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Designing a cost-effective CO_2 storage infrastructure using a GIS based linear optimization energy model

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ABSTRACT

Large-scale deployment of carbon capture and storage needs a dedicated infrastructure. Planning and designing of this infrastructure require incorporation of both temporal and spatial aspects. In this study, a toolbox has been developed that integrates ArcGIS, a geographical information system with spatial and routing functions, and MARKAL, an energy bottom-up model based on linear optimization. Application of this toolbox led to blueprints of a CO_2 infrastructure in the Netherlands. The results show that in a scenario with 20% and 50% CO_2 emissions reduction targets compared to their 1990 level in respectively 2020 and 2050, an infrastructure of around 600 km of CO_2 trunklines may need to be built before 2020. Investment costs for the pipeline construction and the storage site development amount to around 720 m€ and 340 m€, respectively. The results also show the implication of policy choices such as allowing or prohibiting CO_2 storage onshore on CO_2 Capture and Storage (CCS) and infrastructure development. This paper illustrates how the ArcGIS/MARKAL-based toolbox can provide insights into a CCS infrastructure development, and support policy makers by giving concrete blueprints over time with respect to scale, pipeline trajectories, and deployment of individual storage sites.

1. Introduction

Carbon dioxide capture and storage (CCS) may play a significant role in greenhouse gas mitigation policies if stabilisation targets of 450 ppmv or less for the concentration of CO_2 in the atmosphere are to be reached (IEA, 2008b; IPCC, 2007). CCS involves the separation of CO_2 from industrial and energy-related sources, transport to a (underground) storage location and long term isolation from the atmosphere (IPCC, 2005). Extensive research, development and demonstration efforts are needed to further develop this technological option, improve the performance, and reduce its costs. Large-scale implementation of CCS will require the deployment of a whole new infrastructure to transport and store the CO_2 (Odenberger et al., 2009). Although transport and storage are relatively cheap activities in the CCS chain compared to capture of CO_2 which is roughly responsible for 60–75% of CCS costs per tonne CO_2 avoided[1], the required upfront investments needed for construction of trunklines and storage facilities, and the uncertainty regarding their future usage can delay necessary investments in CO_2 infrastructure. A sound planning and design of this infrastructure may help to overcome these barriers. For planning and design it is necessary to take into account synergies and interferences between the infrastructure development and the development of the energy supply system and carbon intensive industrial sectors (e.g. refineries, ammonia, iron and steel). This involves taking into account the timing and spatial aspects, while at the same time assuring the cost-effectiveness of CCS. Four timing aspects are of importance. First, a CO_2 sink (e.g. an empty gas field) should be available when a capture unit becomes operational (e.g. at a power plant). Secondly, the amount of CO_2 captured needs to be matched to the storage potential and the maximum injectivity rate

Abbreviations: CCS, Carbon dioxide Capture and Storage; CHP, Combined Heat and Power generation plant; Ft, Terrain Factor; GIS, Geographic Information System; IGCC, Integrated coal (with possibly biomass) gasification combined cycle power plant; NGCC, Natural gas combined cycle power plant; O&M&M, Operation, Maintenance, and Monitoring; PC, Pulverised coal-fired power plant with possibly co-firing of biomass.

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[1] IPCC estimated transport costs of 1–8 US$/t for 250 km, 0.6–8.3 US$/t for storage, and 13-74 US$/t for capture in power plants (IPCC, 2005). Damen et al. gave ranges of 2–17 €/t for transport and storage in aquifers or hydrocarbon fields, and 5–100 €/t for capture at power plants and industrial units in the Netherlands (Damen et al., 2009). IEA GHG estimated that almost 30 Gt of CO_2 can be transported and stored in Europe for less than 20 €/t when all confined aquifers, and hydrocarbon fields are available (IEA GHG, 2005).

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of the sinks available. Thirdly, short-term matching between sinks and sources should not prevent cost-effective matching in the longer-term, finally, the CO_2 transport flows over time should determine to what extent the CO_2 infrastructure can be over-dimensioned when pipelines are laid down. The spatial aspects that needs to be taken into account are the distances between sources and sinks which largely determine CO_2 transport costs and the exact trajectories of pipelines which also influence the transport costs, and thus the feasibility of specific connections. Furthermore, to take advantages of economies of scale, appropriate spatial clusters of sources and sinks may be defined that can more easily be connected by trunklines. With regard to the cost-effectiveness of CCS, we note that the design of the infrastructure can affect the costs of CO_2 transport and storage (since storage costs are site-specific) and, therefore, influence the competitiveness of CCS in the energy system as a whole. Also, policies related to transport and storage of CO_2 (e.g. allowing CO_2 to be stored only offshore) may influence the cost-effectiveness of CCS at large, and thus its potential role in the total energy system.

Most studies conducted until now only address a limited number of these aspects. For example, routing of CO_2 pipelines has been dealt within the EU research project GESTCO (1999–2003) (Christensen and Holloway, 2004), the IEA GHG study "Building the cost curves for CO_2 storage: European sector" (IEA GHG, 2005), and a study by Middleton and Bielicki (2009). These studies used a Geographic Information System (GIS), to estimate CO_2 transport costs. Whereas in GESTCO a least-cost route was found by taking into account aspects like land use, rivers and existing pipeline corridors (Egberts et al., 2003), the IEA study based its costs calculations on the length of a straight line between sinks and sources multiplied by a factor of 1.15 in order to correct for the actual trajectory. Middleton and Bielicki (2009) developed a tool that not only determines where to build and connect pipelines, but also selects the sources and sinks where to capture and store CO_2 on the basis of cost-minimization. However, in these three studies the availability of sources (the period when CO_2 capture units are operational at these sources) and the availability of sinks (the period when CO_2 can be stored in the sinks) were not matched over time. Among others, the future development of the energy system including new CO_2 sources was not taken into account. In the follow-up project of GESTCO, GeoCapacity (2006–2008) (Geus, 2007), timing aspects are not considered; instead it is being estimated whether the storage potential is sufficient for potential capture sources in the neighbourhood.

In quantitative energy scenario studies of greenhouse gas mitigation options at the national (Broek et al., 2008; Marsh et al., 2005), or world level (IEA, 2008b), the cost-effectiveness of CCS over the coming decades is assessed compared to other CO_2 mitigation options (e.g. energy efficiency, renewables, nuclear). In these studies, location aspects are addressed generally by assuming average transport and storage costs for different types of sinks (aquifers, empty gas and oil fields, coal seams). Therefore, these studies do not sufficiently address the spatial constrains of a CO_2 transport infrastructure. Nevertheless, in the literature some attempts have already been made to include (at some level) temporal and spatial aspects. In the European CASTOR research project (CASTOR project, 2004) for instance, spatial aspects like clusters of sources and sinks representing areas with relatively high density of power plants and hydrocarbon fields, and trunklines between them, were considered. However, the level of spatial detail was limited since GIS was not used to find specific pipeline trajectories. Furthermore, although a development pathway of CCS was taken into account, the timing and structure of the CO_2 infrastructure was pre-determined by user input without considering different alternative infrastructure implementations. Damen et al. (2009) took into account spatial aspects into CCS implementation pathways by differentiating transport costs between clusters of sinks and sources without the use of a GIS. Cremer (2005) dealt with spatial and temporal aspects by integrating a GIS with an energy bottom-up model. In both studies, sinks and sources were matched on a first-come-first-serve basis. Thus, the design of the infrastructure did not take into account long term CO_2 transport or storage requirements.

We conclude that existing tools and studies mostly focus on either the spatial aspects, temporal aspects or cost-effectiveness of CCS. However, planning and designing the development of a CO_2 infrastructure, requires dealing with all of them at once. Doing so is important to support policy makers and market players with decision-making on long term infrastructural issues.

This article aims to assess blueprints for the development of a large-scale CO_2 infrastructure in the Netherlands for the analysis period 2010–2050. Such blueprints must reveal succeeding cost-effective combinations of sources, sinks, and transport lines over this period. Moreover, they should provide insights into the costs, location, and time-path of the individual infrastructural elements. The scope of this study is limited to sources that emit more than 100 kt CO_2 a year in the industrial, electricity and cogeneration sector in which CO_2 capture can be applied[2].

The structure of this paper is as follows. Section 2 describes main aspects of the methodology and the input data used. Results and discussion are presented in Section 3 and 4 respectively. Finally, in the last section conclusions are drawn with respect to the role of CO_2 transport for the deployment of CCS in the Netherlands.

2. Methodology

The techno-economic MARKAL model of the Dutch electricity and cogeneration sector, MARKAL-NL-UU, that was applied to assess possible CCS deployment trajectories in the Netherlands (Broek et al., 2008) is the starting point of this study. The MARKAL (an acronym for MARKet ALlocation) methodology provides a technology-rich basis for estimating dynamics of the energy system over a multi-interval period. This MARKAL energy system consists of two standard building elements: technologies and commodities. Commodities may be energy carriers or materials. Technologies which are implemented in the model by techno-economic data (e.g. required input, efficiency, investment costs) convert commodities into other commodities. Commodities flow from one technology to another thus creating a network structure. MARKAL translates the techno-economic data and possible flows of the energy system into a linear mathematical programming problem and then minimises the net present value of all system costs (Loulou et al., 2004). However, in the MARKAL methodology the possibilities to include spatial aspects are limited. For example, unless explicitly specified, MARKAL cannot account for differences between transport costs according to distances and terrain types between sources and sinks.[3] Also, the closeness of different sinks to each other cannot be investigated in MARKAL. However, ArcGIS, a geographical information system (GIS), offers elaborate spatial functions e.g. to assess distances, or to find cost-effective pipeline trajectories through different terrains from one point to another. Therefore we developed a toolbox that combines MARKAL (version 5.7e) with ArcGIS (version 9.2). Besides temporal and spatial aspects, this toolbox takes into account techno-economic criteria (e.g. costs, efficiency data) as well as policy criteria (e.g. CO_2 targets, allowing CO_2 storage offshore only).

Another important aspect is the choice of the network type in which sources can be connected to sinks in the model. In real life, CO_2 transport can be organised in different forms: point-to-point connection between one source and one sink, via a hub-spoke network, or via a mature transport network[4]. These forms may be developed as subsequent steps in the CO_2 infrastructure (McKinsey&Company, 2008): i.e. in a demonstration-stage (point-to-point), early commercialization stage

[2] This threshold is also applied by IPCC in their Special report on CCS (IPCC, 2005), because CO_2 capture from smaller sources is more costly, and the emissions from the stationary CO_2 sources (excluding the residential sector) represent only a small fraction of total CO_2 emissions.

[3] MARKAL is able to model trade of energy carriers or materials between different regions with the multi-regional feature. However, the modeller is responsible for choosing the right transport costs (e.g. depending on distances) between these regions.

[4] A hub and spoke network pattern is a radial system of routes. The hub could be considered the hub of a wheel with spokes to the outlying locations (Toh and Higgins, 1985). By acting as collection and dissemination points, hubs allow for indirect connections between sources and sinks. A mature transport network is a complex network structure composed of multiple connections between sources and sinks via pipelines of various sizes in diverse ways.

(hub-spoke), and commercial stage (mature network). A point-to-point network is very expensive, because it would consist of separate pipelines for each relevant source–sink combination. In this study we opt for the hub-spoke network form[5] to be able to cover at least the economies of scale of the commercialization-stage[6] of transporting CO_2 from various sources through trunklines to various sinks. In order to model this hub-spoke network, CO_2 sources and sinks need to be clustered into source and sink regions. The CO_2 captured at individual sources in one source region is then transported through so-called satellite pipelines to and collected in the hub of the source region. From there it is transported through a trunkline to a hub in a sink region from where it is distributed via satellite pipelines to several sinks of the sink region.

The research methodology applied in our study can be summarised into seven steps:

1. Inventory of potential CO_2 sinks and their costs (ArcGIS, spreadsheet interface).
2. Inventory of potential CO_2 sources and their costs (ArcGIS, spreadsheet interface).
3. Clustering of sources and sinks into source and sink regions[7] and assessing appropriate locations for the hubs (ArcGIS).
4. Identification of possible trunkline routes between the hubs in the source regions and the hubs in the sink regions, satellite routes within the regions, and estimation of costs per pipeline (ArcGIS).
5. Extension of MARKAL-NL-UU model to incorporate spatial data that are of importance for the design of a CO_2 infrastructure. These data are imported from ArcGIS into MARKAL-NL-UU via a spreadsheet interface that creates extra MARKAL building elements: technologies for potential regional sources, pipelines, and sinks, and extra commodities for all potential CO_2 flows[8] (MARKAL-NL-UU).
6. Running of MARKAL-NL-UU for different variants (e.g. with respect to policy options) to find cost-effective pathways to reach specific CO_2 reduction targets. The model calculates the deployment of CCS and other CO_2 mitigation measures like photovoltaic systems, wind turbines, or biomass co-firing. Furthermore, it assesses which sources, sinks, and transport options will be used over time and to what extent. The analysis period 2010–2050 is divided into 5-year time steps.
7. Presentation and analysis of results (spreadsheet interface, ArcGIS).

The remaining part of this section describes the seven steps in more detail. Fig. 1 presents how the steps are linked via various data flows between ArcGIS, the spreadsheet interface, and MARKAL. Finally, note that in this study a discount rate of 5% is applied, prices are given in €$_{2007}$ unless otherwise stated, and "t" always refers to "tonne CO_2".

2.1. Inventory of sources

2.1.1. Sources

We assume that CO_2 capture will be applied at locations where large-scale sources are currently situated. To determine where CO_2 capture units in principle can be installed, data have been gathered on locations of existing CO_2 point sources in the Dutch power sector and CO_2 intensive industry[9]. The sources selected emit more than >100 kt CO_2 per year in 2004 and are suitable for either retrofit with CO_2 capture or replacement with a CO_2 capture unit. The inventory resulted in 43 locations: 24 existing power plants, and 15 industrial sources. Besides these locations, also four possible new locations at the coast are included[10]. The data on locations are used to cluster sources into "source regions" so that transport options from these regions can be determined (see Section 2.3). Besides location, we collected the following data on the existing sources:

- *Age* of power plants in order to estimate their decommissioning dates. Once a power plant is decommissioned, there are opportunities to build new ones (gas, coal and/or biomass-fired) with or without CO_2 capture units. For industrial units, we assume that the industrial production continues at today's level, and ignore costs for necessary replacement of these units.
- *Capacity* data of power plants to determine the current electric capacity in a "source region". This gives an indication of the minimum future power generation capacity in a region, since it is expected that most existing power generating capacity will be replaced (Pelgrum, 2008). However, the capacity at a location may increase in the future. Capacity data on industrial units (in tonnes product) and associated CO_2 emissions are used to calculate the amount of CO_2 that can potentially be captured at these units.
- *Type* of CO_2 source. The large-scale power plants are either natural gas combined cycle ower plants (NGCC), subcritical or supercritical pulverised coal-fired power plants with possible co-firing of biomass (PC), integrated coal (and biomass) gasification power plants (IGCC), or gas-fired combined heat and power generation plants (CHP). On the basis of these categories, the locations of power plants that can be retrofitted with CO_2 capture are identified assuming that only existing supercritical PCs can be retrofitted. This parameter also determines the possible types of new power plants (with and without capture, and each with their own costs) for a "source region". Most types of power plants can be built anywhere, except for coal-fired power plants that can only be constructed in regions where these already exist or at the new locations at the coast-side. Industrial sources include: ethylene plant, ethylene oxide plant, ammonia plant, hydrogen plant, cement plant, refinery, or iron and steel plant. Depending on the type of industrial plant, costs of a CO_2 capture and compression unit at these different plants are determined.

Cost data of CO_2 capture units for the industrial units are derived from Damen et al. (2009) and of existing and future power plant technologies from the MARKAL-NL-UU model (Broek et al., 2008) and Vosbeek and Warmenhoven (2007) (see Table 1 for investment costs and efficiency input data). The capture units at power plants can be post-combustion units at NGCCs or PCs, or pre-combustion units at IGCCs. Finally, since in the last years a steep increase in prices has occurred, all cost data are updated to €$_{2007}$ monetary units by using the CEPCI index (Chemical Engineering, 2008)[11].

2.2. Inventory of sinks

To determine where and how much CO_2 can be stored in the Netherlands and the Dutch continental plate, CO_2 capacity inventories of hydrocarbon fields and aquifer traps[12] are used. The resulting sink inventory is based on data compiled by Christensen and Holloway (2004), Kramers et al. (2007), and TNO (2007a, 2007b). In the Netherlands there are over 500 oil, gas fields and aquifers. Because not all of them are suitable for CO_2 storage (e.g. they are situated shallower than 800 m or have reservoir rocks with porosity less than 10%), the total amount of options considered is 172 excluding the large Slochteren field[13]. The selection is based on a number of threshold values for specific characteristics of the CO_2 storage reservoirs as shown in Table 2 (Ramírez et al., 2009).

Of the 172 fields 35 are aquifers, 131 are gas fields, 5 are oil fields and 1 field contains both oil and gas. Three of the sinks are "stacked" sinks in which separate fields lay on top of each other. There are slightly more offshore (87) than onshore (81) sinks. Despite this, the potential onshore storage capacity (1.8 Gt) is larger than the offshore storage capacity (1.3 Gt). Potential storage capacities per sink are on average 26 Mt onshore, and 15 Mt offshore. The storage potential of aquifers amounts to 0.3 Gt onshore and 0.1 Gt offshore. Furthermore, to study the possibility of storage outside the Netherlands, also a large aquifer in the Norwegian part of the North Sea is included: the Utsira formation with an estimated capacity of 42.4 Gt (Bøe et al., 2002). For each sink the following data have been collected:

- *Location.* Locations of the potential sinks are determined by *X* and *Y* coordinates, which represent the centroids of the sinks. Here CO_2 could be stored in the future. These locations are also used to cluster sinks into sink regions to determine transport options to these regions.

[5] Also, the IEA states that a hub-spoke network structure would be the most efficient way to connect many emitters to large storage sites (IEA, 2008a).

[6] In an IEA GHG study, it was calculated that although large-scale infrastructures with trunklines and satellite connections will have high initial investment costs, they may eventually lead to lower costs than the gradual evolution of individual pipelines growing to a larger system (IEA GHG, 2005). One reason is that the transport costs per tonne of CO_2 decline in pipelines with higher CO_2 mass flow rates (IPCC, 2005), because the increase in diameter of a pipeline and related material costs is less than the increase in mass flow rate.

[7] A region is defined as a collection of sink or source locations.

[8] To apply this methodology, the MARKAL equations do not need to be modified.

[9] Data were collected from the following sources: (1) the Pollutant Release and Transfer Register, the Dutch national register that administrates among others the CO_2 emissions of the industrial and electricity producing sector. (2) GESTCO, an EU research project (1999–2003) that carried out an extensive inventory of industrial and energy-related CO_2 sources larger than 0.1 Mt/yr for seven European countries (Christensen and Holloway, 2004). (3) GeoCapacity (2006–2008), the follow up of GESTCO covering 22 European countries (Geus, 2007). (4,5) Broek et al. (2008) and Damen et al. (2009), who collected recent data on the electricity park and industrial CO_2 sources.

[10] Three of these are based on energy company plans for new power plants. In the draft of the new structure plan for electricity supply, the Dutch Government also permits power plants at new locations close to the coast (EZ and VROM, 2008).

[11] The Chemical Engineering magazine provides a weighted average index for cost developments called the CEPCI (Chemical Engineering Plant Cost Index), which is widely used for estimating cost of power plant construction, e.g. (Rubin et al., 2007).

[12] The option to store CO_2 in coal bed seams with enhanced methane recovery is not taken into account as unmined coal seams are assumed to have a limited potential in the investigated time frame in the Netherlands considering the current state of technology.

[13] The gas producing field Slochteren in Groningen has an estimated CO_2 storage capacity of about 7 Gt., but is considered unavailable for storage before 2050 (TNO, 2007a).

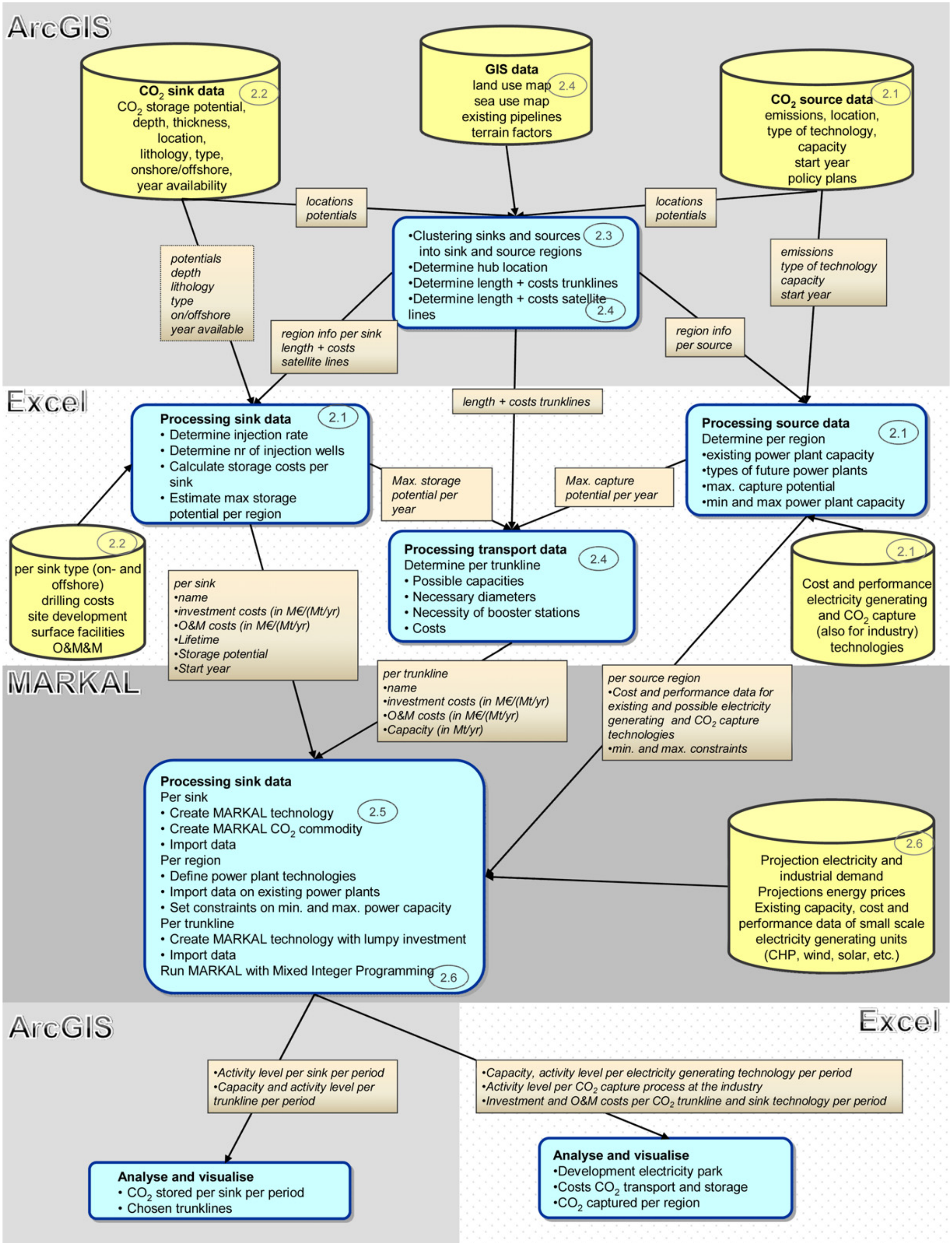

Fig. 1. Scheme of the methodology applied in this study including data flows between ArcGIS, a spreadsheet interface, and MARKAL (the numbers refer to relevant sections in this paper).

- *Type.* The sink can be a deep saline aquifer formation, an (almost) empty oil or gas field. CO_2 storage costs (see Table 3) as well as injectivity rate depend on the type of sink.
- *On- or offshore.* The sink is either located on or offshore. CO_2 storage costs depend strongly on this parameter (CASTOR project, 2004; IEA GHG, 2005).
- *Start year of injection.* Year from which CO_2 can be stored in the sink. It is assumed that aquifers can be used right away. However, CO_2 storage in the oil and gas fields can only start after the economic viable part of these reserves has been exploited. This moment is estimated based on the end year reported in the current winning schemes in the online database, the "Dutch oil and gas portal" (TNO, 2007a).

Table 1
Investment costs and efficiency of electricity generating technologies.

	Total capital requirement (€/kW)				Efficiency (energy output of electricity/energy input of fuel)			
	2010	2020	2030	2040	2010	2020	2030	2040
NGCC	676	608	608	608	58%	60%	63%	64%
PC	1598	1487	1448	1352	46%	49%	52%	53%
IGCC	2005	1798	1691	1521	46%	50%	54%	56%
NGCC-CCS	1146	1014	938	838	49%	52%	56%	58%
PC-CCS	2546	2328	2110	1892	36%	40%	44%	47%
IGCC-CCS	2769	2374	2130	1956	38%	44%	48%	50%
Wind onshore	1227	1075	965	866				
Wind offshore	2433	2028	1919	1892				
Nuclear	2652	2652	2652	2652				
Photovoltaic systems	4325	2703	1352	946				

Abbreviations used: NGCC - natural gas combined cycle power plant, PC - pulverised coal-fired power plant including possibly co-firing of biomass, IGCC - integrated coal with possibly biomass gasification combined cycle power plant.

- *Potential capacity of storage.* Maximum amount of CO_2 that can be stored in the sink. Potential storage capacity for gas and oil fields are estimated based on the Dutch ultimate recoverable methane and oil volumes and area per field.[14] The minimum storage capacity in aquifers is based on the area, average aquifer thickness, porosity, storage efficiency, fraction of porous permeable rock of the aquifer and CO_2 density at reservoir conditions. The methodologies used to calculate the potentials have been described in detail in (TNO, 2007b).
- *Depth, thickness.* Depth is the height of the overburden, and thickness is the height of the reservoir. The drilling costs for the wells are calculated on basis of these parameters and an average cost per meter drilled.
- *Injectivity rate.* The injectivity rate determines how much Mt CO_2 can be injected per well per year. The injectivity rate depends on the reservoir type and the lithology of the reservoir rock and varies between 0.1 and 1 Mt per year per well. This rate is assumed to be constant during the CO_2 injection period. Furthermore, this rate together with the storage capacity is used to calculate the number of wells that are needed.

Investment costs and yearly costs for each sink are determined based on CO_2 storage cost values reported in the European CASTOR project (CASTOR project, 2004). Costs for activities in the oil and gas exploration and production sector, which are similar to CO_2 storage activities, have risen tremendously since 2005 up to the end of 2008. The reason was an increase in the number of activities leading to a shortage of necessary equipment and services. Therefore, we increase the costs provided in the CASTOR study to $€_{2007}$ costs using the CERA (Cambridge Energy Research Associates) Upstream Capital Costs Index (UCCI)[15]. The resulting costs per reservoir type are shown in Table 3.

2.3. Clustering of sources and sinks into source and sink regions

The choice to use a hub-spoke network form to include scale-advantages of transporting CO_2 has implied that sources and sinks have to be first clustered into regions (see above). Ideally, MARKAL-NL-UU could calculate optimal regions itself (e.g. by combining close-by sources where CO_2 will be captured around the same time). However, to feed MARKAL-NL-UU with an appropriate data set for many possible combinations of sources and sinks go beyond the processing capacity of the model as it stands right now[16]. To avoid this problem, the clustering of sources and sinks into regions is done before the MARKAL-NL-UU runs by seeking a cost-effective trade-off between trunkline costs and satellite pipeline costs. Using ArcGIS, we calculate the total annual transport costs for several plausible regional configurations by totalling up the costs of all potential satellite lines within the regions and of the necessary trunklines to or from these regions. Next, we select the configurations with the lowest costs, thus, seeking an optimum between many small regions (short satellite lines and many trunklines) or a few large regions (long satellite lines and few trunklines).

The current geographical distribution of power plants, industrial sources and sinks already form natural clusters of CO_2 sources (because of access to feedstock supplies, access to distribution channels, or other historical reasons to concentrate economic activities, see Fig. 2a) and CO_2 sinks (because of the geological history of The Netherlands, see Fig. 2b). Despite this, alternative configurations are possible. For example, in a few cases it is the question whether remote sources can better be assigned to a separate region or be added to another region in the neighbourhood. In three cases (around Rijnmond, IJmond and Eemsmond, see Fig. 2a) clustering the sources into one large region was assessed versus clustering them into two smaller regions. According to this assessment, it is cheaper[17] to collect the CO_2 in one hub with one trunkline to a sink region than in two hubs with two trunklines to a sink region if this is more than 100 km away from the source region(s). Since most sink regions are more than 100 km away from the source regions, the configuration with the large source regions is chosen. Note that the choice to model a hub-spoke network has limitations: in a mature distributed network, a small trunkline could have a connection to two smaller source regions, which then could be connected to a sink region with a large trunkline. Clustering of sinks is done in a similar manner. In Fig. 2a, the result of the source clustering is shown. The 43 sources are clustered into 7 source regions and 173 sinks are clustered in 8 sink regions with the Utsira formation being considered as a separate sink region.

Finally, by means of the Mean Centre tool of Spatial Statistics function of ArcGIS the location of the regional centres (or hubs), which are the connection points to the trunklines, are determined. This Mean Centre Tool finds the mean centre which is the weighted X and Y coordinate of all sinks or sources in a region. As weight we used the current emissions or storage capacity of the sources or sinks in a region to take care that the large ones are closer to the hub. Thus, for cost-efficient reasons the thicker satellite pipelines needed for the larger CO_2 flows are shorter.

Table 2
Threshold values applied in this study for selecting CO_2 storage reservoirs.

Parameter	Threshold
Capacity	4 Mt CO_2 for gas/oil and 2 Mt CO_2 for aquifers
Thickness reservoir	>10 m
Depth top reservoir	≥800 m
Porosity reservoir (the fraction of void space in the reservoir)	Aquifers: >10%
Permeability reservoir (a measure of the ability of the reservoir to transmit fluids)	Aquifers: an expected permeability of 200mD or more
Thickness seal	≥10 m
Seal composition	salt, anhydrite, shale or claystones
Reservoir composition	Aquifers: sandstones. Hydrocarbon fields: limestone, sandstone, siltstone, carbonates
Initial pressure	Overpressure areas excluded
Salt domes	Relevant for aquifers. Traps located alongside/near salt domes/walls have been excluded because there is a high risk of salt cementation.

2.4. Routing of CO_2 pipelines

In order to estimate the costs of potential CO_2 satellite lines and trunklines[18], it is necessary to include two basic aspects. The first one is that the costs of construction of CO_2 pipelines differ per land-use type. For example, it is more expensive in nature or populated areas than in agricultural areas (Egberts et al., 2003; IEA GHG, 2002). Secondly, placing pipelines in pipeline corridors is favoured because of legal and engineering advantages (Buisleidingenstraat Nederland, 2008; Hendriks et al., 2007). To account for these factors, geographical data on current and future land-use, sea-use, and existing pipeline corridors are included by using four maps. First, we used a map of projected land-use in 2040 published by the Netherlands Environmental Assessment Agency. This GIS maps depicts areas for living, working, agriculture, horticulture, cattle breeding, infrastructure and nature (Kuiper and Bouwman, 2009; MNP, 2007) and is based on the "trend" scenario in which current trends in society are extrapolated. The second map concerns a map of projected use of the Dutch continental shelf in 2050, developed by a joint project of

14 Although it would be better to base the storage potentials on specific ultimate recoverable volumes and depth data per field, these are not publicly available.

15 This index tracks nine key cost areas for both offshore and land-based projects. The CERA-IHS index amounts to 1.67 for the period 2000–2007 and 1.53 for the period 2005–2007 (Offshore Source Magazine, 2007).

16 The solving time of MARKAL-NL-UU ranges from 1 h to 1 day (depending on the variant) Even two alternative sets of regions would increase the solving time of MARKAL-NL-UU in an undesirable way.

17 The costs to transport the CO_2 from individual sources to the hubs in a sink region for a configuration with one large source region is 1–26 M€ per year cheaper than a configuration with two small ones. In the calculation it is assumed that the CO_2 from all sources is captured and transported to a sink region 100–250 km away.

18 Costs will be based on the construction of new pipelines. Re-use of pipelines is not considered in this study, because this would require an in-depth assessment of the existing (natural gas) pipelines, their suitability for CO_2 transport, and an estimation of the time they will be available for CO_2 transport. Furthermore, it is expected that only a few pipelines may be re-used, because most of them will still be needed for gas transport (NOGEPA, 2008).

Table 3
Costs of individual components for underground CO_2 storage[a].

	Unit	Hydrocarbon onshore	Hydrocarbon offshore	Aquifer onshore	Aquifer offshore
Drilling costs	€ per meter	3000	4000	3000	4000
Site development costs[b]	m€	3.0	3.0	24	24
Surface facilities[c]	m€	1.53	15.3	1.53	61.2
Monitoring costs	m€	0.2	0[d]	1.5	1.5
Operating, maintenance, and monitoring costs (O&M&M)[e]	% of investment costs per year	5	5	5	5

[a] The lifetime of the investments are set to a maximum of 25 years. However, many sinks can be filled in a period shorter than 25 years, and for these sinks lifetimes are set accordingly.
[b] Data on the geological structure and reservoir properties of hydrocarbon fields are available, but are scarce for aquifers.
[c] The surface facility costs for offshore aquifers are 4 times higher than those for offshore hydrocarbon fields due to the assumption that no old platforms can be re-used for aquifers.
[d] Data are based on two studies without specific monitoring investments when CO_2 is stored in offshore gas fields.
[e] All fields have the same percentage for O&M&M costs, because according to (TNO, 2007b) higher costs for O&M offshore (IEA GHG, 2005) may be offset by higher costs for monitoring onshore due to stricter health, safety and environmental requirements (Egberts et al., 2005).

several Dutch ministries (IDON, 2005). This map depicts areas for military purposes, sand extraction, pipelines and cables, wind turbine parks, shipping, and nature. The third map deals with existing gas (40 and 60 bar), oil and chemical pipelines published by the Dutch Ministry of Housing, Spatial Planning and the Environment (Speel, 2007). Finally, we used a map with landfall possibilities (locations where onshore and offshore pipelines can be connected) from the Dutch Policy Plan Pipelines (EZ et al., 1984). Even though new locations can be chosen in the future, the government stimulates the usage of existing landfall possibilities (EZ et al., 1984). Currently, four landfall possibilities are pointed out: near Eemshaven, Den Helder, IJmond, and Rotterdam.

2.4.1. Transport investment costs

In this research the investment costs depend on the distance, and therefore, the pipeline trajectory. Determination of this trajectory - the routing - is done using a model in ArcGIS that calculates the least-cost path between two specific points. This model consists of the following steps. First, two terrain factors are assigned to each location (a grid cell of 100 × 100 m) depending on the terrain type and presence of pipeline corridors, respectively. Next, the pipeline investment costs are calculated for each location according to Equation (1). Then, the least costs between one specific point (e.g. the hub in a source region) and all other points on the map is calculated using the algorithm as described in Adriaensen et al. (2003) and ESRI (2007a). Finally, the least-cost path is chosen between two specific points (e.g. between the hub in a source region and the one in a sink region) (ESRI, 2007b). These steps result in the trajectory for the least-cost pipeline and its investment costs.

Thus, by minimising costs certain routes (e.g. through nature and along pipeline corridors) are discouraged and others encouraged (e.g. through agriculture land).

$$I = Ft_{land-use} \times Ft_{corridors} \times C \times D \times L \quad (1)$$

where: I = Investment costs pipeline (€), $Ft_{land-use}$ = Terrain factor for crossing different types of land-use, $Ft_{corridors}$ = Terrain factor for following or deviating from existing pipeline corridors, C = Constant cost factor (1600 $€_{2007}/m^2$) [19], D = Diameter (m) [20], L = Length (m).

In Table 4 the terrain factors used in this study can be found. These values were verified by an expert panel of four pipeline engineers (Pipeline engineers, 2008). The terrain factors were not based on specific literature references, since terrain factors for CO_2 transport in literature do not seem to be supported by robust arguments. For example, the source of the terrain factors used in the DSS tool of the GESTCO project (Egberts et al., 2003) is not mentioned, and in the PH4/6 transmission report of the IEA GHG R&D (2002) the data are based on terrain factors developed for overhead electricity transmission which differ substantially from pipeline infrastructure. The latter terrain factors were also used by the CASTOR project.

Finally, the ArcGIS least-cost routing model results in a list of trajectories and investment costs of all possible source and sink regions pipeline connections. As Table 5 shows two or three[21] pipeline options defined per trajectory, each with a different capacity (i.e. 5, 10, 15, 20, or 25 Mt per year). The choice of capacities depends on the maximum CO_2 capture and storage potential per year for the sink and source regions. Because experience with natural gas pipelines show that pipelines can be used for 40 years, a lifetime of 40 years is assumed for the CO_2 pipelines (Pipeline engineers, 2008).

In the first model runs, some trunklines were chosen that although they connected different regions, they followed for a large part the same trajectory. Because it would be more realistic to build one trunkline that connects several source regions with several sink regions than these parallel trunklines, we also design via-routes trunklines which can be built in stages. Based on the results of the first model runs, four via-routes are selected. The "*via-Limburg*" route connects three source regions (Limburg, Maas and Waal, and Harculo) with the sink regions in the North East of the Netherlands (Twente, Groningen, and Wadden). The "*via-Rijnmond*" route connects the source regions in the West of the Netherlands and Harculo with the sink regions in the North East. The "*via-IJmond*" route connects the source regions in the West with 4 sink regions (North Holland, the offshore, and Wadden). Finally, CO_2 from all CO_2 source regions can be collected at a central *collection point, which is* located offshore in the North of the Netherlands near the island Vlieland (on a junction of multiple existing gas pipelines), and transported via a major trunkline to the Utsira formation.

2.5. Extending MARKAL-NL-UU for the design of a CO_2 infrastructure

The developed ArcGIS/MARKAL interface ensures that MARKAL-NL-UU is extended, so that in a model run, it can be identified which CO_2 infrastructural elements (for storage, capture, and transport) may be constructed and when. First, in MARKAL-NL-UU each sink can be selected (or not) on the basis of its investment and O&M&M costs, availability, potential CO_2 storage capacity, injection rate, and costs for the satellite lines from the region hub to the sink. To accomplish this, each sink is modelled as a separate technology in MARKAL-NL-UU. Secondly, the role of the power sector and CO_2 intensive industry over time, including the role of CCS, can be determined per source region in a model run. Since this depends among others on the age of the existing electricity park in a region, this existing park is specified per region in MARKAL-NL-UU. Furthermore, large-scale future electricity generating technology options are defined per region, so that the model can select in which regions it builds new power plants. Finally, in MARKAL-NL-UU it can be determined which trunklines (including the via-routes) need to be constructed at a certain moment in the analysis period depending on the need for CO_2 transport. Also, the optimal capacity of these trunklines is then chosen based on the amount of CO_2 to be transported. To avoid that the model chooses the cheaper - but in real life impossible option - of building half of a pipeline with a 20 Mt/yr capacity when a pipeline with a 10 Mt/yr capacity is required, trunklines need to be modelled with lumpy investments in MARKAL-NL-UU. This takes care that either a pipeline can be built as a whole in a certain period or not at all. In this case, the solution domain for the pipeline capacity is an integer (e.g. a pipeline can be built once, twice, but not half), and, therefore, the mixed integer programming algorithm[22], a solver for models with integer variables, has to be used (Loulou et al., 2004). In contrast, the usual linear programming algorithm finds solutions in which all variables can take any (non-negative) value.

2.6. Scenario assumptions for MARKAL-NL-UU model runs

The last step in the methodology is running MARKAL-NL-UU to determine the role of CCS and the associated CO_2 infrastructure within the national portfolio of mitigation options for a given year. The scenario inputs that underlie these runs are the following:

[19] Many methods exist to calculate the costs of CO_2 transport (McCollum and Ogden, 2006). We use an adapted version of the formula in Hendriks et al. 2003 (a) which was the basis for the CO_2 transport cost calculations in a Dutch case study (Hendriks et al., 2007). Thus, we can derive the constant cost factor from this case study by subtracting the costs that depend on terrain factors (e.g. for crossing artworks being 17–20% of the total costs) from their Constant cost factor (1900–2000 $€_{2007}/m^2$) which included the costs to cross specific terrains (Hagedoorn, 2007).

[20] The diameter is calculated on the basis of the length and maximum mass flow rate through a trunkline. For one trajectory, two or three pipeline options are defined, each with a different capacity (e.g. 5, 10, 15, 20, or 25 Mt per year).

[21] The selection is limited to two or three capacities per trajectory because of computational constraints.

[22] Mixed integer programming problems require substantially more time and internal memory to solve than pure linear programs (GAMS, 2005). In this study, the CPLEX solver, and a computer with a quad core central processing unit (2.66 GHz each) and an internal memory of 8 Gb are used.

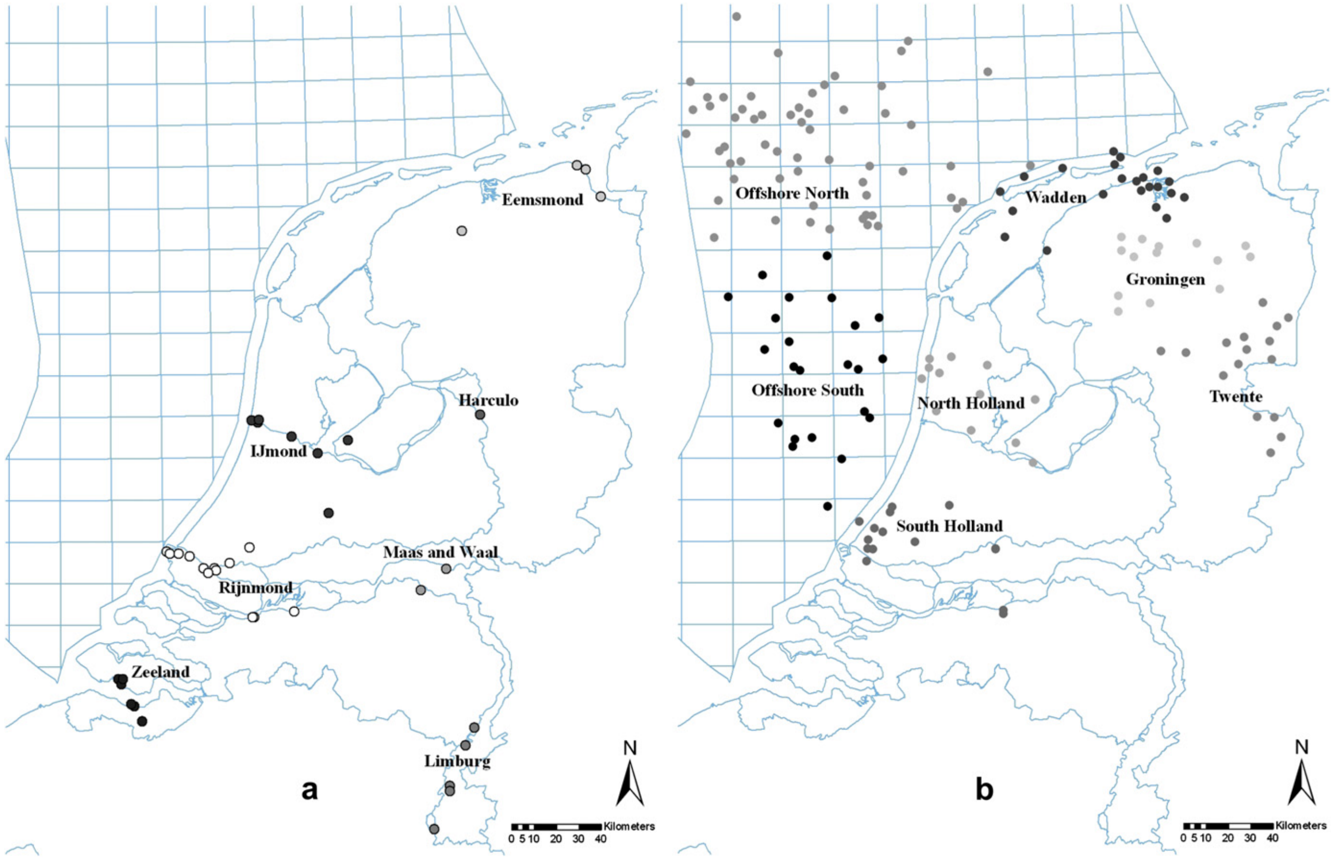

Fig. 2. Source (a) and sink regions (b). Note that the names of the regions are specified in the maps, and all sources and sinks belonging to one region have the same colour.

- The Dutch electricity demand increases from 101 TWh in 2000–175 TWh in 2050. These values are based on the Strong Europe scenario of the Dutch planning agencies (Broek et al., 2008; Janssen et al., 2006).
- In 2020 and in 2050, 20%[23] and 50% less CO_2 is emitted, respectively, in the Dutch CO_2 intensive industry and energy sector compared to 1990 levels.
- The Netherlands changes from an electricity importing country towards a self sufficient electricity producing country in 2020.
- CO_2 streams coming from other countries are not taken into account.
- The share of renewable electricity increases to at least 27% in 2020 and 41% in 2050.
- Nuclear energy phases out.
- The current plans to build two pulverised coal plants in the Rijnmond area (1.8 GW) before 2015 materialise.
- The increase in coal and gas prices up to 2030 is based on the "high growth" scenario in World Energy Outlook by IEA (IEA, 2007). From 2030, we assume that price keep rising at similar rate until 2050[24]. This results in a gas price of 5.5 €/GJ in 2010–11.7 €/GJ in 2050, and a coal price of 2.5 €/GJ in 2010–4 €/GJ in 2050.

2.7. Alternative variants to analyse effects of policy measures and sensitivity analysis

Finally, variants of the base scenario are created to investigate the impact of the availability of storage capacity and various policy measures (i.e. CO_2 targets, or renewable energy policy) on the infrastructure development costs and role of CCS (e.g. exclusion of a certain reservoir type such as CO_2 storage onshore), and to explore the sensitivity of the results to parameters such as the terrain factor, and constant cost factors for pipelines. Besides the *Base case* in which all sinks can be used, two variants with limited storage capacity are explored. In the *Only offshore variant*, it is assumed that CO_2 is only allowed to be stored in offshore sinks (including Utsira) in order to diminish the risk of storage and public opposition to CCS. The *Only offshore – No Utsira variant* is similar to the *Only offshore variant* but excludes the option to store CO_2 in the Norwegian Utsira aquifer. The impact of policy measures is further investigated in the following three variants. First, the *Low renewables variant* is the *Base case* without any renewable electricity targets. In the *R_30/80 variant* CO_2 emissions need to be reduced by 30% and 80% in 2020 and 2050, respectively, compared to the 1990 level. The *R_20/80* is similar to the *R_30/80 variant*, but with a 20% target in 2020. Finally, the variants *CF_1120* and *C_2080* investigate the sensitivity towards a change in the constant cost factor for pipelines: 1120 €/m^2, and 2080 €/m^2, respectively, instead of 1600 €/m^2 in the *Base case*.

[23] The CO_2 reduction target of the Dutch government is 30% less CO_2 emissions in the year 2020 compared to 1990 levels. Several sectors together aim to reduce their emissions of which the electricity sector and industry are part. Hence, the reduction constraints in this study contains a part of the total Dutch emission reduction target.

[24] Although IEA in the Energy Technology Perspectives 2008 report (IEA, 2008b) assumed that prices remain stable after 2030, we consider it plausible that prices increase further due to growing energy demand.

Table 4
Overview of the terrain factors compiled for this study (based on expert opinion).

	Terrain type	factor
$Ft_{land\text{-}use}$	Working/living/horticulture/infrastructure: 'populated'	1.4
	Recreation/agriculture/cattle breeding: 'remote'	1.0
	Rivers and lakes	1.8
	Offshore[a]	0.9
	Nature/wind mill park	10
$Ft_{corridors}$	Following the corridors onshore	1.0
	Following the corridors offshore	0.9
	Deviating from the corridors onshore	1.5
	Deviating from the corridors offshore	1.0

[a] Although, investment costs for offshore pipelines are in general higher than for onshore ones, in the Netherlands due to the complex onshore situation, it appears to be the other way around. Three possible reasons are [Hendriks et al., 2007]:The Dutch soil with a lot of peaty soil complicates the construction of pipelines considerably.Numerous concessions to local authorities and landowners have to be made.The Netherlands is densely populated and has numerous artworks such as waterways and freeways.

Table 5
Examples of modelled trunkline options between hubs in source and sink regions. Length and costs result from the least-routing model.

Source region	Sink region	Length km	Booster station	Investment costs for selected capacities in M€			
				5 Mt/yr	10 Mt/yr	15 Mt/yr	25 Mt/yr
Rijnmond	Twente	194	yes	169		256	311
Rijnmond	Offshore South	104	no	109		152[a]	
Rijnmond	Offshore North	215	yes	187		268	320
Eemsmond	Wadden	70	no	59		92	113
Eemsmond	Groningen	53	no	38		59	73
Limburg	Twente	227	yes	188	244[b]		
Ijmond	Offshore South	69	no	78		105[a]	
Ijmond	Offshore North	167	yes	145		202	238

[a] A trunkline of 20 Mt/yr or more would not be sensible, because even if all sinks in the Offshore South region are used simultaneously less than 15 Mt per year can be injected into these sinks.
[b] A trunkline of more than 10 Mt/yr from Limburg would not be sensible, because even if capture would be applied on all (future) sources in the region, the amount of CO_2 would not exceed 10 Mt per year.

3. Results

3.1. Base case

3.1.1. Development of the electricity generation sector

In the *Base case*, the power generation capacity grows with more than 100% between 2010 and 2050 in order to meet the growing electricity demand and to offset the lower availability of wind and solar capacity. The 50% CO_2 reduction target for 2050 is for a large extent met by the deployment of 8.2 GW of IGCC with CCS and 1.5 GW of PC retrofitted with CO_2 capture (together 20% of the total capacity). Furthermore, due to co-firing of biomass in the coal-fired power plants, biomass energy input will grow to 16% of the primary energy input for electricity generation in 2050. Finally, model results show that onshore wind is cost-effective from the start, and photovoltaic systems (without subsidies) around 2050. To reach the renewable targets of 27% in 2020 and 41% in 2050 renewable electricity, also offshore wind power is being deployed up to 13 GW in 2050. In this reduction scenario in which nuclear power is phased out, CCS contributes on average 26% to the CO_2 reduction in the electricity sector compared to a model run without any CO_2 targets.

3.1.2. CO_2 captured at industry and power plants

Fig. 3 shows the annual amount of CO_2 captured at power plants and industry per region in the Netherlands. A significant amount of CO_2 is transported from the *Rijnmond* region from 2020 onwards. In this region the 1.8 GW of PC capacity built in 2010 is retrofitted with CO_2 capture in 2020, and early opportunities for CO_2 capture at hydrogen, ethylene, and ethylene oxide production facilities are utilised (7.4 Mt per year). In *Zeeland* and in *Limburg*, CO_2 is captured at an ethylene and ammonia factory and transported through the *via-Rijnmond* and *via-Limburg* route. Furthermore, a power plant of 0.3 GW with capture is installed in the *Maas and Waal* region, because it is easy to connect from there to the *via-Limburg* route. Finally, in *IJmond* CO_2 is captured at the steel plant Corus and (part of) a power plant of 0.2 GW. From 2030, large-scale electricity generating capacity with capture is being installed in *Eemsmond* driven by the presence of the onshore gas fields nearby (4.1 GW IGCC-CCS by 2050), and from 2040 also in *IJmond* which is in the vicinity of the offshore fields (2 GW IGCC-CCS). Also in *Rijnmond*, an IGCC-CCS of 1.7 GW is built around 2040. In the end of the analysis period the *Eemsmond*, *Rijnmond* and *IJmond* regions generate all three substantial amounts of CO_2 that needs to be stored (between 10 and 22 Mt per year).

3.1.3. Design of the trunkline infrastructure

Fig. 4 depicts the trajectory and the CO_2 flow rate of the trunklines in the years 2020 and 2050. The flow rate can vary as long as it remains below the chosen trunkline capacity. This chosen capacity depends on the maximum flow rate during the whole period. Consequently, the pipelines are usually underutilised at the beginning. In 2020 the basis for the infrastructure is laid down. There is one direct connection between *IJmond* and *North Holland*. Furthermore, the *via-Rijnmond* route is used to transport the bulk CO_2, with a flow rate of 17 Mt per year from *Zeeland* and *Rijnmond* to the sinks in the *Twente* and *Groningen* regions. Finally, the via-Limburg route is used to transport annually a modest 2 Mt CO_2 captured from the industry in *Limburg* and 2 Mt from a power plant in the *Maas and Waal* region towards the sinks in the *Twente* region. In total 603 km trunkline are constructed of which 283 km for small CO_2 flows from *Limburg, Maas and Waal,* and *Zeeland*. In 2035 the infrastructure slightly changes. Only two direct connections between *Eemsmond* and *Groningen*, and *Eemsmond* and *Wadden* have been added to the pipeline network. By 2050, also the *via-IJmond* route has been constructed making a 15 Mt connection from *Rijmond* and a 5 Mt connection from *IJmond* to the sinks in the *Offshore North* region. Again the flow rate from the *Zeeland*, and *Limburg* only increase slightly as these regions are not in the vicinity of a landfall possibility or onshore sinks.

3.1.4. Trajectories of trunklines and satellite lines

With respect to the trajectories of the trunklines, we find that in general they follow the existing pipeline corridors, except for a few

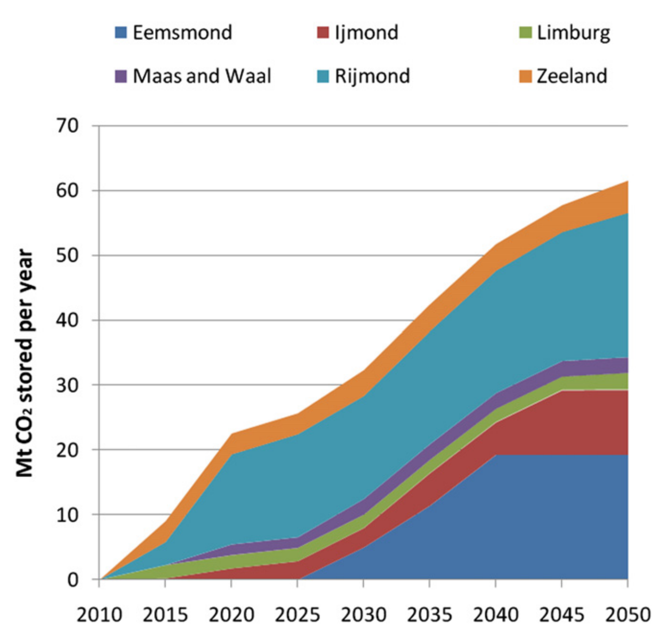

Fig. 3. Annual amount of CO_2 captured at power plants and industry per period per region (*Base case*).

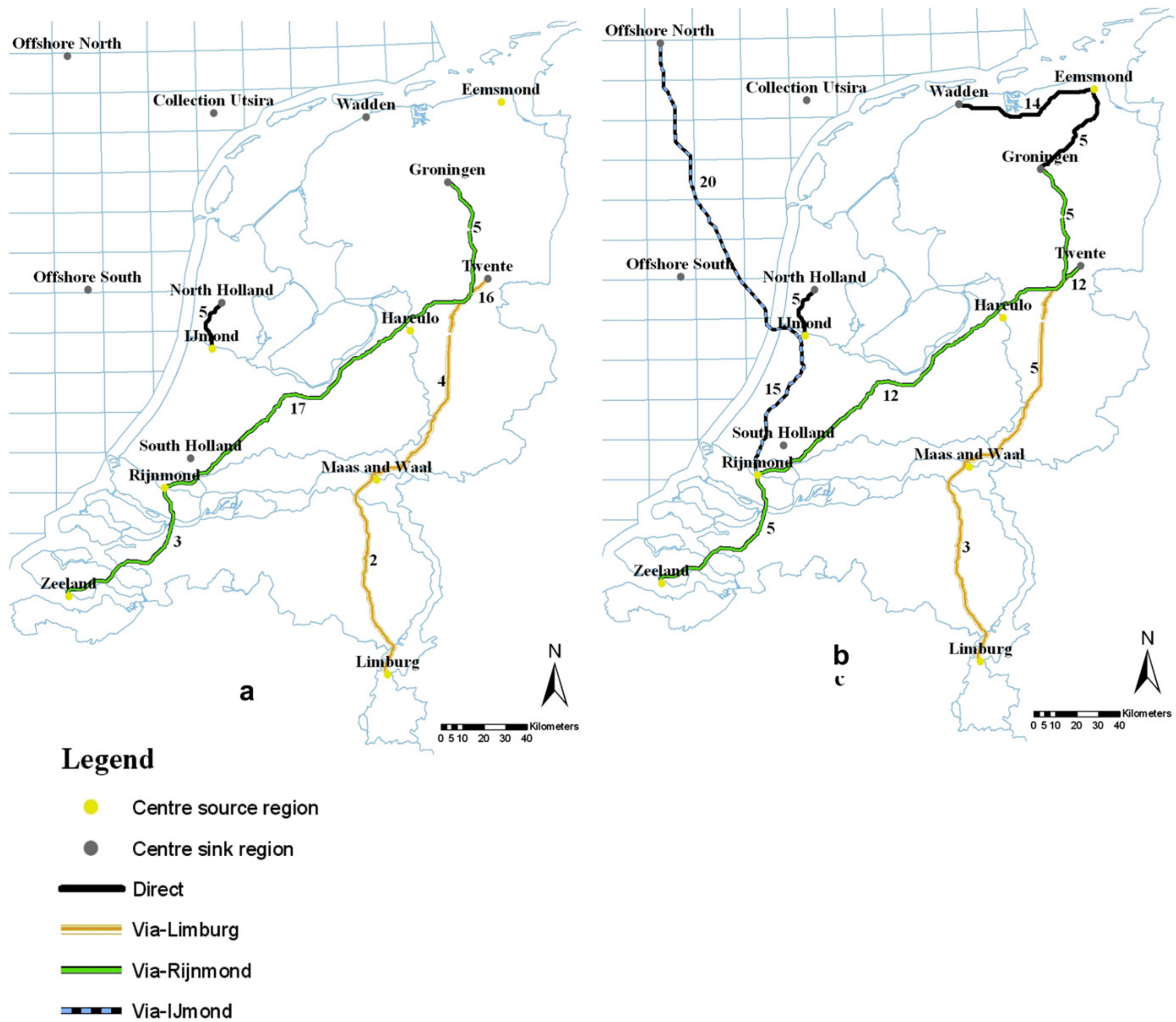

Fig. 4. Trajectories and flow rates (in Mt per year) of trunklines in 2020 (a) and 2050 (b) for the *Base case*.

diversions in case a shortcut turns out to be more cost-effective. In order to illustrate how the routing of the transport network takes into account the projected land use, Fig. 5 shows the trajectories of the satellite pipelines in the *Groningen* sink region. A trunkline delivers CO_2 to the hub in the region from where it can be distributed among 14 potential sinks. However, four of them are not chosen by the model as storage location during the analysis period. The storage activities start in one large field (154 Mt). In 2030 three storage locations are added (between 20 and 73 Mt). In 2040 another two sites of 9 and 10 Mt, and finally in 2050 another 3 small fields are needed. In most cases the size of the storage location, which is a determinant factor for the storage costs (ranging between 1.3 and 9.8 €/t), is more important for the selection of storage sites than the satellite line costs (ranging between 0.4 and 4.8 €/t). Routing through nature (dark green), water (blue) and populated area (red) is preferably avoided as they are assigned with higher terrain factors of respectively 10, 1.8 and 1.4, compared to a terrain factor of 1 for remote areas. The flow rate of the satellite pipelines is in the order of 1–6 Mt/yr and depends fully on the injection rate of the individual sinks.

3.1.5. CO_2 storage over time

Due to a fairly steep increase of CCS deployment in the Netherlands, the amount of CO_2 stored will be around 23 Mt per year in 2020 (see Fig. 7). From 2020 onwards, CCS deployment grows towards 62 Mt/yr in 2050. The cumulative amount of CO_2 captured, transported and stored in 2050 is 1.4 Gt, which is 44% of the Dutch storage capacity.

Fig. 6 shows the geographical location of the sinks and the amount of CO_2 stored in Mt over the analysis period. In total, 10 offshore and 42 onshore sinks out of 172 sinks are selected in the analysis period. Furthermore, only 4 fields with an effective storage capacity smaller than 10 Mt are used. After 2050 more than 1.2 Gt storage capacity is left unused in offshore reservoirs, and 0.6 Gt in onshore reservoirs. The selected sinks have storage costs (including satellite line costs) of less than 8 €/tonne CO_2. However, not all sinks with costs lower than 8 €/tonne have been chosen either because the CO_2 transported to a region could still be stored in other sinks (e.g. in the *Wadden* region) or they are in an area that was too expensive connecting a trunkline to (e.g. *Offshore South*). In

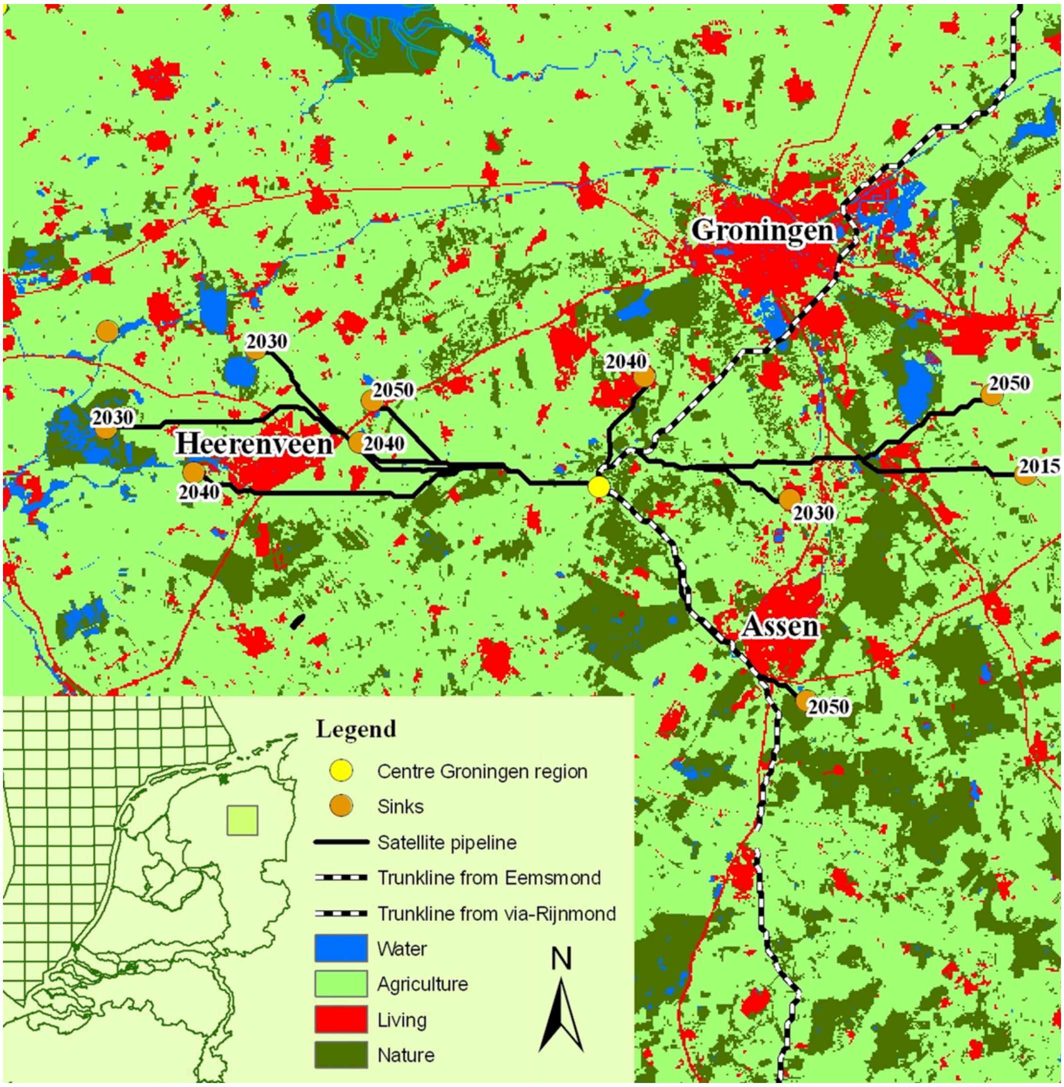

Fig. 5. Trajectories of the satellite pipelines in the Groningen region based on the projected land-use map of MNP. Also the periods in which CO_2 storage at the individual sinks start, are shown. All 10 sinks that are used are depicted with a satellite line to the hub, while the remaining 4 unused sinks (of which 3 are located under the legend) are not.

the *Groningen* region, on the other hand, almost all available sinks will be filled. Offshore sinks are only utilised for storage after 2040 due to higher storage and transport costs and not to sink unavailability[25]: storage costs offshore (including satellite line costs) begin at costs of 3.4 €/t while onshore this is 1.5 €/t.

Not all large fields are used immediately. For example, the stacked gas field Emmen-Zechstein and Emmen-Carboon (see Fig. 6) with a total effective capacity of 92 Mt is used from 2030 onwards, even though it is available for CO_2 storage from the beginning of the analysis period. The seven gas fields in the *Twente* region that are deployed earlier are more cost-effective, because they are even larger (3 out of 7), or because they have higher injectivity rates and/or are located at less depth in the underground (the other 4) compared to Emmen-Zechstein. In this *Base case* with an imposed renewable energy target, no CO_2 is stored in the Utsira aquifer in Norway: the CO_2 storage locations in the Netherlands can cover the CO_2 storage needs against competitive costs.

3.1.6. CO_2 transport and storage costs

In the periods 2015 and 2020, large investments[26] (718 m€) have to take place to build a CO_2 pipeline network in order to meet projected CO_2 transport. Around 2045, a trunkline to the *Offshore North* region is built, which involves an investment of 233 m€. The total investment costs in trunklines between 2010 and 2050 amounts to 1.4 billion euro. The average transport costs for the trunklines are the highest in 2015 (with 6.2 €/t) due to the limited amount of CO_2 that is transported in this period (see Fig. 7), and then decrease rapidly to 2.1 € in 2030. For the remaining of the analysis period, they vary between 1.5 and 2 €/t.

Fig. 7 also shows the annual amount of CO_2 stored. Until 2040 all CO_2 is stored in onshore reservoirs. Around 2040 the share in onshore storage declines, whilst the offshore storage becomes cost-effective. Moreover, Fig. 7 shows that early investments for drilling, site development and surface facilities, and the construction of satellite pipelines in the sink region, are needed around 2015–2020 for the preparation of onshore sinks. Around 2040–2045,

[25] Note that although in practice it may be preferred to start injecting CO_2 shortly after the field stops producing gas or oil, in the current MARKAL-NL-UU sinks can be selected any time after the production of the field.

[26] The transport costs include the costs associated with the trunklines and the satellite lines in the source region. However, the costs for satellite lines in the sink regions are included in the storage costs.

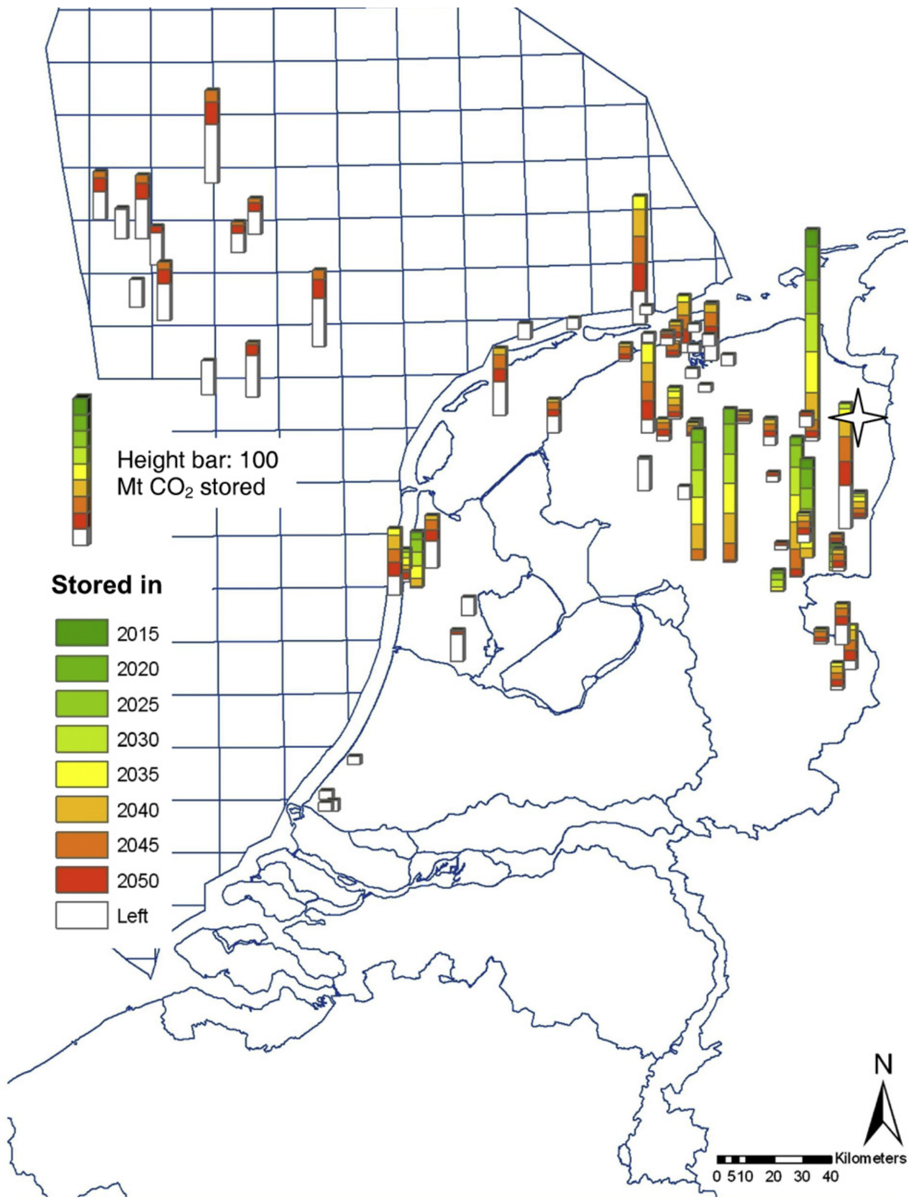

Fig. 6. CO_2 storage over the time period 2015–2050 (*Base case*). Each stacked bar represents a sink. The size and colours relate to respectively the amount and timing of the stored CO_2. A white bar represents the storage capacity that is still available. Note that only the sinks used for storage in the analysis period are depicted. The star indicates the stacked gas field near Emmen.

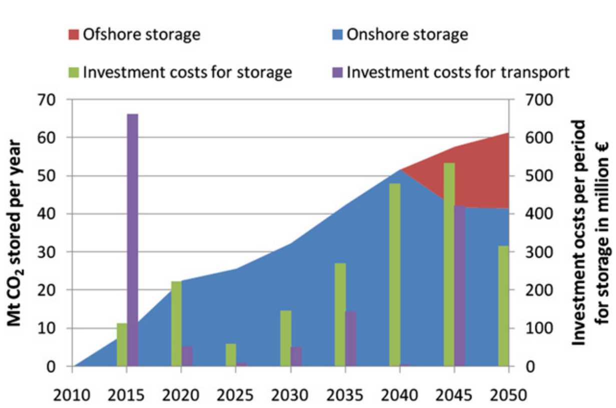

Fig. 7. Annual amount of CO_2 stored and investment costs for transport and storage (including costs for satellite lines) in the period 2010–2050 (*Base case*).

a substantial investment is required for the preparation of offshore sinks. The total investment costs for storage over the analysis period is 2.2 billion €. Furthermore, the average storage costs increase from 1.4 €/t in 2015–3.3 €/t in 2050, because at first CO_2 is stored in large gas fields onshore with low CO_2 storage costs, and later a switch is made to the more expensive smaller and/or offshore gas fields.

3.2. Results of alternative variants and sensitivity to main parameters

The sensitivity of the results towards availability of storage capacity, policy measures, and constant cost factor are presented in this paper[27]. In Table 6 the results of the variants are summarised

[27] The sensitivity towards alternative terrain factors can be found in (Brederode, 2008).

Table 6
CCS deployment and transport and storage costs for different variants.

Variant	Transport costs			Storage costs			CCS deployment			Average contribution of CCS to CO_2 reduction in electricity sector from 2015 to 2050[a]
	€/t CO_2			€/t CO_2			Mt cumulative			
	2020	2035	2050	2020	2035	2050	2020	2035	2050	%
Base	2.7	1.9	1.9	1.7	2.1	3.3	102	555	1363	26
Offshore	3.0	5.3	3.9	4.0	3.0	3.0	99	494	1341	26
Offshore - No Utsira	3.7	2.7	2.1	4.0	4.8	9.4	82	359	917	13
Low renewables	2.1	1.6	3.8	1.9	2.4	1.8	142	732	1670	37
Reduction: 30/80	2.0	1.5	4.5	2.1	2.9	1.8	158	942	2226	45
Reduction: 20/80	2.7	1.6	4.5	1.9	2.7	1.8	120	804	2061	40
Cost factor: 2080	3.4	2.3	2.3	1.8	2.2	3.6	102	555	1363	26
Cost factor: 1120	2.0	1.4	3.1	1.7	2.0	1.4	104	572	1392	27

[a] This refers to the share of CO_2 avoided in the electricity sector by CCS compared to the total amount of CO_2 that need to be mitigated (this total amount is based on a model run without a CO_2 cap).

with respect to the infrastructure (transport and storage) costs, and the cumulative amount of CO_2 stored.

First we highlight a few results per variant. In the *Only Offshore* variant the cumulative amount of CO_2 over the total analysis period is almost equal to the *Base case*. However, the majority of the CO_2 (700 Mt) is stored in the Utsira formation from 2033 onwards (see Fig. 8). The contribution of CCS to CO_2 reduction remains on average 26%, although the transport costs are in some time steps almost three times higher. The low storage costs (being 1 €/t when 40 Mt per year is injected based on the assumptions in this study) in the Utsira formation ensure that CCS remains a competitive option. On the other hand, in the *Only Offshore – No Utsira* variant, the amount of CO_2 stored diminishes by 33% due to limited availability of storage locations. Instead an energy mix with more offshore wind energy is found to be more cost-effective to reach the CO_2 target. In this variant costs of transport plus storage increase substantially (with 72–121%).

In the high reduction variants *R_30/80* and *R_20/80*, the cumulative amount of CO_2 stored is 63% and 51% higher than in the *Base case*, because the total amount of CO_2 that needs to be avoided in these variants is much larger. On the other hand, the transport costs up to 2040 are lower because pipelines are used to the full extent. However, from 2040 onwards, the Dutch storage capacity becomes scarce and a pipeline to Utsira needs to be constructed causing transport costs to be 141% higher than in the *Base case* (from 1.9 to 4.5 €/t).

In the variant without a lower bound for renewable electricity, CCS contributes with 37% to the CO_2 reduction instead of 26% in the *Base case*. In this variant, the share of renewable electricity is 16% in 2020 and 30% in 2050 compared to 27% and 41% in the *Base case*.

In the variant with constant cost factor of 2080 €/m^2 instead of 1600 €/m^2, transport costs increase with more than 23% compared to the *Base case*. In the *CF_1120 variant*, transport costs decrease with over 26% in 2015 and 2035. In this variant, in contrary to the *Base case*, a CO_2 pipeline to the Utsira formation is constructed in 2045 due to the lower CO_2 transport costs. Consequently, in 2050 CO_2 transport costs are higher, but CO_2 storage costs are lower than in the *Base case*. Finally, a change of 30% in the constant cost factor does not have any noticeable effect on the extent of CO_2 reduction by CCS.

Considering the outcome of all variants, we make some observations with respect to costs, necessary pipelines, and contribution of CCS to CO_2 reduction. First costs of the infrastructure vary between 3.4 and 11.5 €/t with 1.4–5.3 €/t for transport and 1.4–9.4 €/t for storage of CO_2. Total investment costs for the infrastructure range from 3.5 to 8.1 billion € during the whole analysis period. The

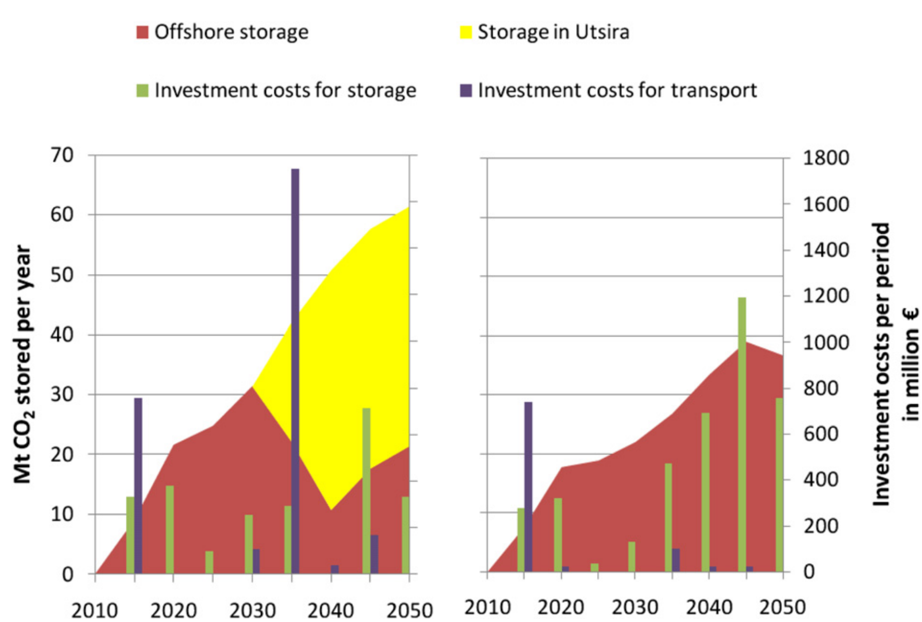

Fig. 8. The annual amount of CO_2 storage and investment costs for transport and storage (including costs for satellite pipelines) in the period 2010–2050 for the *Only offshore variant* (left) and *Only offshore – No Utsira variant* (right).

results also point out that already in 2015, it seems worthwhile to invest in a trunkline from the *Rijnmond* region to either the North East of the Netherlands (with an estimated investment of about 350 m€) or, when no onshore storage is allowed, to the *North Sea offshore* region (for about 330 m€). In the variants two pipeline construction phases are identified: one between 2015 and a second one around 2040. The variants also show that it is cost-effective to over-dimension pipelines in the beginning, so that after 5–10 years the amount of CO_2 transported and stored can increase rapidly. Furthermore, in all variants, trunklines are built to transport the CO_2 from the almost 100%-pure CO_2 streams from sources in Limburg and Zeeland at an early stage. Apparently, since at these sources no major investments are needed for capturing the CO_2, it is worthwhile to invest in these long trunklines to the far off sinks. Additionally, in all onshore variants the *Eemsmond* region is connected to *Groningen* and then to the *Wadden* region, and *IJmond* is connected to the *North Holland* region.

Finally, in many variants (very ambitious reduction targets, limited renewable electricity, or limited storage capacity), the contribution of CCS depends strongly on the availability of the Utsira formation. Without this reservoir, the combined transport and storage costs cannot be kept sufficiently low and the contribution of CCS to the reduction of CO_2 in the electricity sector reduces to 13% on average (compared to 26–45% in variants in which the Utsira formation is available). It is expected that the continuation of CCS deployment after the analysis period (2005–2050) will also depend on whether a very large CO_2 storage reservoir remains or becomes available after 2050 (e.g. the Slochteren field).

4. Discussion

In this section we discuss some of the main limitations of this study. The first point to be highlighted is the choice of the hub-spoke form as starting point for the development of the CO_2 pipeline network. This choice is of importance for two reasons. First, it requires that sources and sinks are clustered into regions with central hubs which are then determining factors in the layout of the infrastructure. However, in the case of CCS, the extent to which sources and sinks could be clustered in completely different way is limited due to the existence of natural clusters of sources and sinks resulting from historical economic or geological factors. The applied modelling approach would, therefore, be harder to apply to other types of transport problems where the locations for supply and demand are completely free to choose or need to be scattered all over the country (e.g. in the case of a hydrogen infrastructure, hydrogen fuelling stations need to be placed at many places). Second, modelling a more complex network with several minor hubs within regions instead of a hub-spoke network could reduce transport costs within regions and thus make a region more attractive. With regard to the second factor, model runs have been done without satellite costs in the North Sea region (Brederode, 2008). The attractiveness of these offshore regions did not seem to change. Furthermore, to take into account the (possible) complexity of the network, this study includes via-routes linking several source regions with several sink regions. Thus, transport costs between regions were reduced by combining several trunklines from several source regions to the same sink region(s) into one trunkline.

Still more insights can be obtained into the design of the infrastructure, when also the following aspects will be addressed:

- In this study we do not include the fact that foreign countries with small CO_2 storage potential like Belgium consider storing their CO_2 in Dutch reservoirs (Wildenborg, 2008). The influence of taking these flows into account is not clear. On the one hand, this additional CO_2 may force up the storage costs as the relative more expensive sinks need to be deployed for CO_2 storage as well. On the other hand, it may lower transport costs from the *Limburg* and *Zeeland* region, because pipelines can be constructed with larger capacities to transport CO_2 from, respectively, Germany and Belgium as well. The pipeline network may thus be designed differently when foreign CO_2 flows must be accommodated by the infrastructure.
- In this research most timing aspects have been taken into account with respect to the availability of sinks and sources. Only the time that a sink remains available after oil or gas production has ceased, was not restricted. However, preferably CO_2 storage should start within 2 years after production in order to avoid abandonment of the field and keep costs of mothballing a platform to a minimum. Taking this aspect into account will probably change the cost-effective design of the CO_2 infrastructure. For example, offshore sinks may be chosen before 2040.
- CO_2 storage potentials of this study were based on the TNO database which is in turn based on publicly available data (TNO, 2007b). However, the storage potential per sink may be either overestimated or underestimated due to lack of sufficient site-specific data (TNO, 2007b). For example, a sink may not be suitable for CO_2 storage due to its performance characteristics (e.g. well integrity, faults, permeability). More detailed data from field operators on the ultimate recovery per field, and site characteristics can improve the quality or change the outcome of this study. Preferably, data should be obtained from local feasibility studies of individual sites. Furthermore, stakeholders may decide to use fields for other purposes such as natural gas storage (Taqa, 2008) or waste water injection from oil production (Drenthe Province, 2007; NAM, 2004). These aspects could diminish or increase the potential storage capacity of the country and hence affect the role of CCS in the mitigation portfolio as was demonstrated in the alternative variants in this paper.
- Taking external safety of CO_2 pipelines explicitly into account may affect the results for two reasons. First, mitigating the risk of a CO_2 pipeline is possible, but would add costs to the pipeline infrastructure (Koornneef et al., 2009). Secondly, it may be necessary to avoid CO_2 pipelines in certain areas. E.g. according to Turner et al. (2006) risk criteria could under certain conditions lead to zoning the land surrounding the pipeline in order to avoid a pipeline closer than 100 m to residential buildings.
- The results are based on the input data in MARKAL-NL-UU and ArcGIS, which are based on the best available knowledge at this moment. However, experience with capture and storage of CO_2 is still limited, and therefore, data on costs and performance can still be improved. Furthermore, prices of equipment and energy are undergoing turbulent changes these days, which makes it hard to have an up-to-date database. Finally, data on CO_2 storage potential and costs need to be assessed further, once more experience is gained with actual CO_2 storage projects.

5. Conclusions

In this paper, we investigated how a CCS infrastructure could be developed within a portfolio of CO_2 mitigation measures to realise a 20% and 50% reduction target in respectively 2020 and 2050 in the electricity and heat generation sector and CO_2 intensive industry compared to the 1990 level. For this purpose, we carried out a quantitative scenario study for the Netherlands with the energy model MARKAL-NL-UU to assess the development of the CCS infrastructure over time, and the geographic information system ArcGIS for its spatial aspects. On the basis of the assumptions in this study, infrastructure consisting of around 600 km of CO_2 trunklines may need to be built before 2020 to reach the CO_2 reduction target of 20% when no additional nuclear power is constructed and the share of renewable electricity is 27% in 2020. Investment costs for the pipeline construction and the storage site development amount to around 720 m€ and 340 m€, respectively. In the variant without renewable energy target, (which results in 16% renewable electricity), an additional investment of 244 m€ in the CO_2 infrastructure is necessary before 2020, especially to prepare more sinks for CO_2 storage (182 m€). Finally, a sensitivity analysis was employed to show the impact of alternative assumptions on the CO_2 infrastructure development. Costs in the different sensitivity variants ranged between 4.0 and 11.5 €/t with 1.5–5.3 €/t for transport and 1.7–9.4 €/t for storage.

Several conclusions which are of importance for stakeholders involved in CCS can be drawn. First, results show that the policy choice to allow the storage of CO_2 onshore or not, is of major importance for the design of the infrastructure. If allowed, a CO_2 transport pipeline from *Rijnmond* to the sinks in the NorthEast of the Netherlands seems a cost-effective option. If not, a trunkline to a mega structure abroad (e.g. the Utsira formation) from around 2030–2035 has to be considered in order to keep CCS costs competitive. Secondly, such a policy decision should be taken as soon as possible because already now preparations should be on the way for constructions of a few large trunklines (planning routes, acquiring permits and licenses) to facilitate the CO_2 storage in the future. For example, it seems worthwhile to already invest around 2015 in a trunkline from the *Rijnmond* region to either the North East of the Netherlands (for around 350 M€) or, when no onshore storage is allowed, to the *North Sea offshore* region (for around 330 M€). Thirdly, the necessary investment decisions need to be underpinned by policy strategies, specific CO_2 reduction targets, and sink evaluations in order to reduce uncertainties with respect to future pipeline use. Although in the variants presented, the average amount of CO_2 stored up to 2025 ranged from 15 to 32 Mt/yr, this may be less (e.g. when CO_2 reduction targets are less strict, nuclear power is considered acceptable, or specific sinks turn out to be unsuitable for CO_2 storage). Fourthly, it should be studied how to take advantage of the early opportunities in *Limburg* and *Zeeland*, which are further away from potential sinks. Although the model results show that it could be cost-effective to construct long pipelines from these locations, other solutions such as storage in the nearby coal seams may also be considered. Alternatively, additional CO_2 flows from Belgium or Germany can make these pipelines more worthwhile to invest in. Finally, although currently capture costs make up the major share in the total CCS costs, storage can become the restricting factor for the cost-effectiveness of CCS in the medium term (2035–2045) if cheap storage locations are filled or not available. It is recommended to seek ways to reduce these costs. For example, by making optimal use of existing wells and platforms, by integrating sinks into one storage facility, and additional search for large aquifers.

With regard to the methodology developed for this study, the results show that an ArcGIS/MARKAL-based toolbox can provide additional insights into the development of a CCS infrastructure. This approach can deliver concrete blueprints over time with respect to scale, possible pipeline trajectories, and deployment of individual storage sites. It can also demonstrate how different policy choices lead to other designs of a cost-effective CCS infrastructure. This toolbox could, therefore, be used to support policy makers and companies in their decisions on CCS-related issues. Consequences of measures, such as the use of a pipeline for CO_2 transport in the Rotterdam region, the construction of capture ready power plants at specific locations can be evaluated with this toolbox.

Further research is required as this study has a number of caveats. The international context of CO_2 transport (e.g. CO_2 flows through or into the Netherlands), specific timeslots when sinks are available, CO_2 from small installations, possibilities to re-use wells and pipelines, and site-specific geological data, were missing. Finally, taking the hub-spoke network as basis imposes limitations to the structure of the network.

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