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DOI
10.7148/2016-0439

Publication date
2016

Document Version
Final published version

Published in
Proceedings - 30th European Conference on Modelling and Simulation, ECMS 2016

http://dx.doi.org/10.7148/2016-0439

A SUPPLY CHAIN OPTIMIZATION FRAMEWORK FOR CO_2 EMISSION REDUCTION: CASE OF THE NETHERLANDS

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KEYWORDS

Carbon Capture, CO_2 reduction, CCS, Optimization, Supply Chain, Mathematical Model.

ABSTRACT

A major challenge for the industrial deployment of a CO_2 emission reduction methodology is to reduce the overall cost and the integration of all the nodes in the supply chain for CO_2 emission reduction. In this work, we develop a mixed integer linear optimization model that selects appropriate sources, capture process, transportation network and CO_2 storage sites and optimize for a minimum overall cost. Initially, we screen the sources and storage options available in the Netherlands at different levels of detail (locations and industrial activities) and present the network of major sources and storage sites at the more detailed level. Results for a case study estimate the overall optimized cost to be €47.8 billion for 25 years of operation and 54 Mtpa reduction of CO_2 emissions (30% of the 2013 levels). This work also identifies the preferred technologies for the CO_2 capture and we discuss the reasons behind it. The foremost outcome of this case study is that capture and compression consumes the majority of the costs and that further optimization or introduction of new efficient technologies for capture can cause a major reduction in the overall costs.

INTRODUCTION

The increasing CO_2 concentration in the atmosphere is directly related to the increase in CO_2 emissions from burning and consumption of fossil fuels, leading to global warming, which is an issue of a great concern today (IPCC 2007). The concentration of CO_2 (396 ppmv) in the atmosphere in 2013 is roughly 40% higher than it was before the industrial revolution, with a growth of approximately 2 ppmv/year in the last ten years (IEA, 2014) and the emission in 2013 is about 56% higher than in 1990. In the Netherlands, the high court has ordered the government to have the emissions cut by at least 20% of the 1990 levels within five years from 2015. The targets for CO_2 reduction by 2030, according to the reports from the Environmental Assessment Agency of the Netherlands and the EU policy, are set at 40% of the 1990 levels, showing a strong commitment to reduce anthropogenic CO_2 emissions.

In the Netherlands, out of the CO_2 emissions totaling 180 Mtpa, which were almost constant over the past few years, approximately 109 Mtpa of CO_2 is emitted by stationary sources from the energy and manufacturing sector (equal to approximately 60% of the total emissions). Efficient use of energy, use of alternative fuels and energy sources, and applying geo-engineering approaches (afforestation and reforestation) can all lead to reduction of CO_2 emissions to the atmosphere (Dennis et al. 2014), but CO_2 capture, transport and sequestration/storage (CCS) has been considered as an important strategy for bulk mitigation of CO_2. According to the International Energy Agency's roadmap, 20% of the total CO_2 emissions should be removed by CCS by year 2050 (Zaman and Lee 2013). The stationary sources provide us with an easier opportunity for bulk reduction in CO_2 emissions nationwide.

The CCS process involves the capture and separation of CO_2 in bulk (from either stack gas or other intermediate gas streams) and then isolating it from the atmosphere through geological sequestration. The nodes of the CCS supply chain problem are the CO_2 source(s), capture process(es), transportation via pipeline(s) and the geological storage sites. A major challenge for the industrial deployment of a CO_2 reduction methodology is to reduce the overall cost and the integration of all nodes of the CO_2 reduction system (Hasan et al. 2014).

In this work, we design a network consisting of sources, a capture system (technologies and materials) and the storage sites to be transported to for the Netherlands. We design the network such that the overall costs for 25 years of operation and 54 Mtpa (30% of the 2013 levels) reduction of CO_2 is minimized. We will also evaluate what the preferred post combustion technologies are. Initially, we develop a Mixed-Integer Linear Optimization (MILP) model for the reduction of CO_2 emissions through CCS. The model is represented a set of constraints and an objective function. Later, for the case study, we first screen the sources at different levels of detail (both for locations and industrial activities) and investigate how the level of detail affects the overall costs in order to select the appropriate required level of detailing. Then, we group the clusters of storage options available in the

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Netherlands according to the geographical locations to present the network of major sources and storage sites. Having established the supply chain structure, we use the model for minimizing the overall costs in order to find the optimal network connecting sources and storage sites. Finally, we discuss the results and the outcomes obtained and the reasoning behind it.

PROBLEM STATEMENT

The whole network consisting of CO_2 sources, capturing CO_2 from the sources with the technologies and materials available, and transporting it to the storage sites can be viewed as a supply chain network problem (Hasan et al. 2014). Sources can be seen as the suppliers of CO_2, and capacity restrictions for each storage site can be related to the demands of each site which are satisfied by transporting the CO_2 from the capture plant to the storage sites through a pipeline. Basically, the supply chain consists of sources, plants with capture technology and materials and geological storage sites (see Fig. 1). In this work, we have considered that the capture plants are located in the source site to avoid transport of flue gases.

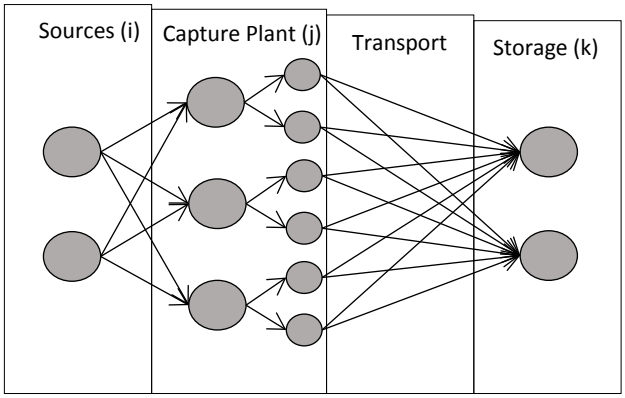

Figure 1 Carbon Capture and Storage Scheme

The problem statement is as follows:

Given:

1. Sources: type & location, yearly CO_2 emissions and compositions
2. CO_2 capture and compression technologies: materials and costs
3. Transportation: distance and quantity to be transported, transportation mode and costs
4. Sequestration/storage: type, location, storage capacity, injection costs and storage limit
5. CO_2 reduction target

Determine:

1. Source and the quantity to be captured
2. Technology and material combination to be used for the CO_2 capture of each selected source
3. Sequestration/storage sites to be used and quantity to be stored in each site
4. Network topology to capture, transport & store CO_2

The objective of the model is to minimize the overall CCS network costs, leading to an optimized structure.

CCS SUPPLY CHAIN NETWORK MODEL DEVELOPMENT

We setup a Mixed-Integer Linear Program (MILP) model to solve the supply chain problem presented in the previous section.

Basic Modelling Assumptions

- The source and capture plants are considered to be in the same and fixed location to avoid transportation of flue gases.
- One to one coupling of source and capture nodes. This means, it is assumed that one source node can be connected to only one capture node and one capture node can receive from only one source node.
- No alternative competing mode of transport to pipeline transport is considered.
- A source node can be connected to only one storage node, but a storage node can receive from multiple source nodes.
- Profit functions such as utilization, carbon tax, etc. are not considered.
- Network structure remains constant throughout the chosen time horizon of 25 years.

MINIMIZE

$$C = \sum_{i,j,k} (CC_{i,j,k} + TC_{i,j,k} + SC_{i,j,k}) \quad (1)$$

s.t.

$$\sum_{j,k} X_{i,j,k} \leq 1 \qquad \forall\ i \in I \quad (2)$$

$$\sum_{i,j} CS_i * FR_{i,j,k} \leq \frac{CU_k^{max}}{Yrs} \qquad \forall\ k \in K \quad (3)$$

$$\sum_{i,j,k} CS_i * FR_{i,j,k} \geq 54 \quad (4)$$

$$FR_{i,j,k} \leq 0.9 * X_{i,j,k} \qquad \forall\ (i,j,k) \in (I,J,K) \quad (5)$$

Eq. 1 shows the objective *C*, overall costs, as a sum of capture and compression costs ($CC_{i,j,k}$), transportation costs ($TC_{i,j,k}$) and storage costs ($SC_{i,j,k}$). $X_{i,j,k}$ is a binary decision variable that selects a source *'i'* and only one suitable technology-material combination *'j'* and a storage site *'k'* per source and Eq. 2 is a constraint to facilitate this. CS_i is the total emissions from source *'i'* and $FR_{i,j,k}$ is 0-1 continuous variable that gives the fraction of CO_2 that is going to be captured from source *'i'*. Eq. 3 ensures that the maximum storage limit of each storage site *'k'* (CU_k^{max}) is not exceeded. *'Yrs'* appearing in the Eq. 3 means the number of years of operation (25 years in our case). Eq. 4 checks if the minimum targeted CO_2 reduction of 54 Mtpa (30% of the 2013 levels) is achieved. Eq. 5 is a constraint, which makes sure that if a source is selected, no more than 90% is captured from that source. The additional computational benefit is avoidance of the

Proceedings 30th European Conference on Modelling and Simulation ©ECMS Thorsten Claus, Frank Herrmann, Michael Manitz, Oliver Rose (Editors)
ISBN: 978-0-9932440-2-5 / ISBN: 978-0-9932440-3-2 (CD)

multiplication of variables $FR_{i,j,k}$ and $X_{i,j,k}$ and thereby linearizing the model reported by Hasan et al. (2014). Before going into the details of costs of capture and compression, we need to decide on the technologies and materials to be considered. The four leading capture and compression technologies selected based on maturity and Total Readiness Level are Absorption, Pressure Swing Adsorption (PSA), Vacuum Swing Adsorption (VSA) and Membrane separation (Abanades et al. 2015; Hasan et al. 2014; Zaman and Lee 2013).

$$CC_{i,j,k} = \left(IC_{i,j,k} + OC_{i,j,k} + DC_{i,j,k}\right) * Yrs \qquad (6)$$

Eq. 6 shows capture and compression costs as a sum of Investment costs ($IC_{i,j,k}$), Operating costs ($OC_{i,j,k}$) and the flue gas Dehydration costs ($DC_{i,j,k}$). Optimizing the capture and compression costs, which depends on flue gas composition and flow rate, is an important step towards reducing the total cost and there have been various efforts to optimize the overall and individual processes. Hasan et al. in their work have optimized various capture and compression technologies and materials and reported the costs for the leading technologies and material combinations in terms of CO_2 composition (X_{CO2}) and flue gas flow rates (F_i in mol/s) (Hasan et al. 2012a; Hasan et al. 2012b; Hasan et al. 2014). The basic assumptions considered in their cost model are that the technology-material combination is able to capture at least 90% of CO_2 from the flue gas with the least product purity of 90% CO_2 at 150 bar pressure of CO_2 product.

$$IC_{i,j,k}\left(\frac{€}{yr}\right) = \alpha * X_{i,j,k} + \left(\beta x_{CO_2}^{n} + \gamma\right)F_i^{m} * \left(m_{11}FR_{i,j,k} + m_{12}X_{i,j,k}\right) \qquad (7)$$

$$OC_{i,j,k}\left(\frac{€}{yr}\right) = \alpha_o * X_{i,j,k} + \left(\beta_o x_{CO_2}^{n_o} + \gamma_o\right)F_i^{m_o} * \left(m_{21}FR_{i,j,k} + m_{22}X_{i,j,k}\right) \qquad (8)$$

Eq. 7 and 8 shows the linearized version for the investment and operating costs per year presented by Hasan et al. (2012; 2014) and the cost model's assumptions and basis can be found in their work. Their model mainly becomes non-linear because of the exponent in $FR_{i,j,k}$. For each of the 13 technology/material combinations considered, the costs are linearized with less than 5% overall relative error compared to the original model. Linearization also allows the model to choose the $FR_{i,j,k}$ freely, rather than assuming it constant as was done by Hasan et al. (2014). The flue gas dehydration costs contribute 9.28 €/tCO_2 captured uniformly. Fig. 2 shows the capture and compression costs as a function of the composition of CO_2 in the flue gas, for a constant flue gas flow rate of 10 kmol/s and $FR_{i,j,k}$ = 0.9. The figure is very similar to that provided by Hasan et al. (2014). It can be clearly seen that absorption is preferred for cases with a very low CO_2 composition in the flue gas, whereas adsorption is preferred for cases with higher compositions. This also shows that the applied linearization does not significantly change the costs of the various material-technology combinations and provides results almost the same as that by the original model presented by Hasan et al. (2014).

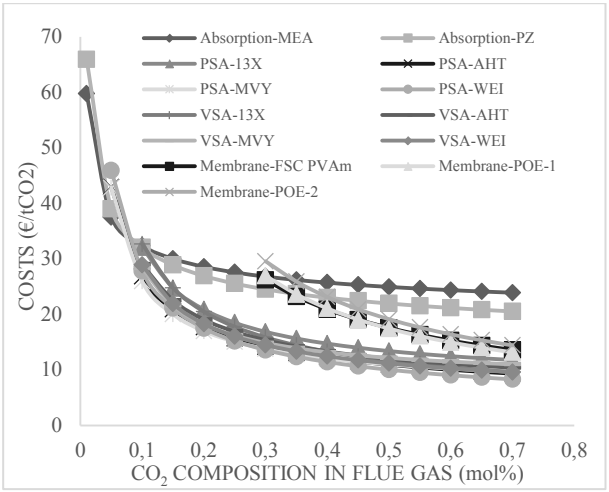

Figure 2 Capture and compression costs for different technology material combinations (Flue gas flow rate = 10 kmol/s)

Modeling of the transportation node(s) also received attention. The review by Knoope et al. (2013) gives a good overview of all the available models. In our work, we use the model presented by Serpa et al. (2011), as it provides us with a linear model and also cost as a function of the quantity transported. We consider a terrain factor, F_T of 1.2, (which can also be taken as a correction factor for distances) and we also add 16 kms to the distance ($D_{i,k}$) for access to a suitable injection site within storage formation (Dahowski et al. 2004). Eq. 9 shows the function for the transport cost that we use in this model. The yearly operation and maintenance costs (OM_t) of transportation are taken as 4% of the investment costs. There are also no distinction made between transportation costs in land and sea.

$$TC_{i,j,k} = Investment + Operating\ Cost = \left[\left(\alpha_t * CS_i FR_{i,j,k} + \beta_t * X_{i,j,k}\right) * F_T * \left(D_{i,k} + 16\right)\right] + OM_t * Investment\ cost * Yrs \qquad (9)$$

For the storage and injection costs, Jansen et al. (2011) give an average investment (I_{well}) and operating costs (OM_{well}) per well and to calculate the number of wells, we use a parameter maximum injection capacity per well (IC^{max}) given by Hasan et al. (2014). Although the well construction, operation and maintenance depend on the type of the storage site and individual well characteristics (like depth, location – offshore & onshore etc.), we assume it to be a constant for the simplicity of the model itself. Eq. 10 shows the storage and injection cost that we use in our model.

$$SC_{i,j,k} = Investment + Operating\ Cost = \left(I_{well} + Yrs * OM_{well}\right)\left(\frac{CS_i FR_{i,j,k}}{IC^{max}}\right) \qquad (10)$$

CASE STUDY

Data analysis and interpretation

Sources

Data for the CO_2 sources are obtained from the Netherlands Government's Pollutant Release and Transfer Register database and the "Centraal Bureau voor de Statistiek" for the year 2013. The database divides sources with different levels of detailing, according to their location (Total, Province level, Community (municipality) level and Individual location) and industrial activities (Sector level, Sub-Sector level, and Individual Activity level). Initially, to analyze the data, Province – Subsector combination was taken as the others are either less detailed or too detailed. In the total emissions of 180 Mtpa, 242 large stationary sources (leaving out emissions from educational institutions, recreation clubs, etc.) account for ~109 Mtpa, approximately 60% of the total emissions. Out of those 242 sources, the top 35 sources (all ≥ 0.5 Mtpa) account for ~98 Mtpa. We decided to go into different levels of detailing with the same criteria and consider sources only above 0.5 Mtpa emissions.

Four different combinations are considered:
- Province – Sub-Sector
- Province – Individual Activity
- Community – Sub-Sector
- Community – Individual Activity

Obviously, the number of sources and the total emissions are bound to vary when we go into various levels of detail (see Fig. 3) It can be seen that the number of sources are almost constant around 34 and this may be related to the fact that when going into more detail the larger sources getting split into two or more parts. The emissions decrease initially, as expected, and become almost constant at the community level.

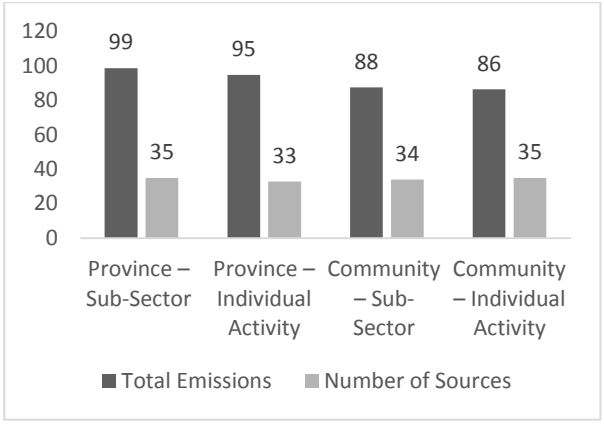

Figure 3 Total Emissions (Mtpa) and Number of sources in each level of detail

Typical CO_2 compositions of flue gas are used for various sources. Fig. 4 shows the composition distribution for the sources at the community-individual activity level. Most of the sources lie in the composition range of 7% and 20%. Only 3 of the 35 sources have a CO_2 composition above 20%. The flue gas composition plays a major role in the capture costs of CO_2 – the lower the CO_2 composition in the flue gas, the higher the costs.

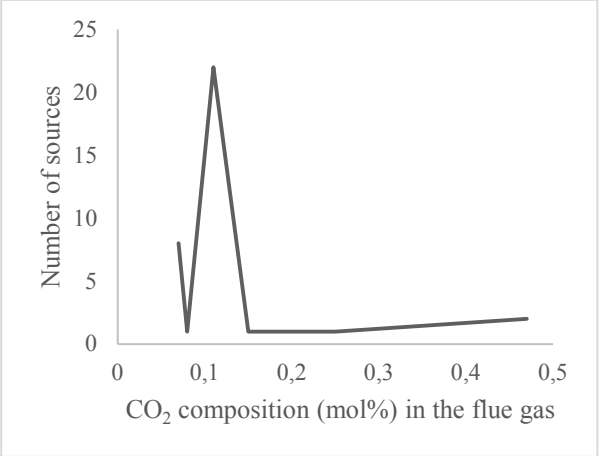

Figure 4 The composition distribution of various sources at the Community-Individual activity level

Fig. 5 shows the objective (total costs for CCS) for different levels of detail. The higher the level of detail, the higher the costs are, as anticipated. It can be noted that the cost becomes almost constant with less than 1% change between the Community-Subsector level and the Community-Individual Activity level. This also shows that going into further detail than the Community-Individual Activity level is not necessary, as there is no noticeable change in the objective.

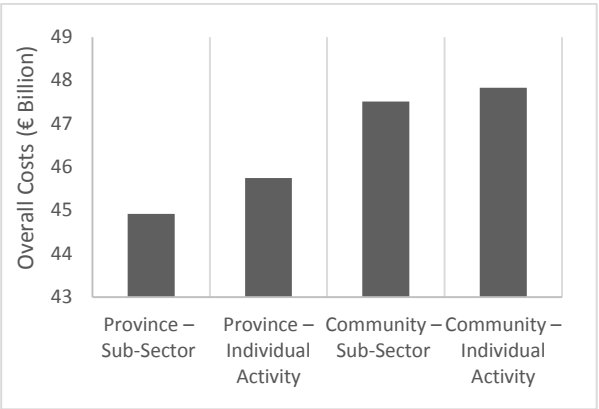

Figure 5 Total costs as a function of the level of detail. clearly showing that the costs become constant at the community - activity level.

Further case & optimization study is evaluated with the data at the level of Community-Individual activity. Fig. 6 shows the location of the sources spread across the Netherlands. It can be clearly seen that the major emitters of CO_2 are located in the western and south-western part of the Netherlands.

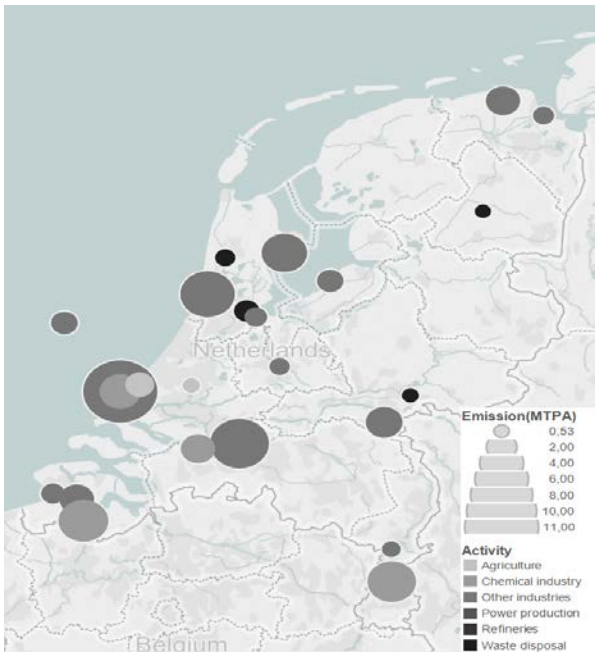

Figure 6. Netherlands map locating the top 35 stationary sources

Storage sites

The storage data were obtained from DHV and TNO (2009), Ramirez et al. (2010), Damen et al. (2009) and Neele et al. (2013). Although there are several hundreds of individual storage sites, the geographical location of the storage sites represented in the above publications on the map of the Netherlands (clusters of storage sites) were grouped manually to reduce the overall problem size to 47 cluster groups, out of which 31 are oil & gas groups, 12 are saline aquifer groups and 4 are groups of coal seams. The storage capacity for each group is estimated on the basis of the known total capacity of each type of storage in the Netherlands. Storage estimation of 47 groups summed to approximately 11 Gt. Out of the 47 storage groups, the top 15 groups contributed to more than 10 Gt of storage and for the ease of implementation, only these 15 storage sites were considered for the case study. Of the 15 storage sites chosen, 11 are oil & gas sites, 3 are saline aquifers and 1 of them is an un-mineable coal seam.

Fig. 7 indicates the geographical location of the grouped storage sites on the map of the Netherlands, where each circle represents the center of the group and size of the circle represents the capacity of the storage. The figure shows that most of the large storage groups are in the north and north-eastern part of the Netherlands. The Groningen site (the biggest circle in Fig. 7) contributes to 7.35 Gt of storage possibility. An important assumption is that all these storage sites are free, ready and available for CO_2 storage and the CO_2 injection platform is going to be built from scratch. Also no costs related to delay by public protests for injection in these storage clusters are assumed.

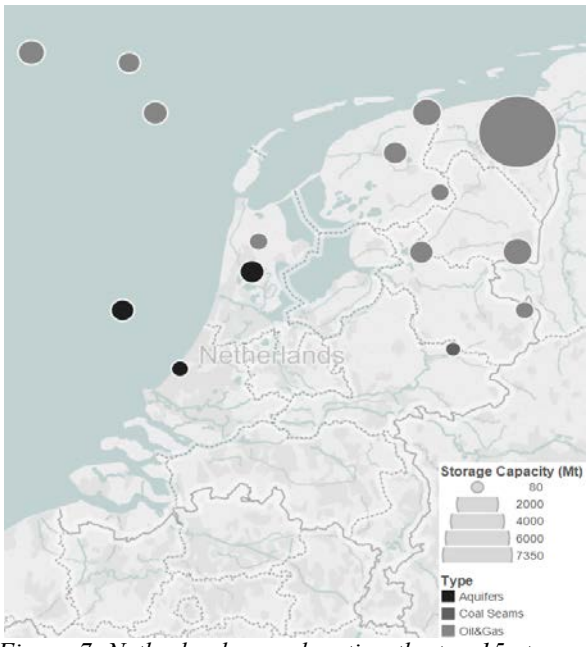

Figure 7. Netherlands map locating the top 15 storage site

Results and discussion

As discussed in the previous section, we consider 35 sources, 13 technology-material combinations for capture & compression and 15 grouped storage sites to inject CO_2. So, the total number of discrete variables are 6825 (35 × 13 × 15). Thus an enormous reduction in the number of sources and storage sites has helped decreasing the size in the model, which also helps in the interpretation of the results. The presented Supply Chain optimization model was used to optimize the costs of the capture of 54 Mtpa of CO_2 and storage for 25 years. A summary of the resulting minimized costs can be found in Table 1.

Table 1 Overall costs and cost per ton basis for the optimal CCS network in the Netherlands

	Overall Costs (€Billion)	Cost (€/tCO_2/yr)
Total Expenditure	47.83	35.43
FG Dehydration Costs	12.53	9.28
Capture and compression	30.70	22.74
Sequestration	2.7	2
Transport	1.9	1.42

While, dehydration, storage and transportation add to the total costs, the costs of capture and compression, as expected, is the major contributor. Although we used different cost functions for storage/injection and transportation costs, the cost proportions are very similar to the ones obtained in Hasan et al. (2014). The

total costs for 25 years of operation of CCS is estimated at €47.8 billion and €35.43 per year per ton of CO_2 captured. The storage or injection costs just accounts for 2 €/ton whereas the transportation costs accounts for only 1.42 €/ton. The pipeline costs are often underestimated as the majority of the models reported in the literature keep the cost of natural gas pipelines constructed before 10 – 15 years as the basis, whereas the CO_2 pipelines generally operate at higher pressures (Knoope et al. 2013). The storage costs may also be underrated, but even if the storage costs are 3 or 4 times more, the capture and compression costs with 22.74 €/ton will still remain the largest among all the costs for CO_2 emission reduction. Thus, the main takeaway finding is that the capture processes cause the major lump of expenses and further optimization or invention of new technologies at much lower costs for capture can cause a major change in the overall costs. The optimized network is shown in Fig. 8. The thinner end shows the source and the thicker end shows the storage site and thickness is also proportional to the quantity captured, transported and injected in each storage site. For the optimal design, 18 sources and 9 storage sites are selected by the model. Out of the selected 9 storage sites, 5 storage sites are oil & gas sites, 3 are saline aquifers and 1 of them is an un-mineable coal seam.

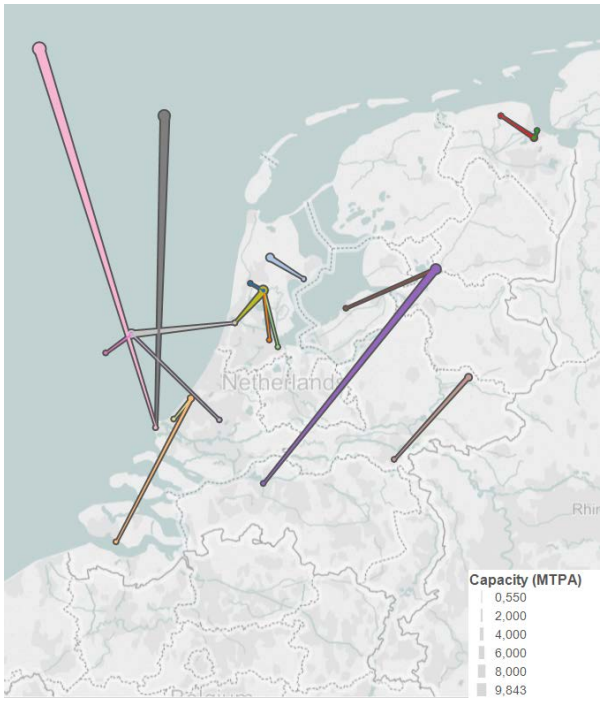

Figure 8 Optimal network for Carbon Capture and Sequestration for the Netherlands

Fig. 9 shows the storage occupancy of each of the storage groups and it can be clearly seen that there still exists more than 85% of the CO_2 storage capacity even after 25 years of operation to reduce 54 Mtpa. The biggest storage site of all, the Groningen gas field (storage site 9 in the Fig. 9), still has almost 100% storage capacity left. To start with, it maybe because of the straightforward linear relation for costs which doesn't take into account the scale effect of the storage. Furthermore, it is because of the fact that most of the sources selected are from the western or south western part of the Netherlands, whereas the Groningen site is in the Northeastern part of the Netherlands and the transportation cost is comparable to the storage cost.

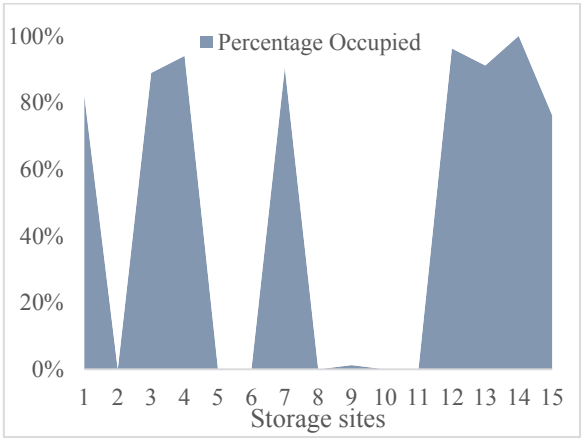

Figure 9 The storage occupancy after the 25 years of optimal operation

In the technology aspect, only 3 out of the 13 technology-material combinations are chosen - 17 of the 18 selected sources use pressure swing adsorption and only 1 use absorption (Fig. 10). In the material feature, MVY (a type of zeolite) based adsorption is strongly preferred over the WEI (another type of zeolite) based one (15 times to two times). In absorption, piperazine (PZ) is preferred over Mono Ethanol Amine (MEA). This shows that the heuristic choice of MEA absorption or absorption in general may not always be the most cost-effective one. Songolzadeh et al. (2014) also found that adsorption is the most preferred post-combustion capture technology at higher feed gas pressures and they also state that adsorption can have a much lower energy consumption and cost for the capture of CO_2. Another reason why adsorption is the most often selected technology in the optimization, is that 17 of the 18 selected sources have a medium to high CO_2 compositions in the feed flue gases (>10%). Absorption is preferred when the concentrations are below 8% at higher flue gas flow rates. This shows that the costs and the selection of the technology depend both on composition and flow rate.

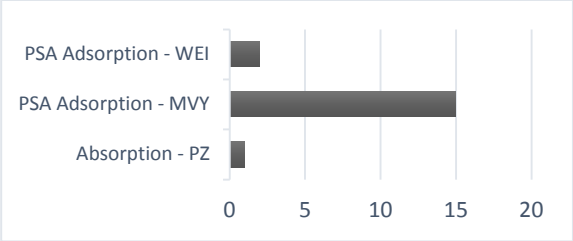

Figure 10 The most preferred technology-material combinations.

CONCLUSIONS & RECOMMENDATIONS

An MILP model is developed and applied to synthesize a national CCS network by optimizing the total costs of this network. Appropriate sources, capture processes, transportation connections and CO_2 storage sites were selected. The MILP model has a linearized relation for the estimation of capture and compression costs. This linearization allows the model to choose the fraction captured from each source instead of assuming it to be a constant. We analyzed different data sets with different detailing for the sources in the Netherlands and came up with a definitive data set, by checking the variation in the objective function, to carry out the case study. The optimal cost achieved by considering the most mature technologies close to commercialization and using an efficient network design, was found to be €47.8 billion for 54 Mtpa of CO_2 reduction in the Netherlands for 25 years of operation. Pressure Swing Adsorption (PSA) was significantly preferred over the heuristic choice of absorption and the difference in costs were also noted to be considerable. It was also concluded that, even after the 25 years of operation, there is still more than 85% of the total storage capacity left across the Netherlands for CO_2 injection. Although the estimate for storage and transportation costs may not be very accurate, a clear conclusion from the relative contribution to the costs is that the capture & compression cost is the major contributor to the total costs. It is therefore recommended to further optimize existing technologies or develop new technologies with much lower capture costs to cause a further major reduction in the overall costs.

REFERENCES

Abanades, J.C.; B. Arias; A. Lyngfelt; T. Mattisson; D.E. Wiley; H. Li; M.T. Ho; E. Mangano; S. Brandani. Emerging CO_2 capture systems, *International Journal of Greenhouse Gas Control 40 (2015) 126–166*

Centraal bureau voor de Statistiek, Netherlands

Dahowski, R.T.; Dooley, J.J.; Davidson, C.L.; Bachu, S.; Gupta, N., 2004. A CO_2 storage supply curve for North America. *PNWD-3471, 1–92*.

Damen, K.; Andre´ Faaij; Wim Turkenburg. Pathways towards large-scale implementation of CO_2 capture and storage: A case study for the Netherlands, *International Greenhouse gas Control 3 (2009), 217-236*

Dennis, Y. C. Leung; Caramanna, G.; M. Mercedes Maroto-Valer. An overview of current status of carbon-di-oxide capture and storage technologies, *Renewable and Sustainable Energy Reviews, 39 (2014) 426–443*

Hasan, M. M. F.; Baliban, R. C.; Elia, J. A.; Floudas, C. A., Modeling, simulation, and optimization of postcombustion CO_2 capture for variable feed concentration and flow rate. 1. Chemical absorption and membrane processes. *Ind. Eng. Chem. Res. 2012, 51, 15642−15664*

Hasan, M. M. F.; Baliban, R. C.; Elia, J. A.; Floudas, C. A., Modeling, simulation, and optimization of post-combustion CO_2 capture for variable feed concentration and flow rate. 2. Pressure swing adsorption and vacuum swing adsorption processes. *Ind. Eng. Chem. Res. 2012, 51, 15665−15682*

Hasan, M. M. F.; Fani Boukouvala; Eric L. First; and Floudas, C.A., Nationwide, Regional, and Statewide CO_2 Capture, Utilization, and Sequestration Supply Chain Network Optimization, *Ind. Eng. Chem. Res. 2014,53,7489-7506*

IEA, 2014, *CO2 EMISSIONS FROM FUEL COMBUSTION highlights*, International Energy Agency

IPCC. 2007. Summary for policymakers. In: climate change 2007: the physical science basis, contribution of working group i to the fourth assessment report of the intergovernmental panel on climate change. *Geneva: World Meteorological Organization /United Nations Environment Program*

Jansen, F.; Rob Steinz; Boudewijn van Gelder. Potential for CO_2 storage in depleted fields on the Dutch Continental Shelf – Cost estimate for offshore facilities, *Energy Procedia 4 (2011) 3079–3086*

Knoope, M.M.J.; Ramirez, A.; and Faaij, A.P.C., A state-of-the-art review of techno-economic model predicting the costs of CO_2 pipeline transport, *International Journal of Greenhouse Gas Control 16 (2013) 241–270*

Neele, Filip; Cor Hofstee; Rob Arts; Vincent Vandeweijer; Manuel Nepveu; Johan ten Veen; Frank Wilschut. Offshore storage options for CO_2 in the Netherlands, *Energy Procedia 37 (2013) 5220 – 5229*

Pollutant Release and Transfer Register of the Government of the Netherlands

Ramírez, A.; Saskia Hagedoorn; Leslie Kramers; Ton Wildenborg; Chris Hendriks. Screening CO_2 storage options in The Netherlands, *International Journal of Greenhouse Gas Control 4 (2010) 367–380*

Serpa, J.; Morbee, J.; Tzimas, E. 2011. Technical and economic characteristics of a CO_2 transmission pipeline infrastructure. *JRC62502, 1–43*

Songolzadeh, M.; Mansooreh Soleimani; Maryam Takht Ravanchi; and Reza Songolzadeh. Carbon Dioxide Separation from Flue Gases: A Technological Review Emphasizing Reduction in Greenhouse Gas Emissions, *Hindawi Publishing Corporation, The Scientific World Journal, Volume 2014, Article ID 828131*

TNO; DHV 2009 Potential for CO_2 storage in depleted gas fields on the Dutch Continental Shelf

Zaman, M. and Lee, J. H. Carbon capture from stationary power generation sources: A review of the current status of the technologies, *Korean J. Chem. Eng., 30(8), 1497-1526 (2013)*