the theoretical ratio – i.e. based on pore volume replacement – is somewhat higher, in the order of 3 Mt CO_2 /bcm of gas produced. But engineering constraints (e.g. with or without local compression), geological factors (hysteresis in filling the original gas bearing reservoir volume) and a safety margin (maximum injection pressure not exceeding the original reservoir pressure) in practice will lead to a somewhat lower effective ratio, that we have set at 2.5 Mt CO_2 / bcm gas produced, as was done in a recent CCS study on offshore gas fields (ref. 10). In the injection simulations of that study, pressures were not allowed to exceed the original pas pressure of a field.

Indeed, it is one of the objectives of a demonstration project to test the actual injection capacity under pressure constraints. Should the observed injection capacity be lower than expected, injection will have to be reduced or stopped earlier. In that case it will be useful to have a second nearby field as a backup.

Figure 3 shows the subset of the 245 gas fields resulting from Step 1, that have a CO_2 storage capacity between 0.5 and 10 Mt. The map shows the location of possible candidates in the Rijnmond onshore area and in the nearshore P15/P18 area, as well as in the province of Noord Holland (near the IJmond) and the adjacent nearshore Q8 block.
The majority of fields with a storage capacity in the search range are located at more than 150 km from the Pernis hydrogen factory (and even more from the Yara plant) in the northern Netherlands and in the central offshore K- and L-quadrants.

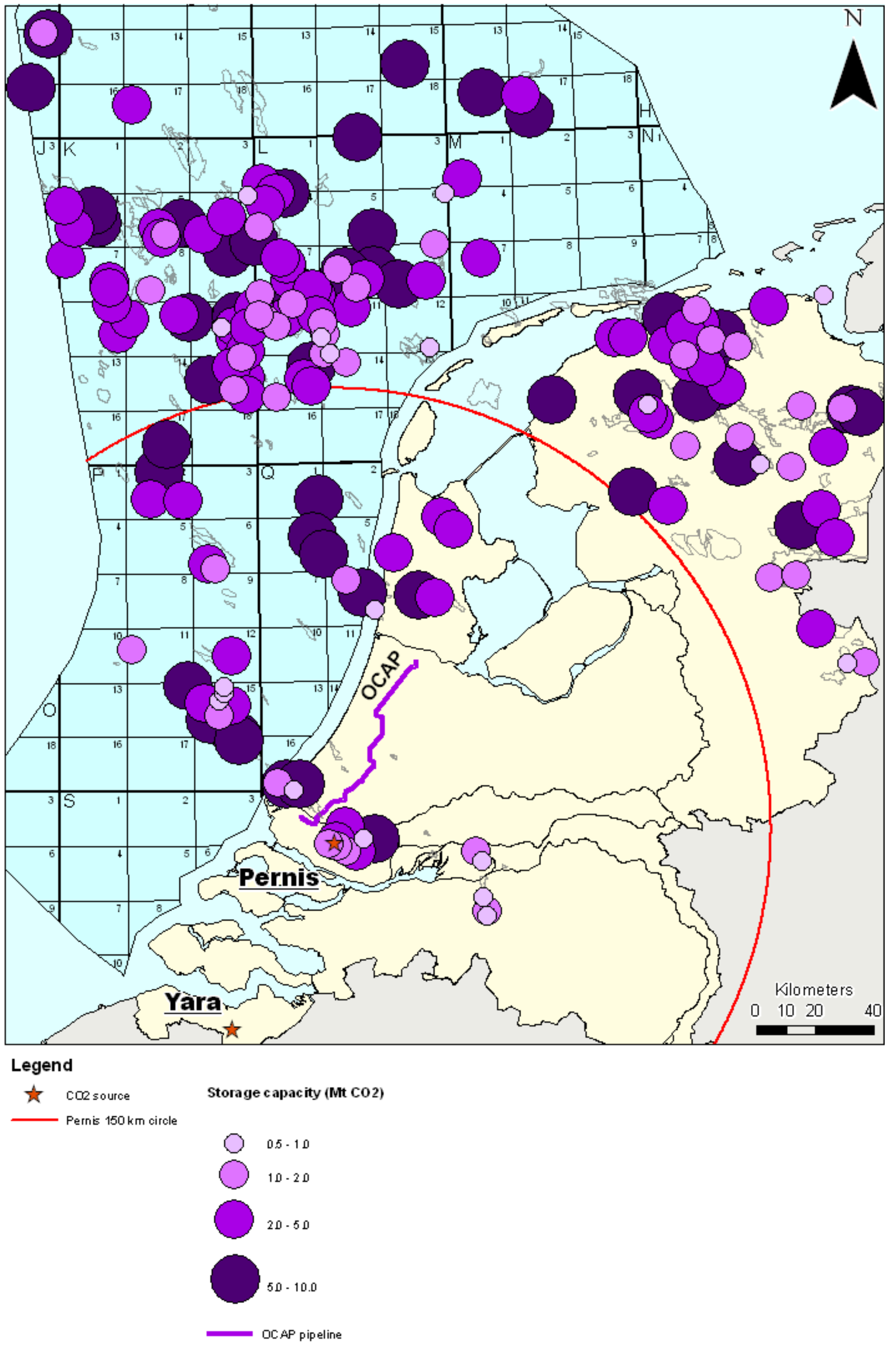

Figure 3 The subset of the 245 gas fields resulting from Step 1, that have a CO_2 storage capacity between 0.5 and 10 Mt.

Cost effectiveness

CO_2-effectiveness has been defined by the poCCS as a parameter, that is determined by the distance between source and sink, related to the costs of the demonstration project (App. 1). The term CO2-efficiency relates to the entire climate benefit of the project (cradle to grave), therefore the term cost-effectiveness is more appropriate here.

In the view of TNO-AGE the rationale is, that project investment and operational costs are preferably to be assigned and spent in such a way, that – within the available budget - the learnings of the demonstration project are optimized. Leaving cost of capture apart (since pure CO_2 sources are supposed in this first demonstration phase), there should be a reasonable balance between costs of transportation on one hand and of injection, storage and monitoring on the other.

Designing a detailed pipeline trajectory from the source to the potential storage locations is beyond the scope of this study. However, CO_2-efficiency can at least be treated in a semi-quantitative sense, as will be discussed below.

Information from CATO research (ref. 4) and information from companies involved in the construction of onshore pipelines indicates costs in the order of 1 MEuro/km for the construction of a 16 inch pipeline. Long distance transport requires compressor stations to transport the CO_2 with the desired pressure. Roughly every 50 km a next compressor station is needed. As an example table 2 shows the approximated CAPEX and OPEX for pipelines and transport compression for a three year period (the duration of the demonstration project.

Transport distance (km)	CAPEX pipelines (MEuro)	CAPEX compressors (MEuro)	OPEX/yr (MEuro)	Total costs for 3 years (MEuro)
25	25	3.5	0.5	30
50	50	7	1	60
100	100	14	2	120
150	150	21	3	180

Table 2 CAPEX and OPEX for pipeline and compression for different lengths of transportation.

From the table it can be read that costs multiply by approximately 6 when the Barendrecht location (less than 25 km distance form the source) is compared to the maximum search distance of 150 km.
As an example, the construction of a 25 km new CO_2 transport pipeline segment would require an investment in the order of 25 MEuro, being almost equal to the amount of financial support from government to the demonstration project.

In view of the above argument on pipeline costs 150 km is a rather long distance. However, poCCS wanted to avoid discarding possible candidate fields too early in the process of determining suitability. Moreover, our choice does account for the use of the existing OCAP pipeline, running from the Rotterdam area to the Amsterdam area. This pipeline already is in use for CO_2 transport and may be considered a 85 km ‘extension cord' from the Rotterdam area to possible storage candidate fields in the province of Noord Holland and de adjacent nearshore.

Long distance transport will also require larger pipe diameters and/or more compression power. The latter also significantly increases the operational costs for the extra energy consumption. In turn, the extra energy consumption produces additional CO_2 emissions. For the proposed Barendrecht project with a transport distance of 17 km, every tonne of CO_2 transported and injected is expected to give rise to 0,05 tonne of CO_2 emissions, mainly coming from the compressors, i.e. 95% CO_2-efficiency in these terms (ref. 5). This efficiency will decrease with increasing transport distance.

For the purpose of screening in Step 2, poCCS has adopted a maximum straight line distance of 150 km from the Pernis hydrogen factory to a storage candidate (see red circle in Figure 3). N.B! Actual pipeline trajectories will be even longer due to existing infrastructure and land use (see table 2).

4.2 Results from the screening

Applying the above mentioned screening criteria for availability, storage capacity and distance narrows down the number of selected gas fields to 12. Table 2 shows their characteristics, including the estimated distance to the Pernis source along existing pipeline trajectories of the national gas grid. Out of these 12 fields, 4 are located onshore and 8 offshore (Castricum Zee is considered offshore as it is located under the North Sea with its well hooked up to platform Q08-A). Three offshore fields have already ceased production and are currently shut in, i.e. in principle there still is access through the wells. For the fields that currently are shut-in, timely availability is more certain than for the others.

This result from screening in Step 2 has been input to the next Step 3: Evaluation.

Field name	Current operator	Current status	On/offshore	Storage capacity	Estimated distance
				Mt CO_2	*km*
P15-E	TAQA	producing	offshore	0.5	75
Sprang	Northern Petroleum	producing	onshore	0.7	80
Castricum Zee	Wintershall	shut-in	offshore	0.7	100 + 22
P15-C	TAQA	producing	offshore	0.7	75
Barendrecht	NAM/SCS	producing	onshore	0.8	20
Loon op Zand	Northern Petroleum	producing	onshore	1.1	80
L13-FH (sub sea)	NAM	shut-in	offshore	1.7	210
P06-South	Wintershall	producing	offshore	1.9	150
P15-12 (sub sea)	TAQA	producing	offshore	1.9	75
P06-D	Wintershall	producing	offshore	4.6	150
Schermer	TAQA	producing	onshore	6.1	85 + 40
Q08-A	Wintershall	shut-in	offshore	7.8	100 + 22

Table 2 Fields resulting from screening, sorted by storage capacity. Estimated distance is an approximation of distance measured along the national gas pipeline grid. For those locations that can make use of existing pipelines (OCAP and offshore to Q08) the distance has been split into existing pipeline + new pipeline distances.

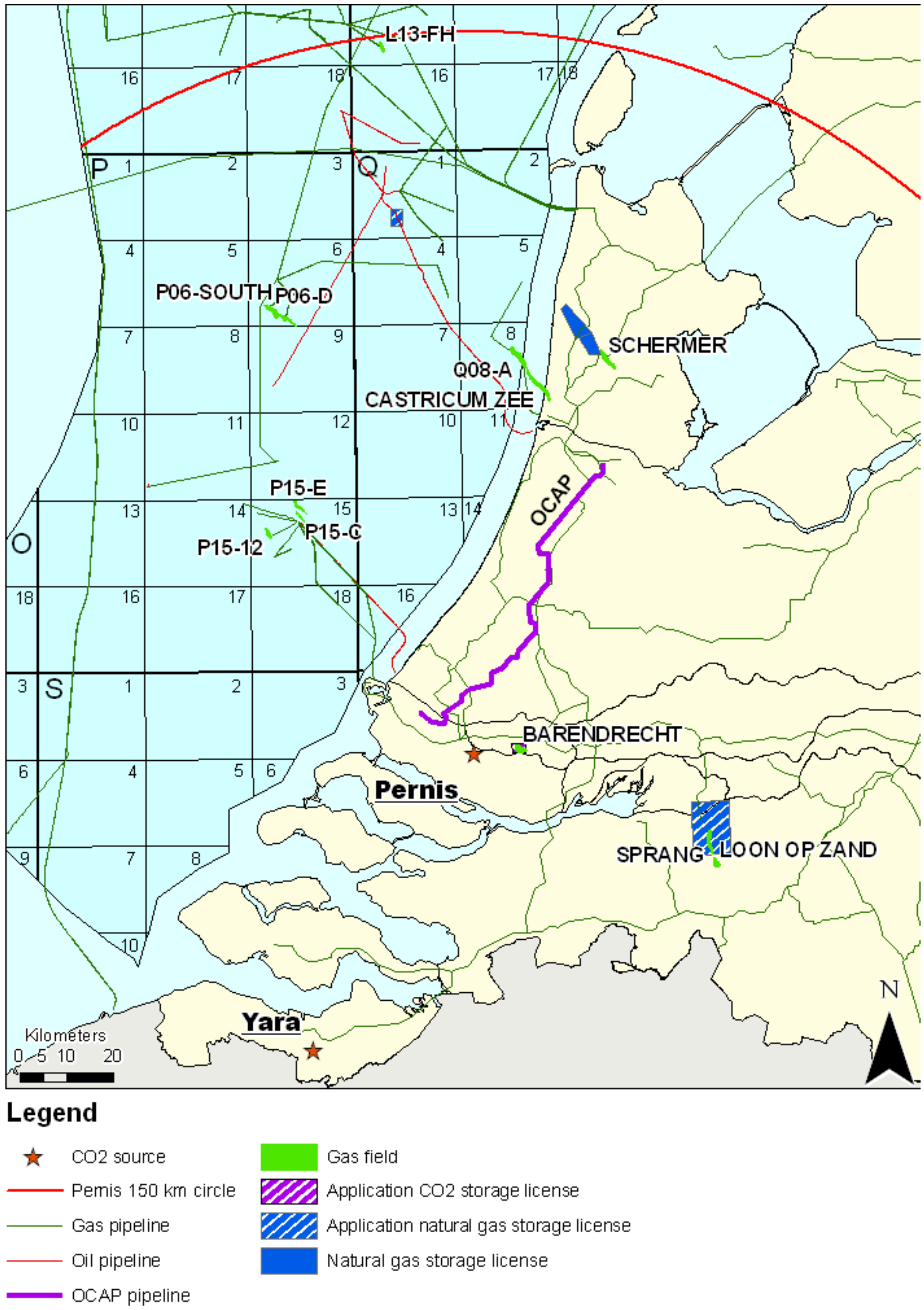

Figure 4. Fields resulting from the screening.

5 Step 3: Evaluation

5.1 Introduction

For the final step, the poCCS has requested to evaluate the fields, that have passed the Step 2 screening, in terms of suitability and safety. The table from the AMESCO report (ref. 2) was to be used (see App. 3). TNO-AGE also has been asked to apply supplementary criteria deemed necessary for determining the suitability of a field for the purpose of this study.

TNO-AGE has used the AMESCO scheme to score the 12 candidate fields in order to visualize their relative merits with respect to the various parameters. Supplementary criteria have been developed primarily considering the suitability of the 12 screening gas fields in terms of:

- Accessibility for adequate monitoring (essential for a demonstration project);
- Options for combining smaller and larger fields;
- Transport routes.

5.2 The AMESCO scheme

Appendix 3 contains a copy of the table called 'Suitability of depleted gas fields for CO_2-storage', that has been published as part of the AMESCO generic environmental impact assessment study (ref. 2, Table 8.1, p. 121).
The table contains criteria that relate to the suitability of depleted gas fields for CO_2-storage from a safety and environmental impact point of view. It contains the following (groups of) parameters:

- Wells:
  - Existing and former penetrations (wells);
- Geology:
  - Reservoir depth;
  - Faults;
  - Cap rock;
  - Reservoir rock;
  - Residual reservoir gas;
- Surface features and uses.

TNO-AGE has the following remarks on the AMESCO scheme:

* The AMESCO study has been a generic environmental impact study. The purpose of scoring the table was to provide input for a policy making tool for ranking storage sites in a certain region. To our best knowledge such a tool does not exist as yet in a form that has been tested on practical cases.

* Because of its generic nature, AMESCO cannot replace a detailed Environmental Impact Assessment (EIA) at the specific project/ site level. The only existing detailed EIA for a CO_2 transport and storage project in the Netherlands is the one that has been made for the Barendrecht project. We refer to that study (ref. 6) and the evaluation thereof by the official Dutch Commission for EIA ('Commissie MER')

(ref. 7) as the state of the art on safety and environmental impact assessment for CO_2 transport and storage projects in the Netherlands.

* The AMESCO table only allows for analyzing suitability on a comparative scale: no absolute criterion for suitability can be extracted from it. Moreover, the relative weight of the scores for the various (dislike) scores is not presented. Therefore, even a comparison of two individual fields cannot be expressed in a unique way (unless they would differ in only one aspect).

5.3 Results of AMESCO scoring

Table 2 shows the properties of the 12 fields according to the AMESCO table.

Existing and former penetrations (wells)
Wells will have to be carefully monitored to ensure well integrity. When the wellbore can be entered with modern equipment and measurement tools, necessary workover activities can be executed to ensure well integrity. In this project no detailed information on well integrity could be incorporated. Wells which have been plugged and abandoned have been assumed not to be re-entered for a demonstration project.

Seven of the twelve screening fields have only one well penetration.
Four fields have two wells penetrating the reservoir. Except for the discovery well in Castricum Zee all these wells are either in production or suspended.
The Schermer field has been penetrated by four wells of which three were drilled in the 1960's. One of these wells has been plugged and abandoned. For the AMESCO score this is expressed by a downgrade of the Schermer field to Medium since the well has been plugged and abandoned prior to 1985 (there are no data on the present day status of the borehole available in public domain). For the Castricum Zee field the AMESCO score is a 'Good minus' as the well was plugged and abandoned after 1985. On the other hand a risk evaluation of these wells may indicate that re abandonment or other corrective measures associated with high costs may be needed for these wells. Especially on the (small) scale of the demo project, this may add significantly to the project costs which are considered a drawback.

Reservoir depth
AMESCO scores greater depth better, because it means a thicker barrier to the atmosphere and because the potential uplift will have a smaller expression at the surface.

Except for Barendrecht, Q8-A and Castricum-Zee, all reservoirs are at a depth larger than 2500 m. Barendrecht, Q8-A and Castricum-Zee are at a depth of 1600 - 1700 m. It is noted, that the potential leakage path through the overburden is very unlikely and, if any, very slow in comparison with potential leakage paths along well penetrations. Therefore, TNO-AGE views reservoir depth as a characteristic with very limited weight in the overall EIA.
For the fairly small fields under consideration here, the expression of subsidence due to gas production has been very modest (cm's) and any uplift is expected to be no larger than that. For the offshore fields the uplift argument is considered irrelevant.

Faults

From a geological point of view the selected fields show resemblance in structural properties. All gas fields are located in tilted fault blocks. Regional maps (ref. 8) show no faults bisecting or bordering the reservoir that extend to the surface. All structures have proven gas field sealing capacities, which implies the estimated permeability of the faults is low or virtually zero.

Cap rock

L13-FH has Zechstein salt as top seal which is considered most secure. All the other reservoirs are sealed by a claystone layer. Barendrecht is overlain by 90 m claystone. All other reservoirs fall in the AMESCO category of more than 100 m gross seal thickness. In the view of TNO-AGE, the overriding argument is, that gas fields all have a proven primary seal for natural gas and that the physical thickness is not necessarily a unique measure of the sealing capacity.

All 12 reservoirs show an original gas composition with a CO_2 content below 2%. Therefore, the CO_2 content provides no preference for any of the selected reservoirs.

Reservoir rock

Injectability (or ‘injectivity’) has been scored in a qualitative way, primarily by considering past production performance information. Sustained injection rates in order of 0.2 Mt/yr (equivalent to 0.27 mln. Nm^3/day) per well – the minimum rate required for the demonstration project – are considered feasible for most reservoirs, except perhaps for the very poor quality ones. Loon op Zand and Sprang fall into that category. Although drilling extra wells may increase the injectivity, this is not considered a realistic option for the demonstration project due to the high costs involved (approx. 10 million Euro’s per well onshore). Moreover, poor injectivity reservoirs - by definition - are not representative for the larger portfolio of storage candidate fields and as such are less obvious candidates for a demonstration project.

All fields considered have sandstone as the main reservoir rock lithology.

TNO-AGE has not scored the likelihood of earth tremors during injection.
To our knowledge, there is no straightforward way of predicting that likelihood from observations during the production phase without a detailed modelling study.

Residual reservoir gas

The concentration of H_2S in the residual gas is below the quoted 0.5%.
We have no information on the BTEX content.

Surface features and uses

The well locations of the onshore fields have been matched with information on land use above the reservoir. The Barendrecht is under built area, while the other onshore fields, according to the AMESCO table score better with respect to land use above the reservoir. However, for the Barendrecht project a detailed EIA has been made. The evaluation of that MER by the official Commissie MER did not give rise to any prohibitive factors for storing CO_2. We consider this to be the state of the art.

For offshore fields we have argued that the existing platform will be accessible for CO_2 storage after cessation of gas production.

Scoring 'proximity of vulnerable objects to potential leakage paths from the reservoir' was deemed beyond the scope of this investigation. A far more detailed EIA study would be required, including a specification of 'vulnerable objects'.

Summary of AMESCO scoring

From the Wells perspective, only Schermer scores Medium having one old abandoned well. All other fields score Good.
From a Geological point of view, none of the 12 candidate fields scores less than between Good and Medium, except for Sprang and Loon op Zand that score 'poor' on injectivity.
From the Surface features and uses, the score from Table 2 has not been further evaluated by TNO-AGE. Detailed EIA studies are required.

Field name	# wells	Spud year wells	Reservoir depth (m)	Faults to surface	Seal lithology	Seal thickness (m)	CO_2 % in gas	Injectivity	Reservoir lithology	Main Land use above reservoir
P15-E	1	2003	>2500	No	claystone	>100	0.5	Fair -Good	sandstone	Offshore
Sprang	1	1994	>2500	No	claystone	>100	1.87	Poor	sandstone	Forestry
Castricum Zee	2	2000 (P&A) 2001	1000 – 2500	No	claystone	>100	0.21	Fair -Good	sandstone	Nature/sea shore
P15-C	1	2003	>2500	No	claystone	>100	0.5	Fair -Good	sandstone	Offshore
Barendrecht	2	1984, 1996	1000 – 2500	No	claystone	50 – 100	1.17	Fair -Good	sandstone	Built area
Loon op Zand	1	1991	>2500	No	claystone	>100	1.52	Poor	sandstone	Agriculture
L13-FH	1 (ssc)	1988	>2500	No	claystone	>100	1.34	Fair-poor	sandstone	Offshore
P06-South	2	1990, 2000	>2500	No	claystone	>100	0.95	Fair -Good	sandstone	Offshore
P15-12	1 (ssc)	1990	>2500	No	claystone	>100	0.1	Fair -Good	sandstone	Offshore
P06-D	1	2000	>2500	No	claystone	>100	0.95	Fair -Good	sandstone	Offshore
Schermer	4	1964, 1965 (P&A), 1965, 1995	>2500	No	claystone	>100	1.6	Fair -Good	sandstone	Agriculture; Nationaal Landschap Laag Holland
Q08-A	2	1982, 1985	1000 – 2500	No	claystone	>100	0.24	Fair -Good	sandstone	Offshore

(ssc) = sub sea completion

Table 2 Scores for the AMESCO criteria

5.4 Supplementary criteria

Supplementary criteria have been developed primarily considering the suitability of the 12 screening gas fields in terms of:
- Accessibility for adequate monitoring and well intervention
- Options for combining smaller and larger fields;
- Transport routes and timing (timely matched capacity between source and sink).

5.5 Scoring on the supplementary criteria

Accessibility

<u>Via wells</u>
Especially for a demonstration project, adequate access for monitoring is a logical and essential prerequisite. During the injection and post injection stabilization phases, easy access through wells will be needed. In this respect we consider the presence of two wells an advantage over just one well: if 2 wells are available and re-usable, one well can be used for injection and the other for monitoring e.g. the movement of the CO_2 through the reservoir and reservoir pressure build up during injection. Moreover there would be a back up injection well available in case injectivity problems would be encountered in the first well.
From Table 2 it follows, that Barendrecht, P06-South and Q08-A have this advantage over the 7 single well cases. Note, that Castricum-Zee has had two well penetrations, one of which has been plugged. Schermer has had 4 well penetrations, one of which has been plugged and adandoned.

The single well subsea completions L13-FH and P15-12 are not considered suitable candidates for CO_2 storage demonstration, because subsea completions allow less direct contact with the reservoir and well interventions are more difficult an costly than for normal well completions.

<u>On surface</u>
There still is much debate, as to what monitoring equipment from surface (including perhaps shallow boreholes) is to be installed at CO_2 storage sites. Various geophysical and geochemical techniques are mentioned. Active seismic monitoring may not be a practical technique for monitoring the front of CO_2 in a (depleted) gas field; passive seismic monitoring (run form boreholes), on the other hand, may provide useful information on the geomechanical state of the storage reservoir.

A prerequisite for (near) surface monitoring is that such monitoring is allowed in the area above the CO_2 storage site. Depending on the technique applied, there may be physical and/or legal constraints. In general these constraints are expected to be tighter onshore. Eventually, it will be up to the storage developer to prove that his monitoring equipment and programme are adequate to manage risks and for meeting the storage licence conditions.

Options for a combination of a small and a larger field

As explained earlier in this report, options for combining an early available small field with a larger follow-up are considered advantageous, in particular in view of the cost effectiveness of the transport infrastructure to be constructed and the CO_2 efficiency associated to that.

Onshore fields

For the Barendrecht (0.8 Mt) demonstration project proposal, the nearby Barendrecht-Ziedewij gas field (10 Mt) has been planned as follow up.

A similar synergy option is not present for Loon op Zand: the only nearby Waalwijk-Noord field, together with Sprang, is part of a storage licence for natural gas.

Schermer, being medium sized with 6 Mt storage capacity, has no small (1-2 Mt) nearby precursor available on time.

Offshore fields

Castricum-Zee (0.7 Mt) volume-wise could potentially team up with Q08-A (both have their wells from the same platform).

The P15/P18 area contains a number of gas fields, of which P15-E (0.5 Mt) and P15-C (0.7 Mt) belong to the smaller ones. These two fields could volume-wise potentially team up with one of the larger fields in the P15/P18 area.

Block P6 has the P6-A gas field as the main field, with candidates P6-South (1.9 Mt) and P6-D (4.6 Mt) as satellites. P6-South could be the early small field, with P6-D as a follow up.

Result
Four candidate combinations of a small and a larger field remain:

1. Barendrecht with Barendrecht-Ziedewij;
2. Castricum-Zee with Q08-A;
3. P15-E or –C with a larger field from the P15/P18 cluster;
4. P6-South with P6-D.

Transport routes and timing

Combination 1. has by far the shortest distance to the Pernis source (and even to the Yara source) and hence the highest CO_2-efficiency.
Combination 2. can benefit from using the existing OCAP pipeline and the existing offshore pipeline to the Q8-A platform. Yet, additional compression will be needed.
Combinations 3. and 4. cannot benefit from existing transport infrastructure: the gas export lines from these clusters of fields will be in use at least until 2015.

The Rotterdam Climate Initiative recently has published an update of their envisaged business case (ref. 9), in the following phased development is presented:

Phase	**Starts in**	**Rate (Mt CO_2/yr)**	**Storage fields**
1	2013	1	Q8-A
2	2015	5	Q8-A + P15/P18
3	Around 2017	9	Q8-A + P15/P18 + P6
4	Post 2020	15-30	P15/P18, P6, L10

This development pertains to the same fields, that are the possible follow-up candidates in the Combinations 2, 3 and 4. It is also clear that, according to RCI's present planning, Q8-A would be the only field actually injecting CO_2 in 2013. Fields in the blocks P15, P18 and P6 will only be connected in 2015 and later; this development would be too late in order to accommodate a small scale demonstration project.

6 Conclusions

TNO-AGE has investigated the site selection for a small scale CCS demonstration project.

The application of three selection criteria: availability for storage before 2012, storage volume between 0.5 and 10 Mt of CO_2 and a distance less than 150 km to the source of the CO_2 has resulted in a short list (shown below) of 12 gas fields which could serve as storage sites. Four of these fields are situated onshore and eight offshore.

Field name	Storage capacity	AMESCO score	AMESCO reason	Monitoring potential / accessibility	Potential for combination of small field with larger follow up
	Mt CO_2				
P15-E (offshore)	0.5			1 well only	yes
Sprang	0.7	poor	poor injectivity	1 well only	
Castricum Zee (offshore)	0.7	'good minus'	1 abandoned well	1 well only (long reach well) under protected area*	
P15-C (offshore)	0.7			1 well only	yes
Barendrecht	0.8	poor	under built area*		yes
Loon op Zand	1.1	poor	poor injectivity	1 well only	
L13-FH (offshore)	1.7			1 well only (subsea completion)	
P06-South (offshore)	1.9				yes
P15-12 (offshore)	1.9			1 well only (subsea completion)	
P06-D (offshore)	4.6			1 well only	
Schermer	6.1	medium	1 old abandoned well	under protected area*	
Q08-A (offshore)	7.8				

* is not a (geo-)technical criterion

Subsequently, these fields have been evaluated with regards to the (generic) AMESCO scheme of safety and environmental impact criteria and the additional criteria as identified by TNO_AGE. .The supplementary criteria identified by TNO-AGE pertain to the accessibility for monitoring and managing the storage site and the potential for combination of small fields with larger follow up fields. The important scores are shown in the above table.

Please note that all scores are relative. A negative score is a drawback, but not a cut-off per se. However, poor injectivity and old abandoned wells are considered to be major drawbacks that make selection not preferable.

From this list the fields Sprang, Castricum-Zee, Loon op Zand, L13-FH, P15-12 and Schermer score less favourable because of (geo-) technical reasons discussed in this report.

The fact that the Barendrecht field is located under a built area, is not of a (geo)technical nature and therefore impossible to weigh against the other geotechnical factors considered.

Finally, the potential of combining a small field (0.5 -2 Mt) with a nearby larger field (up to 10 Mt) as follow-up and/or backup has been considered. From that evaluation four possible combinations ('projects') result:

- Barendrecht with Barendrecht-Ziedewij;
- Castricum-Zee with Q8-A;
- P15-E or P15-C with a larger field in blocks P15/ P18 ;
- P6-South with P6-D.

Of these fields Barendrecht and P06-South do not have any (geo-)technical drawbacks with regard to the criteria and level of detail applied in this study.

The feasibility the three offshore projects will crucially depend on the possibilities to integrate these in the plan, that has recently been published by the Rotterdam Climate Initiative (ref. 11). That plan involves a phased CCS development in Q8-A (as from 2013), blocks P15/P18 (as from 2015) and block P6 (as from 2017). The time window for achieving this seems very restricted, but is was beyond the scope of this study to evaluate this aspect.

We conclude that from the 12 fields selected as potentially suitable for a small scale demonstration project of CO_2 storage, the Barendrecht and P06-South field do not have any (geo-)technical drawbacks with regards to the criteria applied. The other 10 fields score less on the applied AMESCO and/or additional criteria.

7 References

1. Natural resources and geothermal energy in the Netherlands, Annual review 2008
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2. AMESCO
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   Selectieleidraad Europese Aanbesteding
   SenterNovem, 25 mei 2007

4. MARKAL study CATO
   Report 2009.

5. Aanvraag vergunning o.b.v. de Wet Milieubeheer voor het Barendrecht project

6. MER Ondergrondse opslag van CO_2 in Barendrecht
   NAM B.V. (december 2008)

7. Ondergrondse opslag van CO_2 in Barendrecht
   Toetsingsadvies over het milieueffectrapport
   Commissie MER, rapport nummer 2047-172 (april 2009)

8. Geological Atlas of the Subsurface of the Netherlands – onshore
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9. CO_2 Capture , transport and Storage in Rotterdam
   Report 2009
   Rotterdam Climate Initiative (Aug. 2009)

10. Potential for CO_2 storage in depleted gas fields on the Dutch Continental Shelf
    Phase 1: Technical assessment
    Netherlands Oil and Gas Exploration and Production Association
    and the Ministry of Economic Affairs (June 2008).

8 Signature

Utrecht, 12 October 2009

TNO Built Environment and Geosciences

B.M. Schroot
Head Advisory Group for the Ministry of Economic Affairs

9 Appendices

1. Opdrachtbrief
   Toelichting op onderzoek naar locatiekeuze voor demonstratie CO_2-opslag in Nederland.
   Memo Projectorganisatie CCS to TNO-AGE (attn.dep. team leader), dated July 30, 2009 (ref. CCS / 9135285).
2. Data and information
3. AMESCO table

Appendix 1 Opdrachtbrief

Toelichting op onderzoek naar locatiekeuze voor demonstratie CO_2-opslag in Nederland

Behandeld door

Datum
30 juli 2009
Memonummer
CCS / 9135285

Aanleiding
Het voornemen bestaat om in Barendrecht CO_2-opslag te realiseren. Het project van initiatiefnemer Shell CO_2 Storage B.V. heeft in Barendrecht grote weerstand opgeleverd, zowel bij bewoners als bij de gemeente. Het College en de Raad hebben zich officieel tegenstander van het project verklaard. Hierbij wijst de gemeente op de risico's voor de volksgezondheid, m.n. van de omwonenden van de voorziene opslaglocatie, het bijna lege gasveld Barendrecht. In deze context vraagt de gemeente Barendrecht waarom dit project uitgerekend in Barendrecht zal plaatsvinden. De gemeente wijst daarbij op de bevolkingsdichtheid van de wijken gelegen boven de gekozen opslaglocatie.

De ministers Cramer (VROM) en Van der Hoeven (EZ) hebben d.d. 26 juni 2009 in een brief (bijgevoegd) aan de burgemeester van Barendrecht toegezegd dat er via aanvullend onderzoek antwoord zal worden gegeven op de vraag van de inwoners van Barendrecht of er voldoende is afgewogen waarom men in Barendrecht deze opslag wil realiseren. In aanvulling op het MER over CO_2-opslag in Barendrecht zal nader worden geduid en alsnog bekeken worden of de locatiekeuze Barendrecht een goede optie is.

Achtergrond
De Nederlandse overheid heeft zich ten doel gesteld om in 2015 twee grootschalige CCS demonstratieprojecten operationeel te hebben. Ter voorbereiding van deze grootschalige demo's (en de latere grootschalige uitrol na 2020) is het noodzakelijk om op kleinere schaal praktijkervaring op te doen met de organisatie van CO_2-opslag in Nederland. Leereffecten worden gerealiseerd tijdens de voorbereidende stappen, gedurende de opslag en zo mogelijk ook in de periode direct na sluiting.

Voor een kleinschalige demonstratie van CO_2-opslag is het belangrijk dat:
- Beoogde leereffecten moeten zoveel mogelijk voor 2015 gehaald zijn.
- Bij voorkeur wordt de gehele keten (injectie, opslag en afsluiting van het reservoir) zoveel mogelijk gedemonstreerd in de periode tot 2015.

Doel onderzoek

- Dit onderzoek moet inzicht geven in de afwegingen die leiden tot een overzicht van de meest geschikte locaties om CO_2-opslag in Nederland op kleine schaal te demonstreren. Bestuurders en inwoners van Barendrecht moet getoond worden hoe de geplande CO_2-opslaglocatie Barendrecht zich in deze fase verhoudt tot andere potentiële velden.
- Daarnaast moet de studie input leveren voor de nationale afweging van meest geschikte velden om CO_2-opslag te demonstreren in het kader van het Rijksinpassingsplan voor dit project.

Aanpak

Voor de uitvoering van de inventarisatie van potentiële locaties voor CO_2-opslag heeft de Projectorganisatie CCS de volgende aanpak voor ogen:

- Het startpunt van de inventarisatie is alle potentiële gasvelden voor CO_2-opslag op het Nederlandse vaste land en NCP (Nederlands Continentaal Plat). Gasvelden worden het meest geschikt geacht voor CO_2-opslag vanwege hun intrinsieke veiligheid.
- In een tweede stap wordt uit alle gasvelden een selectie gemaakt op basis van (tenminste) onderstaande criteria:
  - A. Tijdige beschikbaarheid als CO_2-opslaglocatie. Het veld dient uiterlijk eind 2012 beschikbaar te zijn voor CO_2-opslag. Een tijdige beschikbaarheid is noodzakelijk vanwege het karakter van het project als demonstratieproject in de aanloop naar opschaling van CCS.
  - B. Opslagcapaciteit. Velden met een opslagcapaciteit tussen 0.5 en 10 Mt CO_2 worden meegenomen in de analyse. Er dient rekening gehouden te worden met mogelijke combinaties van kleine velden.
  - C. CO_2-efficiency. De efficiency van een potentiële CO_2-opslaglocatie wordt bepaald door de afstand van bron tot opslaglocatie in relatie tot de te maken kosten voor een demonstratieproject.
- De velden die door het selectieproces komen worden verder onderzocht op geschiktheid voor CO_2-opslag (toetsing op geschiktheid en veiligheid). Hierbij dient gebruik gemaakt te worden van de reservoirkarakteristieken, zoals opgesteld in de AMESCO-studie (bijgevoegd). De AMESCO-criteria alleen zijn niet voldoende om de geschiktheid van een veld te bepalen. Opdrachtnemer wordt gevraagd om waar nodig additionele criteria toe te passen om de geschiktheid van een veld te bepalen.

Het rapport wordt publiekelijk beschikbaar gemaakt. Dit betekent dat de bedrijfsvertrouwelijke informatie die gebruikt wordt geanonimiseerd weergegeven dient te worden.

Bij de selectie en de toetsing op geschiktheid zal gebruik gemaakt moeten worden van vertrouwelijke gegevens over de betreffende velden. Opdrachtnemer is verantwoordelijk voor het organiseren dat gebruik kan worden gemaakt van vertrouwelijke operatorgegevens in dit onderzoek.

Deze studie richt zich in principe op aanvullend onderzoek naar potentiële opslaglocaties voor de zuivere CO_2 die afkomstig is van de waterstoffabriek van Shell in Pernis. In het kader van een bredere afweging vraagt de Projectorganisatie CCS aandacht te geven aan mogelijke andere bronnen van zuivere CO_2 en de mogelijke opslaglocaties.

Toetsing onderzoek
Gezien de bijzondere omstandigheden waarbinnen dit onderzoek plaatsvindt heeft de projectorganisatie CCS besloten het eindresultaat van het aan TNO gevraagde onderzoek ter toetsing voor te leggen aan een externe partij. Dit biedt de bestuurders van Barendrecht extra zekerheid ten aanzien van de zorgvuldigheid en onafhankelijkheid van het onderzoek. De voorgestelde partij is Det Norske Veritas (DNV). Momenteel wordt bezien of deze partij een geschikte persoon kan leveren om de gevraagde toets uit te voeren.

Planning
Voorstel is om in de week van 14 – 18 augustus 2009 een startoverleg te hebben om de aanpak door te nemen en definitief te maken.

De uitkomsten van dit onderzoek zullen meegenomen worden in de besluitvorming van de ministers van VROM en EZ over Barendrecht als locatie voor het demonstreren van CO_2-opslag. Hiertoe dient het onderzoek begin oktober afgerond te zijn.

15 September 2009: Voorlopige resultaten beschikbaar
2 Oktober 2009: Definitieve rapport beschikbaar

Appendix 2 Data and information

The table below lists the data types which have been used for this study. The DINO-database which is maintained by TNO contains data as supplied by the industry to the Minister of Economic Affairs according to the Mining Act.

Confidentiality
The table below also indicates certain data types to be confidential. The confidentiality restricts the publication of the results of the inventory. Confidentiality terms are in accordance with the Mining Act.

GIS
The data have been compiled in a Geographic Information System - GIS (ARCGIS 9.2). GIS is a tool that allows creating interactive queries (user created searches), analysing spatial information and presenting the results of all these operations. For instance this tool enables to select those gas fields that will cease production before 2012 and lay within a certain distance form the source Pernis.

Data type /GIS-layer	item	source	Remark	confidentiality
CO_2 Source	Location	Google Maps	Shell Pernis refinery	no
Gas Fields	Name	DINO public database		no
	Location	DINO public database		no
	End date production	Annual report ex Mining Decree art 113	As reported in the annual reports 2009.	yes
	Storage capacity	DINO confidential database,	Calculated form data on production, reserves and ultimate recovery	yes
	Recovery factor	DINO confidential database		yes
	Geological features	Production plans and confidential reports	Reservoir, seal, structure, fault depth, gas composition	yes/no
Wells	Number of wells	DINO public database		no
Land use	Type Classes	Dataset Landelijk Grondgebruik Nederland 5	Agriculture, forestry, nature reserves, build areas, water	no
		DINO public database		no
Licence areas	Location	DINO public database		no
	Operator	DINO public database		
Pipe lines	On and offshore main transportation pipelines	DINO public database		no

Table 3, data types used in this study with their sources and confidentiality status.

Appendix 3 AMESCO table

Suitability of depleted gas fields for CO_2-storage (taken from Ref. 2, Table 8.1, p. 121)

CRITERIA	Reservoir characteristics				
	Good		Medium		Poor
Existing and former penetrations					
Number of wells abandoned before 1985	0	0	1	2	3
Number of abandoned wells in total	0	2	4	7	>10
Number of wells to be abandoned	4	8	20	40	100+
Reservoir depth					
Depth of reservoir (m)	>2.500	1.000-2.500	800-1.000	500-800	<500
Faults					
Fault approach to surface (m)	>1.000	1.000 - 500	500 -150	150 - 10	< 10 (surface)
Number of faults	0	1-5	> 5	> 5	> 5
Assessed fault permeability	uniformly low		very uncertain		uniformly high
Cap rock					
Cap rock	salt	claystone (low permeability)	claystone (medium permeability)	other	other
Cap rock thickness (m)	> 100	50-100	30 - 50	< 30	< 30
CO_2 in original gas phase in reservoir (%)	20	5	0	0	0
Reservoir rock					
Reservoir injectability	very good		medium		very tight
Reservoir rock	sandstone	carbonates	other	other	other
Earth tremor likelihood during injection (%)	0	10	50	100	100
Residual reservoir gas					
H_2S and BTEX in reservoir gas phase (%)	< 0.5	0.5 - 1.0	1 - 5	5 - 10	> 10
Surface features and uses					
Land use above reservoir	agricultural		nature reserve		urban
Proximity of vulnerable objects to potential leakage paths from the reservoir (m)	>100	50-100	25-50	10-25	<10