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ScienceDirect
Energy Procedia 1 (2009) 4071–4078
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-9

An integrated GIS-MARKAL toolbox for designing a CO_2 infrastructure network in the Netherlands

Machteld van den Broek[a]*, Evelien Brederode[a], Andrea Ramírez[a], Leslie Kramers[b], Muriel van der Kuip[b], Ton Wildenborg[b], André Faaij[a], Wim Turkenburg[a]

[a] *Group Science, Technology and Society, Copernicus*
Institute for Sustainable Development and Innovation, Utrecht
University, Heidelberglaan 2, 3584 CS Utrecht, Netherlands
[b] *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_2. 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_2 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.

Keywords: *CO_2 capture and storage; MARKAL; geographic infomration system; linear optimisation; CO_2 infrastructure*

1. Introduction

To reach stabilization targets of 450 ppmv CO_2-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_2 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_2. 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_2 infrastructure. A tool, which can support this planning process, requires dealing with both temporal (e.g. time when power plants with CO_2 capture need to come online in a port folio of CO_2 reduction measures and when sinks become available) and spatial aspects (e.g. locations of CO_2 sources and sinks). Furthermore, this tool should be able to take into account criteria

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* Corresponding author. Tel.: +31-30-2532216; Fax: +31-30-2537601.
E-mail address: m.a.vandenbroek@uu.nl

doi:10.1016/j.egypro.2009.02.214

which determine whether a specific sink for CO_2 storage is a cost-effective option, suitable, and can be connected to one or more CO_2 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_2 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_2 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_2 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_2 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_2 targets, preferences for a certain reservoir type such as only CO_2 storage offshore).

In the Netherlands (NL) CCS is expected to play a major role in a strict CO_2 mitigation strategy due to the presence of many large CO_2 point sources (~69 Mt per year from sources above 100 kt CO_2 in 2005 which is 39% of total Dutch CO_2 emissions) and a considerable effective capacity for CO_2 storage (~3.1 Gt CO_2 excluding the Slochteren field [2]). Conversely, the planning and realization of a large scale CO_2 infrastructure may take a long time in this densely populated country. Also CO_2 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_2 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_2 infrastructure. The scope of the study is limited to sources that emit more than 100 kt CO_2 in the industrial, electricity and cogeneration sector in which CO_2 capture can be applied. In this paper, a discount rate of 5% has been applied, all costs are in €$_{2007}$, and "t" always refers to tonne CO_2.

2. Methodology

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

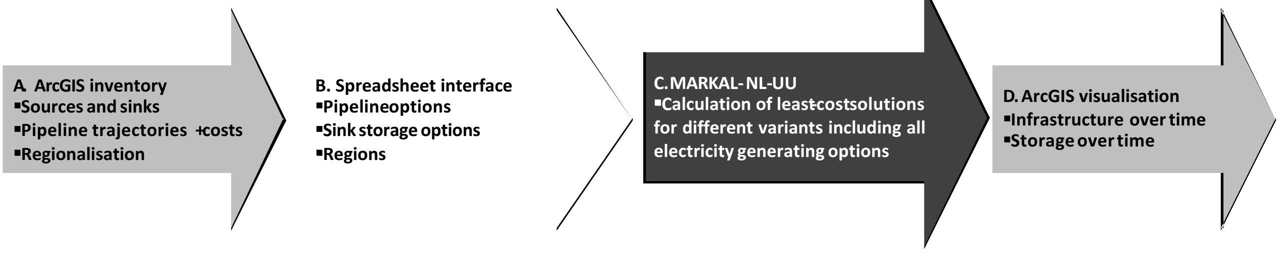

Figure 1. Schematic representation of the methodological approach

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[2] The Slochteren field has an estimated storage potential of 7.4 Gt, but is probably only available for CO_2 storage after 2050 .

A. During the first step data regarding potential CO_2 capture sites, CO_2 storage locations, and possible CO_2 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_2 storage pyramid since geological (e.g. minimal depth of 800 m to store CO_2 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_2 storage potential, its availability in time, and injectivity are estimated.
- The inventory of potential sites where CO_2 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_2 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 $€_{2007}$ monetary units by using the CEPCI index.
- In ArcGIS, CO_2 sources and sinks are clustered into source and sink regions, to model the advantage of economies of scale to transport CO_2 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_2 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_2 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_2 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 /offshore
	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_2 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_2 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_2 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_2 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_2 cap going from 20% in 2020 to 50% in 2050 (compared to the 1990 level) is assigned on the CO_2 emissions from the Dutch CO_2 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_2, 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_2 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_2 cap) can be attributed to CCS. Figure 1 depicts the amounts of CO_2 that are captured in each region. It also shows that the total amount of CO_2 captured grows steadily from 9 Mt CO_2 stored per year in 2015 to 62 Mt in 2050. Over the whole analysis period a cumulative amount of 1.3 Gt of CO_2 will be captured and stored. Most CO_2 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_2 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_2 is also captured at a power plant in this region.

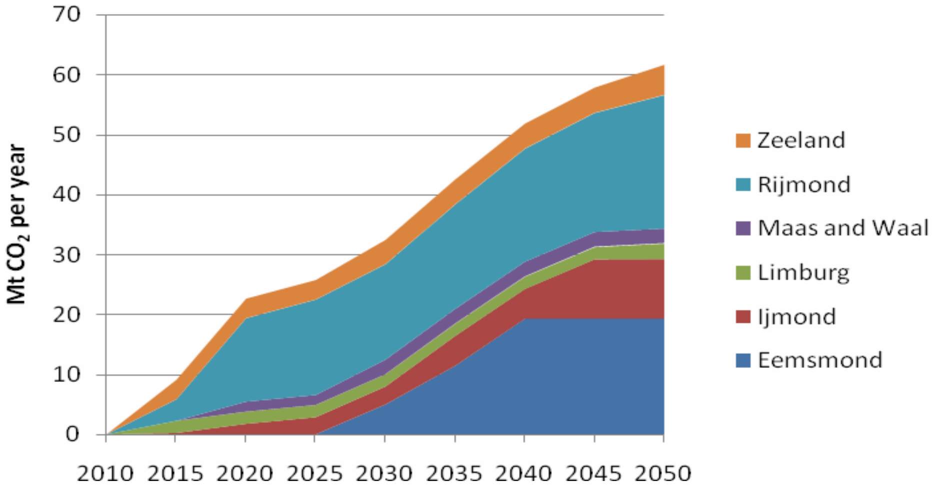

Figure 1. Annual amount of CO_2 captured at power plants and industry per region (base variant)

Figure 2a provides us with information on how much CO_2 is stored in each sink during the analysis period. It demonstrates that CO_2 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_2 flows through these pipelines in 2020[3]. 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_2 flows. Costs of CO_2 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[4] increase from 1.4 €/t in 2015 to 3.3 €/t in 2050, because cheap sinks are preferably filled first.

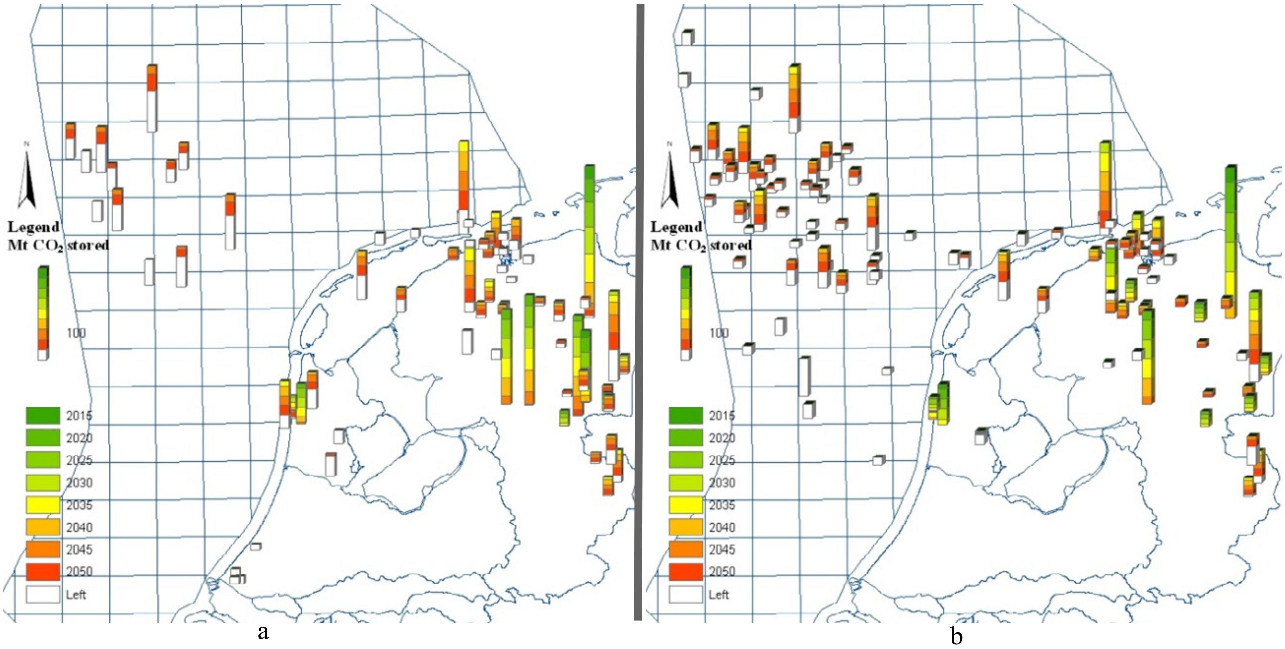

Figure 2. CO_2 storage over the time for the base variant (a) and the 70-performance variant (b). Each stacked bar represents a sink. The size and colours relate to respectively the amount and timing of the stored CO_2. A white bar represents the storage capacity that is still available. Note that only sinks are depicted that are used for CO_2 storage during the analysis period.

70-performance variant. In the 70-performance variant CCS retains its role in a CO_2 mitigation strategy compared to the base variant (1% less), only a shift takes place in configuration of the infrastructure. Figure 2b shows the CO_2 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_2 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_2 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_2 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_2 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

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[3] Note that these model outcomes are also available for other periods (i.e. for each 5-year time step).

[4] Storage costs include the costs for the satellite line from a trunkline to a specific sink

in the base variant, storage of CO_2 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_2 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_2 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).

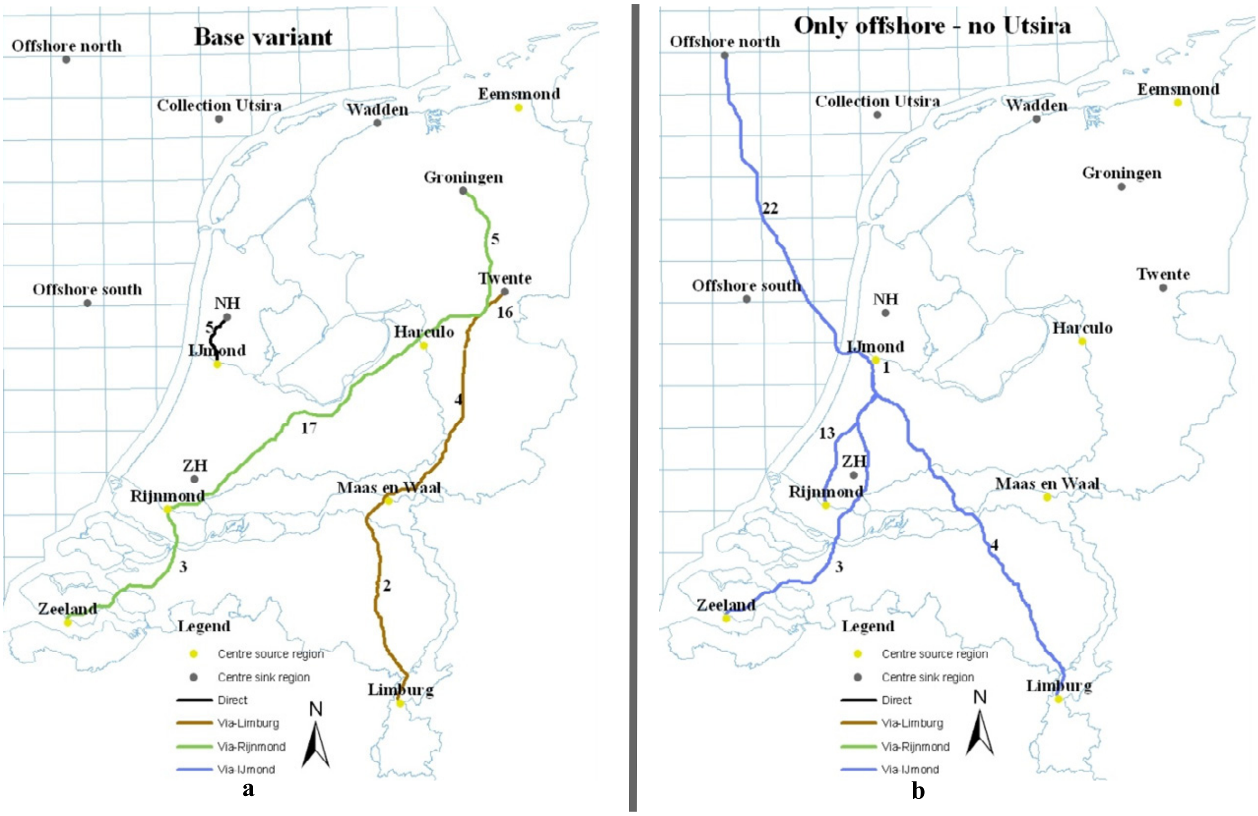

Figure 3. Routing and flow rates (in Mt per year) of trunklines in 2020 for the base variant (a) and the offshore variant (b)

4. Discussion

Results show that the design of the cost-effective CO_2 infrastructure changes significantly when a policy would be implemented that restricts CO_2 storage onshore. On the other hand, when only specific sinks are excluded as a viable option for CO_2 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_2 storage sites, is not in place yet. So far the criteria themselves to assess performance and risks of CO_2 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_2 storage pyramid for a specific CO_2 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 (→ 2.3 Gt) or by forbidding onshore storage all together (→ 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_2 inflow into these sinks to the CO_2 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[5]. 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_2 infrastructure can develop in a portfolio of CO_2-mitigation measures.

Application of this toolbox in NL, shows that CCS can have a significant role in a scenario in which CO_2 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_2 emission reduction in the electricity and cogeneration sector and achieve around 50% CO_2 reduction in the CO_2 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_2. 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_2 trunklines needs to start from 2012. Consequently, the design of a CO_2 infrastructure is urgently needed, especially, in a densely populated country as NL in which the CO_2

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[5] 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_2 storage sites, and into the timing when capture units need to be built or when sinks will be used forCO_2 storage. Secondly, the toolbox may support the identification of sinks in the upper part of the techno-economic CO_2 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_2 storage once that has been formalized. The combination of MARKAL and ArcGIS proofed 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_2 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_2 storage or the costs to mothball them, were not taken into account. Also, possible CO_2 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_2 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.

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