

## GHGT-9

## An integrated GIS-MARKAL toolbox for designing a CO<sub>2</sub> infrastructure network in the Netherlands

Machteld van den Broek<sup>a\*</sup>, Evelien Brederode<sup>a</sup>, Andrea Ramírez<sup>a</sup>, Leslie Kramers<sup>b</sup>,  
Muriel van der Kuip<sup>b</sup>, Ton Wildenborg<sup>b</sup>, André Faaij<sup>a</sup>, Wim Turkenburg<sup>a</sup>

<sup>a</sup>Group Science, Technology and Society, Copernicus  
Institute for Sustainable Development and Innovation, Utrecht  
University, Heidelberglaan 2, 3584 CS Utrecht, Netherlands

<sup>b</sup>TNO Built Environment and Geosciences, Princetonlaan 6, 3508 TA Utrecht, Netherlands

---

### Abstract

Large-scale implementation of carbon capture and storage needs a whole new infrastructure to transport and store CO<sub>2</sub>. Tools that can support planning and designing of such infrastructure require incorporation of both temporal and spatial aspects. Therefore, a toolbox that integrates ArcGIS, a geographical information system with elaborate spatial and routing functions, and MARKAL, an energy bottom-up model based on linear optimization has been developed. Application of this toolbox for devising blueprints of a CO<sub>2</sub> infrastructure in the Netherlands, shows that early knowledge on the availability, potential, and suitability of sinks is of major importance for a cost-effective design of the infrastructure.

© 2009 Elsevier Ltd. All rights reserved.

**Keywords:** CO<sub>2</sub> capture and storage; MARKAL; geographic information system; linear optimisation; CO<sub>2</sub> infrastructure

---

### 1. Introduction

To reach stabilization targets of 450 ppmv CO<sub>2</sub>-equivalent in the atmosphere, studies show that carbon dioxide capture and storage (CCS) may play a significant role (IPCC, 2007; IEA, 2008). CCS consists of the separation of CO<sub>2</sub> from industrial and energy-related sources, transport to a (underground) storage location and long-term isolation from the atmosphere. Large-scale implementation of CCS would need a new infrastructure to transport and store CO<sub>2</sub>. In order to plan and design such infrastructure it is necessary to get insight into the synergies and interferences between the development of the energy supply system and that of the CO<sub>2</sub> infrastructure. A tool, which can support this planning process, requires dealing with both temporal (e.g. time when power plants with CO<sub>2</sub> capture need to come online in a portfolio of CO<sub>2</sub> reduction measures and when sinks become available) and spatial aspects (e.g. locations of CO<sub>2</sub> sources and sinks). Furthermore, this tool should be able to take into account criteria

---

\* Corresponding author. Tel.: +31 -30-2532216; Fax: +31 -30-2537601.

E-mail address: [m.a.vandenbroek@uu.nl](mailto:m.a.vandenbroek@uu.nl)

doi:10.1016/j.egypro.2009.02.214

which determine whether a specific sink for CO<sub>2</sub> storage is a cost-effective option, suitable, and can be connected to one or more CO<sub>2</sub> sources. In short, it should be able to determine whether it is part of the "matched capacity" in the techno-economic resource-reserve pyramid for CO<sub>2</sub> storage capacity (Bachu et al., 2007; Bradshaw et al., 2007). This pyramid consists of four slices representing different types of capacity potentials. At the bottom is the "theoretical capacity" representing the physical limit of what the geological system can accept. The second slice is the "effective capacity", a subset of the theoretical capacity adapted to a range of geological and engineering cut-off limits. The third slice is the "practical capacity", the part of the effective capacity in which legal and regulatory, infrastructure and general economic barriers have been accounted for. At the top of the pyramid is the "matched capacity" being the subset of practical capacity that matches the CO<sub>2</sub> sources with the storage sites. The cost-effectiveness depends on the costs and potential of the specific sink, and the suitability on the efforts needed to manage risks (e.g. leakage or ground movement) associated with the CO<sub>2</sub> storage. Crucial factors for this suitability are performance characteristics related to the seal, overburden, faults, wells, and biosphere of the sinks.

Existing tools and studies regarding the design of a CO<sub>2</sub> infrastructure have so far not taken into account all these aspects. To overcome this gap, we developed a toolbox which integrates ArcGIS, a geographical information system with elaborate spatial and routing functions, and MARKAL, a linear optimization model that gives insight into possible development pathways of energy systems. The toolbox takes into account techno-economic details (e.g. costs, efficiency data), sink performance characteristics as well as policy choices (e.g. CO<sub>2</sub> targets, preferences for a certain reservoir type such as only CO<sub>2</sub> storage offshore).

In the Netherlands (NL) CCS is expected to play a major role in a strict CO<sub>2</sub> mitigation strategy due to the presence of many large CO<sub>2</sub> point sources (~69 Mt per year from sources above 100 kt CO<sub>2</sub> in 2005 which is 39% of total Dutch CO<sub>2</sub> emissions) and a considerable effective capacity for CO<sub>2</sub> storage (~3.1 Gt CO<sub>2</sub> excluding the Slochteren field<sup>2</sup>). Conversely, the planning and realization of a large scale CO<sub>2</sub> infrastructure may take a long time in this densely populated country. Also CO<sub>2</sub> storage in the underground will only be allowed when the expectations on the performance of the sink are positive. Cut-off performance criteria are, therefore, of utmost importance for sink selection and, consequently, they influence the design of the infrastructure. This article aims to assess how the development of a large-scale CO<sub>2</sub> infrastructure in the Netherlands for the analysis period 2010-2050 depends on criteria regarding the performance of sinks and related policy choices. The outcomes are blueprints of the infrastructure that reveal succeeding cost-effective combinations of sources, sinks, and transport pipelines over this period. Moreover, they provide insights into the costs, location, and time-path of the individual infrastructural elements. Finally, this article intends to show how the ArcGIS/MARKAL toolbox could support stakeholders in their decision-making process regarding CO<sub>2</sub> infrastructure. The scope of the study is limited to sources that emit more than 100 kt CO<sub>2</sub> in the industrial, electricity and cogeneration sector in which CO<sub>2</sub> capture can be applied. In this paper, a discount rate of 5% has been applied, all costs are in €<sub>2007</sub>, and "t" always refers to tonne CO<sub>2</sub>.

## 2. Methodology

The applied methodology in this research consists of four successive steps as depicted in figure 1.

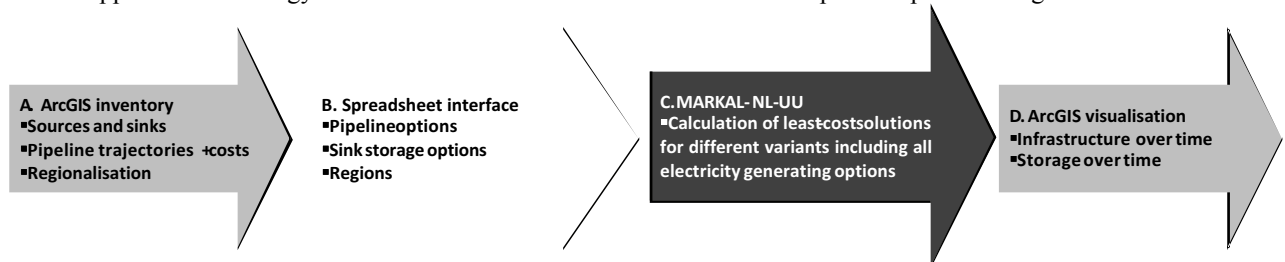


Figure 1. Schematic representation of the methodological approach

<sup>2</sup> The Slochteren field has an estimated storage potential of 7.4 Gt, but is probably only available for CO<sub>2</sub> storage after 2050.

A. During the first step data regarding potential CO<sub>2</sub> capture sites, CO<sub>2</sub> storage locations, and possible CO<sub>2</sub> pipeline trajectories are collected in ArcGIS.

- The sinks included in the analysis are 145 potential hydrocarbon fields and 27 aquifers (including onshore and offshore reservoirs) with a total potential storage capacity 3.1 Gt. Currently, this publicly available dataset of the Dutch geological reservoirs is in the bottom part of the "effective capacity" slice in the techno-economic CO<sub>2</sub> storage pyramid since geological (e.g. minimal depth of 800 m to store CO<sub>2</sub> in supercritical state) and engineering cutoff limits have been used to a certain extent (TNO, 2007). Furthermore, also an economic criterion to only consider fields with a storage capacity > 4 Mt for hydro-carbon fields and > 2 Mt for aquifers is applied since it does not seem economically viable to use smaller fields at the moment. For each individual sink the CO<sub>2</sub> storage potential, its availability in time, and injectivity are estimated.
- The inventory of potential sites where CO<sub>2</sub> can be captured results in 43 sources consisting of 24 existing power plants, 15 industrial plants (e.g. fertilizer manufacturing, hydrogen, or steel production facilities), and 4 locations for new power plants. The capture units at power plants can be post-combustion units at NGCCs or PCs, or pre-combustion units at IGCCs. Cost data for these units, and for power plant technologies (including renewable electricity generation technologies) are derived from the MARKAL-NL-UU model (Broek, 2008). Data on CO<sub>2</sub> capture units for the industry are derived from Damen (2007). Since in the last years a steep increase in prices have occurred, all cost data are updated to €<sub>2007</sub> monetary units by using the CEPCI index.
- In ArcGIS, CO<sub>2</sub> sources and sinks are clustered into source and sink regions, to model the advantage of economies of scale to transport CO<sub>2</sub> from various sources through trunklines to various sinks. Source regions include 4 regions close to the coast which are (starting from the South of NL): *Zeeland* with a few pure CO<sub>2</sub> stream sources, *Rijnmond* with many industrial sources in the Rotterdam harbor, *IJmond* with a large steel plant, and *Eemsmond* in the North being close to onshore sinks (see figure 3 for the regions on the map). Inland, we have the regions *Limburg*, *Harculo*, and *Maas and Waal* with only small existing CO<sub>2</sub> sources. Sink regions consist of 3 onshore regions in the North East of the Netherlands: *Wadden* (with storage potential of 0.41 Gt), *Groningen* (0.38 Gt), and *Drenthe* (0.69 Gt), and two onshore regions in the West: *North Holland* (0.24 Gt) and *South Holland* (0.09 Gt). Furthermore, we distinguish two offshore regions: *offshore south* (0.32 Gt) and *offshore north* (0.98 Gt). Finally, in ArcGIS, the routings of possible trunklines between these regions are identified with least-cost routing functions. The pipeline construction costs are differentiated per land-use type, and a preference was given for following the existing hydrocarbon pipeline corridors. Future land-use is addressed via GIS maps developed by the Netherlands Environmental Assessment Agency. Finally, for each trajectory several trunkline capacities per routing are defined (e.g. for a maximum of 5, 15, or 25 Mt CO<sub>2</sub> flow per year).

Table 1 Overview performance characteristics

Group	Parameter	Categories
Seal	Proven sealing	field evidence gas /field evidence oil /no field evidence
	Seal thickness	>200m / 100-200m / 50-100m / 10-50m / <10m
	Seal composition	Salt / shale / clay stone / anhydrite / marl
Overburden	Overburden	3200-4000m / 2400-3200m / 1600-2400m / 800-1600m / <800m
Fault	Natural seismicity	Stable / slightly unstable / unstable offshore / unstable onshore
	Fault displacement	Base: Permian / Zechstein / Triassic and Jurassic / Cretaceous / Tertiary / Miocene
	Number of faults	0 / 1 / 2 / 3 / > 3
Wells	Number of wells	0/1-15/16-25/26-35/36-45/>45
	Accessibility of wells	onshore rural area /onshore urban area /o ffshore
	Timing of closure	not abandoned / after 1976/ 1967-1976/before 1967
Biosphere	Biosphere	offshore/ onshore rural area / onshore urban area

B. In the second step, specific investment costs per sink were calculated on the basis of depth, thickness, CO<sub>2</sub> storage potential, and injectivity per well in a spreadsheet interface. Additionally, in order to study the possible effect of a cut-off criteria related to the suitability of sinks on the design of the infrastructure, we used a sink ranking from Ramirez et al. (2008). They have screened the Dutch CO<sub>2</sub> storage options on the basis of the performance characteristics in table 1. We chose, as an example, a threshold value of 70 (on a scale of 0-100, with "100" being the best estimated performance) below which the sinks are not considered suitable in one model variant (see below). This cut-off criteria results in a decrease in storage potential of 50%, 60%, and 100% in respectively, the onshore regions *Twente*, *North Holland*, and *South Holland*, and 65% in the *South Offshore* region. In the other three sink

regions, the effect was less than 7%. Furthermore, almost all aquifers have been disregarded due to the precautionary principle so their use is postponed until sufficient knowledge is gathered.

C. The third step is to calculate the technological configuration of the energy system and CO<sub>2</sub> infrastructure by minimizing net present value of the energy system costs with the MARKAL model generator (Loulou, 2004). The starting point for this exercise was the MARKAL-NL-UU model of the Dutch electricity sector and large CO<sub>2</sub> emitting industries (Broek, 2008). The MARKAL-NL-UU model runs are driven by scenario assumptions based on the Strong Europe scenario of the Dutch planning agencies (Janssen, 2006; Broek, 2008). In this scenario the Dutch electricity demand increases from 101 TWh in 2000 to 175 TWh in 2050. Furthermore, a CO<sub>2</sub> cap going from 20% in 2020 to 50% in 2050 (compared to the 1990 level) is assigned on the CO<sub>2</sub> emissions from the Dutch CO<sub>2</sub> intensive industry and energy sector. With respect to other mitigation options, it is assumed that the share of renewable electricity increases to at least 20% in 2020, and 30% in 2050, and that nuclear power generation phases out (following current policies). Note that in the result section, while we focus on the deployment of CCS and its associated infrastructure, MARKAL-NL-UU has calculated the total electricity mix (i.e. shares of renewable and fossil fuel electricity generation technologies)

Within this Strong Europe scenario the following variants are compared: a "base variant" in which all Dutch sinks are considered suitable for storage of Dutch CO<sub>2</sub>, a "70-performance variant" in which only Dutch sinks are available that have performance above the threshold value of 70, and an "offshore variant" in which storage is only allowed in Dutch offshore sinks.

D. In the last steps, results are exported to ArcGIS to analyze and visualize the outcomes in geographic maps.

### 3. Results

First results show that in all variants CCS is a cost-effectiveness measure in a strategy to reduce CO<sub>2</sub> emissions by 20% and 50% in, respectively, 2020 and 2050 compared to 1990. In the next section we discuss each variant.

**Base variant.** In the base variant, on average 26% of the reduction of emissions in the power sector (compared to a variant without a CO<sub>2</sub> cap) can be attributed to CCS. Figure 1 depicts the amounts of CO<sub>2</sub> that are captured in each region. It also shows that the total amount of CO<sub>2</sub> captured grows steadily from 9 Mt CO<sub>2</sub> stored per year in 2015 to 62 Mt in 2050. Over the whole analysis period a cumulative amount of 1.3 Gt of CO<sub>2</sub> will be captured and stored. Most CO<sub>2</sub> is captured in the *Rijnmond* region, and from 2035 also in the *Eemsmond* region in the North of NL. However, also small amounts are captured in *Zeeland* and *Limburg* due to the presence of sources with pure CO<sub>2</sub> flue gasses and, hence, minimal or no capture costs. As the *Maas and Waal* region can connect easily to the trunkline coming from *Limburg*, some CO<sub>2</sub> is also captured at a power plant in this region.

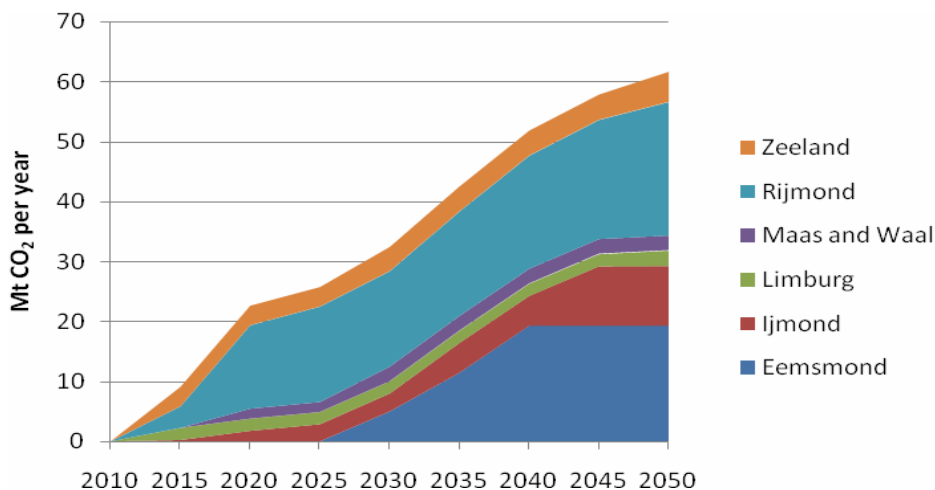


Figure 1. Annual amount of CO<sub>2</sub> captured at power plants and industry per region (base variant)

Figure 2 a provides us with information on how much CO<sub>2</sub> is stored in each sink during the analysis period. It demonstrates that CO<sub>2</sub> is first stored in onshore fields due to the lower storage costs onshore, and later in offshore fields. Figure 3a depicts the trunklines built before 2020, and the CO<sub>2</sub> flows through these pipelines in 2020<sup>3</sup>. The flows increase later on in the analysis period, which is possible because the trunklines have been over-dimensioned at the start already reckoning with the upcoming increase in CO<sub>2</sub> flows. Costs of CO<sub>2</sub> transport vary from 6.2 €/t in 2015, which are high as a consequence of the under-utilization of the pipelines at that time, to 1.9 €/t in 2050. On the other hand the storage costs<sup>4</sup> increase from 1.4 €/t in 2015 to 3.3 €/t in 2050, because cheap sinks are preferably filled first.

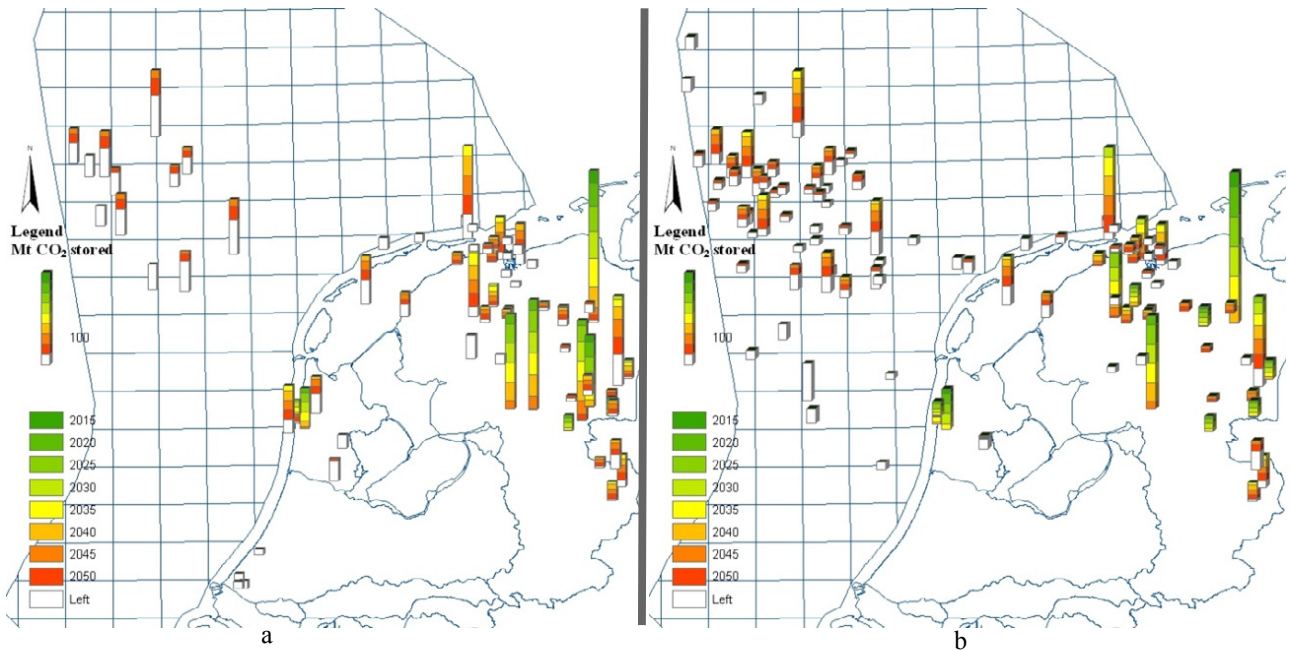


Figure 2. CO<sub>2</sub> storage over the time for the base variant (a) and the 70-performance variant (b). Each stacked bar represents a sink. The size and colours relate to respectively the amount and timing of the stored CO<sub>2</sub>. A white bar represents the storage capacity that is still available. Note that only sinks are depicted that are used for CO<sub>2</sub> storage during the analysis period.

**70-performance variant.** In the 70-performance variant CCS retains its role in a CO<sub>2</sub> mitigation strategy compared to the base variant (1% less), only a shift takes place in configuration of the infrastructure. Figure 2b shows the CO<sub>2</sub> storage per sink for this variant. When we compare this map with the one in figure 2a, we can deduce that in the 70-performance variant less CO<sub>2</sub> is stored onshore, and more offshore. Moreover, the fields onshore that are still suitable, are filled earlier. It is noteworthy, that although the suitable potential in the South Offshore is 65% less than in the base variant, fields in this region are chosen for CO<sub>2</sub> storage at the end of the analysis period. By contrast, they were not necessary in the base variant due to sufficient availability of cost-effective storage locations onshore and the North Offshore. In the 70-performance variant, storage of CO<sub>2</sub> offshore needs to start 10 years earlier for CCS to maintain its role. In this variant, costs of transport and storage are on average 10% and 20%, respectively, higher than in the base variant. Finally, 58% of the total suitable capacity for storage has been filled by 2050, while in the base variant this was 44%.

**Offshore variant.** In the offshore variant, the role of CCS diminished to on average 13% of the total reduction of CO<sub>2</sub> emissions. In figure 3 the trunklines in the year 2020 are depicted for the offshore variant (b) and the base variant (a). In both variants the role of CCS takes up fast (9 and 8 Mt per year in the base and offshore variant, respectively), and therefore, considerable investments are needed in trunklines before 2020 (720-760 m€). However

<sup>3</sup> Note that these model outcomes are also available for other periods (i.e. for each 5-year time step).

<sup>4</sup> Storage costs include the costs for the satellite line from a trunkline to a specific sink



in the base variant, storage of CO<sub>2</sub> is concentrated in the North East of the Netherlands, while in the offshore variant it switches to the North offshore region. Furthermore, the amount of CO<sub>2</sub> captured grows only to 40 Mt per year in 2040 and then starts declining in contrast with the base variant in which it keeps growing to 62 Mt per year in 2050. Although the total cumulative amount of CO<sub>2</sub> stored in this variant is much lower (0.9 Gt instead of 1.3 Gt in the base variant), overall investments in storage facilities up to 2050 are significantly higher (4.8 billion € including the costs for drilling of wells and satellite lines to the individual sinks compared to 2.2 billion € for the base variant).

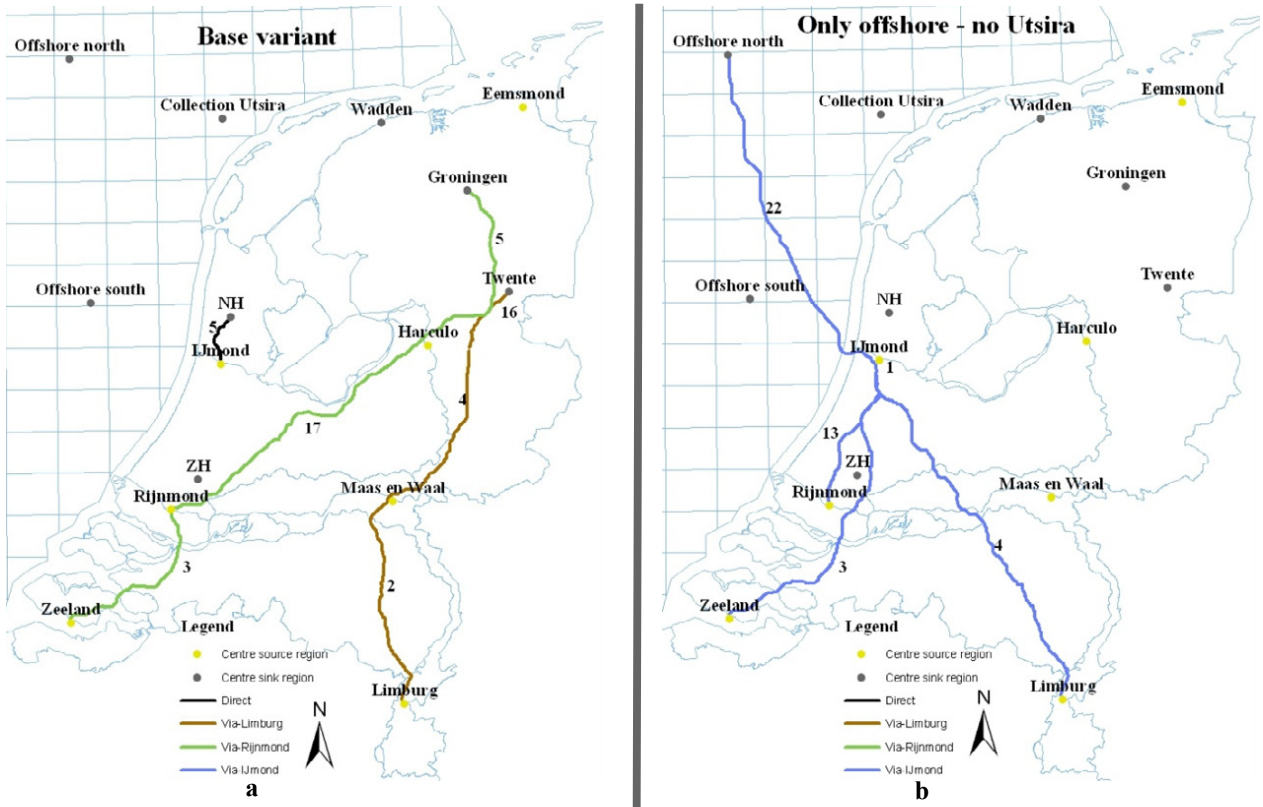


Figure 3. Routing and flow rates (in Mt per year) of trunklines in 2020 for the base variant (a) and the offshore variant (b)

#### 4. Discussion

Results show that the design of the cost-effective CO<sub>2</sub> infrastructure changes significantly when a policy would be implemented that restricts CO<sub>2</sub> storage onshore. On the other hand, when only specific sinks are excluded as a viable option for CO<sub>2</sub> storage, because of possible performance risks, the lay-out of the main infrastructure does not have to change drastically. In that case still enough other storage possibilities are available in the same area, namely, the North East of NL. A trunkline from Rijnmond to there would also in the situation in which less suitable fields are excluded (the 70-performance variant), be a worthwhile option to consider. However, the satellite pipeline infrastructure in the North East would be substantially different due to another choice of fields which are farther away from each other, and the need for extra fields (because a number of large fields have been excluded in the 70-performance variant). It is difficult to design this infrastructure when legislation providing clarity on minimum criteria that sinks must meet to be allowed as a CO<sub>2</sub> storage sites, is not in place yet. So far the criteria themselves to assess performance and risks of CO<sub>2</sub> storage sites are not specified, let alone regulation on procedures how to assess the risks (TNO, 2007). Early consideration on these issues will be a pre-requisite to efficiently plan the infrastructure for CCS towards 2020.

The cumulative amounts that were stored during the analysis period were 1.4, 1.3, and 0.9 Gt for the base, 70 - performance, and offshore variant, respectively. We can consider these different approximations of the "matched capacity" in the techno-economic CO<sub>2</sub> storage pyramid for a specific CO<sub>2</sub> reduction scenario in NL. The toolbox started from the "effective capacity" being 3.1 Gt, and then showed that also legal aspects could be accounted for (as an example) by requiring a specific performance ranking ( $\rightarrow$  2.3 Gt) or by forbidding onshore storage all together ( $\rightarrow$  1.3 Gt). Thus, we have shifted more into the bottom part of the "practical capacity" part of the pyramid. Next, MARKAL chooses sinks partly on the basis of their cost-effectiveness compared to storing it in other sinks while at the same time keeping the cost-effectiveness of CCS in mind in relation to other mitigation measures (such as wind or solar energy). Additionally, the choice of sinks by MARKAL depends on their location, availability, and the possibilities of matching the CO<sub>2</sub> inflow into these sinks to the CO<sub>2</sub> outflow from capture units at other locations. Actually, cost-effectiveness issues (addressed in the "practical capacity" slice) and matching issues (addressed in the "matching capacity" slice) cannot be dealt with independently of each other. On the one hand, the choice of sinks depends on the specific storage costs per sink, and influences the routing and costs of pipelines. On the other hand, matching of (multiple) sources with (multiple) sinks affects the transport costs to sinks, and thus also their cost-effectiveness. With the MARKAL calculation, we have moved at once to the "matched capacity" part of the pyramid. It is noteworthy that the outcomes of this research show that in most cases it would neither be physically possible nor economic to do matching on a one to one basis. In each case multiple sources are connected via trunklines to multiple sinks, so that different flow rates from capture units can be tuned to different injectivity rates into sinks, and transport costs are shared.

It is expected that also different estimations of the storage potential have an impact on the design of the infrastructure. Currently two databases, from TNO and NOGEPa, exist that estimate the Dutch storage potential (TNO, 2007; NOGEPa, 2008). According to TNO, the offshore storage potential is around 1.3 Gt (including 0.14 Gt in aquifers) while according to NOGEPa the offshore storage potential (excluding aquifers) is 0.9 Gt<sup>5</sup>. We based this research on the TNO database, because this is a publicly available dataset with characteristics per sink. However, the storage potential per sink may be either overestimated or underestimated due to lack of sufficient site specific data (TNO, 2007). Such assessments of storage capacity should actually not be used, as also Bradshaw et al. (2007) argues, as basis for a concrete strategy or investment decisions. It is expected that more detailed data from field operators on the ultimate recovery per field, and site characteristics can improve the outcome of this study. Preferably, data is even obtained from local feasibility studies of individual sites.

## 5. Conclusion

In this research we combined the energy bottom-up model MARKAL and the geographic information system, ArcGIS, to assess how the deployment of CCS and the construction of a CO<sub>2</sub> infrastructure can develop in a portfolio of CO<sub>2</sub>-mitigation measures.

Application of this toolbox in NL, shows that CCS can have a significant role in a scenario in which CO<sub>2</sub> emissions need to be reduced by 20% and 50% in 2020 and 2050, respectively, compared to 1990 levels in case nuclear power phases out. CCS would then contribute on average 13-26% to the CO<sub>2</sub> emission reduction in the electricity and cogeneration sector and achieve around 50% CO<sub>2</sub> reduction in the CO<sub>2</sub> intensive industry between 2015 and 2050. The locations of industrial sources can be considered as cornerstones for the set-up of the infrastructure, since at these locations it is most cost-effective to start collecting CO<sub>2</sub>. Furthermore, while over-dimensioning pipelines will cause high upfront investments, it will pay-off since there are ample opportunities in the NL for capture as well as storage.

For CCS to play a major role in 2020, construction of CO<sub>2</sub> trunklines needs to start from 2012. Consequently, the design of a CO<sub>2</sub> infrastructure is urgently needed, especially, in a densely populated country as NL in which the CO<sub>2</sub>

---

<sup>5</sup> Cut-off criteria in this study were: only fields with more than 2.5 Mt storage capacity that were producing, temporarily ceased production, or have a Field Development Plan were considered (the abandoned fields were left out). Furthermore, these fields are expected to have a reasonable injectivity because the permeability-thickness are above the chosen threshold value of 0.25 Dm.

infrastructure may conflict with other land use functions. Clarity on the required performance of sinks, realistic estimates of their potential, and an early decision on whether onshore storage is allowed are of importance for designing the infrastructure so that the CCS option is fully taken advantage of.

With regard to the toolbox we make the following three observations. First, it provides insights into cost-effective locations of capture plants and CO<sub>2</sub> storage sites, and into the timing when capture units need to be built or when sinks will be used for CO<sub>2</sub> storage. Secondly, the toolbox may support the identification of sinks in the upper part of the techno-economic CO<sub>2</sub> storage pyramid, the "matched capacity". It takes into account cost-effectiveness of specific sinks and could also include performance requirements according to regulation with respect to CO<sub>2</sub> storage once that has been formalized. The combination of MARKAL and ArcGIS proved valuable for the matching of sources and sinks since it can deal with both the temporal as well as the spatial aspects of connecting multiple sources to multiple sinks. Thirdly, because the toolbox allows for results to be visualized in maps making the development of a CO<sub>2</sub> infrastructure more imaginable, it could be used as communication tool among stakeholders.

In this research there are still some caveats, which will be addressed in future work. For instance, the limited time-slot in which the current platforms on the North Sea can be re-used for CO<sub>2</sub> storage or the costs to mothball them, were not taken into account. Also, possible CO<sub>2</sub> flows from and to neighboring countries have not been included yet. Furthermore, cost data need to be periodically updated and checked by industrial partners in order to assure that modeling results are close to real developments.

This research is part of the CATO program, the Dutch national research program on CO<sub>2</sub> Capture and Storage. CATO is financially supported by the Dutch Ministry of Economic Affairs under the BSIK program. More information can be found on [www.co2-cato.nl](http://www.co2-cato.nl).

## 6. References

- Bachu, S., D. Bonijoly, et al., 2007. "CO<sub>2</sub> storage capacity estimation: Methodology and gaps." International Journal of Greenhouse Gas Control 1(4): 430-443.
- Bradshaw, J., S. Bachu, D. Bonijoly, R. Burruss, and N. P. C. Sam Holloway, Odd Magne Mathiassen, 2007. "CO<sub>2</sub> storage capacity estimation: Issues and development of standards." International Journal of Greenhouse Gas Control 1: 62-68.
- Broek, M. A. v. d., A. Ramirez, E. Brederode, L. Kramers, M. van der Kuip, T. Wildenburg, A. Faaij, W. Turkenburg, 2008. "Designing a CO<sub>2</sub> infrastructure in line with the development of the energy supply system (in preparation)."
- Broek, M. v. d., A. Faaij, and W. Turkenburg, 2008. "Planning for an electricity sector with carbon capture and storage, Case of the Netherlands." International Journal of Greenhouse Gas Control 2: 105-129.
- Damen, K., 2007. Reforming fossil fuel use. The merits, costs, and risks of carbon dioxide capture and storage. Copernicus Institute. Utrecht, Utrecht University. **Phd**.
- IEA, 2008, Energy technology perspectives 2008, IEA, Paris
- IPCC, 2007, Climate Change 2007: Mitigation of Climate Change, Summary for Policymakers,
- Janssen, L., V. Okker, J. Schuur 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
- Loulou, R., G. Goldstein, K. Noble, 2004, Documentation for the MARKAL Family of Models, ETSAP, Paris
- NOGEPA, Ministry of Economic Affairs, 2008, Potential for CO<sub>2</sub> storage in depleted gas fields at the Dutch Continental Shelf, Phase 1: Technical assessment, DHV, TNO,
- Ramirez, A., Saskia Hagedoorn, Leslie Kramers, Ton Wildenburg, Chris and Hendriks, 2008. Screening CO<sub>2</sub> storage options in the Netherlands. 9th International Conference on Greenhouse Gas Control Technologies, Washington D.C.
- TNO, 2007, Options for CO<sub>2</sub> storage in the Netherlands - Time dependent storage capacity, hazard aspects, and regulations, 2007-U-R0564/B, TNO Built Environment and Geosciences, Utrecht