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

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

[a] Group Science, Technology and Society, Copernicus Institute for Sustainable Development and Innovation, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[b] TNO Built Environment and Geosciences, Princetonlaan 6, 3508 TA Utrecht, The Netherlands

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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

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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.

* Corresponding author. Tel.: +31 30 2532216.
E-mail address: m.a.vandenbroek@uu.nl (M. van den Broek).

[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

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[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.