Development and Implementation of Supply Chain Optimization Framework for CO2 Capture and Storage in the Netherlands

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Abstract

In this work, we develop a mixed integer linear optimization model that can be used to select appropriate sources, capture technologies, transportation network and CO2 storage sites and optimize for a minimum overall cost for a nationwide CO2 emission reduction in the Netherlands. Five different scenarios are formulated by varying the location of source and storage sites available in the Netherlands. The results show that the minimum overall cost of all scenarios is €47.8 billion for 25 years of operation and 54 Mtpa capture of CO2. Based on the investigated technologies, this work identifies Pressure Swing Adsorption (PSA) as the most efficient for post-combustion CO2 capture in the Netherlands. The foremost outcome of this study is that the capture and compression is the dominant force contributing to a majority of the cost.

Keywords: Carbon Capture, CO2 reduction, Supply Chain, Optimization, CCS, Mathematical Model

1. INTRODUCTION

The increasing CO2 concentration in the atmosphere is directly related to the increase in CO2 emissions from burning and consumption of fossil fuels, leading to global warming, which is an issue of a great concern today [1]. CO2 is the most dominant human-influenced greenhouse gas, and its total emissions have increased from about 22.7 billion tonnes to about 35.3 billion tonnes per annum (56% higher) between 1990 till 2013 [2]. In the European Union (EU-28), trends of the 7 top emitters show that Germany is the largest emitter followed by the UK, Italy and France, with Netherlands, Poland and Spain being the other three [3]. There has been a lot of interest to cut carbon emissions all around the world and specifically 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, showing a strong commitment to reduce anthropogenic CO2 emissions [4] [5] [6]. In addition, the carbon tax which is expected to increase exponentially also gives an enormous motivation to reduce CO2 emissions [7]. In the Netherlands, out of the total CO2 emissions of 180 Mtpa (constant over the past few years), 109 Mtpa of CO2 is emitted by stationary sources from the energy and manufacturing sector.
(approximately 60% of the total emissions) \[8\]. These stationary sources provide us with an opportunity for bulk reduction of CO\(_2\) emissions nationwide.

Efficient use of energy, the use of alternative fuels and energy sources, and applying geo-engineering approaches (afforestation and reforestation) can all lead to reduction of CO\(_2\) emissions into the atmosphere \[9\], 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 (IEA) road map, 20% of the total CO\(_2\) emissions should be removed by CCS by 2050 \[10\]. As we are close to the implementation of CCS in the Netherlands, it is important to develop a framework or a structure for its nationwide scale deployment.

Fig. 1 shows a schematic representation of the whole CCS process. The CCS process involves the capture and separation of CO\(_2\) in bulk (from either stack gas or other intermediate gas streams) and the subsequent isolation from the atmosphere through geological sequestration \[11\]. A major challenge for the industrial deployment of a CO\(_2\) reduction methodology is to reduce the overall cost and integrate all nodes in the CO\(_2\) reduction system. Although the development of CCS technologies has seen a large increase recently, there are still major gaps in knowledge of the cost of capture, transport and storage processes \[12\].

Different capture options are possible based on type of the plant: (i) post-combustion capture, (ii) pre-combustion capture, (iii) oxy-fuel combustion on capture, and (iv) chemical looping or calcium looping \[13, 10, 14\]. Post-combustion capture is a process that involves the capture of CO\(_2\) from flue gas after combustion in any stationary source and the separation is mainly from flue gas and nitrogen. Pre-combustion capture, means, capturing CO\(_2\) before the combustion of fuel takes place. Pre-combustion capture mainly involves the processing of syngas (CO and H\(_2\)), which is produced as an outcome of gasification, with oxygen or steam to produce CO\(_2\) and H\(_2\) and separate them later on to use H\(_2\) as the fuel to produce electricity. Oxy-Combustion capture is similar to post-combustion capture with the difference being that fuel is burnt with pure oxygen instead of air, thereby forming only CO\(_2\) and water, which is separated thereafter. Recently, a promising concept called chemical looping (or calcium looping) combustion has received significant attention \[15, 16, 17, 18\]. Chemical looping is based on the transfer of oxygen from the combustion air to the fuel by means of a solid oxygen carrier (such as a metal oxide), avoiding direct contact between fuel and air \[13\]. In this work, we only consider the post-combustion capture of CO\(_2\) as almost all existing plants can be retrofitted to include this and also most of the current cluster of CCS projects are based on post-combustion capture \[19\]. Different physical or chemical processes like absorption by chemical solvents, adsorption by solid sorbents, membrane separation, cryogenic processes, microbial processes etc. have potential for post-combustion capture of CO\(_2\) \[10, 11\]. However, not all these processes
are suitable or economically attractive to capture CO\textsubscript{2} from every source because there are various factors that affect the choice of a suitable capture process such as feed gas characteristics (composition, flow rate, pressure, and temperature), source type (power generation, gasification, gas upgrading, etc.), source fuel type (solid or gas), capture performance rating (CO\textsubscript{2} purity, recovery, energy penalty, etc.), and cost. According to the updated capture toolbox from Intergovernmental Panel on Climate Change (in their special report IPCC SR) provided by Abanades et al. [18], it can be understood that only two technologies are complete which are demonstrated at industrial scale for post combustion CO\textsubscript{2} capture, (viz.) chemical absorption and adsorption. Membranes are not yet commercially applied for post-combustion CO\textsubscript{2} capture. However, recent developments like hybrid membranes and multi-stage separation show some promise and hope for the future [19] [20].

CO\textsubscript{2} can be transported in a gaseous, liquid or, rarely, in solid phase. Pipeline is the most preferred and mature transportation mode for transportation of CO\textsubscript{2}. It has also been identified as the most economical mode for transport of large volumes of CO\textsubscript{2}. Transportation by ship can only be considered competitive when there is a need to transport over long distances (like transporting to other countries). Thus, in this work, only pipeline transportation of CO\textsubscript{2} will be considered [21]. In just over two decades, geological storage of CO\textsubscript{2} has grown into an important mitigation option from a limited interest concept. The main reason for the increase in confidence for this technology is the growth of technology by research and its demonstration [20]. There are many types of storage options available, such as depleted oil and gas reservoirs, deep unused saline aquifers (offshore and onshore), deep unmineable coal seams and other suggested options (basalts, oil shales, cavities). In each case, geological storage of CO\textsubscript{2} is accomplished by injecting it in dense form into a rock formation below the earth’s surface, that previously held (or is still holding) fluids such as natural gas and oil or brine. In oil and gas fields, the use of CO\textsubscript{2} for enhanced oil recovery (EOR) and enhanced gas recovery (EGR) is a frequently applied option. In coal seams, storing CO\textsubscript{2} and simultaneously enhancing the methane production could also be an option. However, this is still in the demonstration phase [21]. The EGR option is not proven and for this reason, it is not considered in this work. In Netherlands, as not many oil reservoirs for storing CO\textsubscript{2} are available, EOR is also not considered [22].

There are several publications reviewing the possible options and processes available for utilization of CO\textsubscript{2} worldwide [23] [24] [25] [26] [27]. The study conducted by Global CCS institute [28] gives a good overview of most of the options available and assesses the current and future demand for CO\textsubscript{2} across industries. CO\textsubscript{2} - EOR was portrayed to be the most dominant utilization technology and most of the other reuse technologies still have a lot of development left before they can be implemented. In Netherlands, CO\textsubscript{2} - EOR is not a viable option as the storage availability is almost negligible. It is noted however that the Dutch greenhouse sector has a good potential for the use of CO\textsubscript{2}. The report made by Dutch society of applied natural scientific research (TNO) for the Dutch ministry of economic affairs shows the current and future demand for CO\textsubscript{2} in greenhouse sector [29]. The demand, based on the data presented in that report, is only 0.5 Mtpa for 2013 and in future, the demand may go upto 1.5 to 2 MTPA. However, it is noted that these numbers have a high
uncertainty and that there is no agreement on a figure because of many influencing factors. Because of all these reasons, the utilization options are not considered in this work.

The objective of this work is to develop a mixed integer linear optimization (MILP) model to optimize the overall supply chain network costs for CO$_2$ reduction containing sources, capture plants and storage sites, and implement that for different scenarios in Netherlands. A network consisting of sources, a capture system (technologies and materials) and the storage sites for the Netherlands is designed such that the overall cost, for 25 years of operation and 54 Mtpa (30% of the 2013 levels) reduction of CO$_2$, is minimized. The preferred post combustion technologies are also evaluated in the process. In this work, initially, a MILP model for the reduction of CO$_2$ emissions through CCS is developed. The model contains a set of constraints and an objective function. Later, the sources at different levels of detail (both for locations and industrial activities) are screened and investigated to see how the level of detail affects the overall cost to select the appropriate level of detail. Then, the clusters of storage options available in the Netherlands are grouped according to the geographical locations to present the network of major sources and storage sites. Having established the supply chain structure, the model is used for minimizing the overall costs to find the optimal network connecting sources and storage sites for different scenarios to compare. Finally, we discuss the results and the outcomes.

2. MODEL DEVELOPMENT

2.1. PROBLEM STATEMENT

The whole network consisting of sources, capturing CO$_2$ from sources with the technologies and materials available, and transporting it to the storage sites can be viewed as a supply chain network problem [11]. 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 (see Fig. 2).

![Figure 2: CCUS Supply Chain Network Scheme](image)
The following assumptions form the basis for the model:

- The source and capture plants are considered to be in the same and fixed location to avoid transportation of flue gases;
- One source node can be connected to only one capture node and one capture node can receive from only one source node (one to one coupling), though in principle connecting multiple sources to one capture plant is possible;
- No alternative competing mode of transport to a 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 (EGR, EOR or ECBM), carbon tax, etc. are not considered;
- The Network structure is fixed throughout the chosen time horizon of 25 years;
- All capture systems have the same availability (= nominal run hours/year).

Based on the above assumptions, a problem statement is formulated as follows:

*Given:*

1. Sources: type & location, yearly CO\(_2\) emissions and compositions
2. CO\(_2\) capture and compression technologies: materials and costs
3. CO\(_2\) transportation: distance and quantity to be transported, transportation mode and costs
4. CO\(_2\) sequestration/storage: type, location, storage capacity, injection costs and storage limit
5. CO\(_2\) reduction target

*Select:*

1. Sources from the given set of sources \((i \in (1,\ldots,I))\) and quantity to be captured from each selected source \(i\)
2. Technology and material combination \((j \in (1,\ldots,J))\) to be used for the CO\(_2\) capture of each selected source \(i\)
3. Storage sites to be used \((k \in (1,\ldots,K))\) and quantity to be stored in each site
4. Network topology to capture, transport and store CO\(_2\)
Objective:

The objective of the model is to minimize the total CCS network costs, which includes capture and compression costs (flue gas dehydration costs included), transportation costs and the storage injection Costs, leading to an optimized structure.

Total CCS costs = Capture & Compression costs + Transport costs + Storage Injection costs

2.2. CCS SUPPLY CHAIN NETWORK MODEL

The CCS Supply Chain Network is modelled as a Mixed Integer Linear Programming (MILP) model and is presented in this section.

2.2.1. SETS

Stationary sources considered are represented by ‘i’, capture and compression facilities are represented by ‘j’ and the geological storage sites as ‘k’.

\[ i \in (1, ..., I) \text{ – Sources} \]
\[ j \in (1, ..., J) \text{ – Capture system} \]
\[ k \in (1, ..., K) \text{ – Geological storage sites} \]

2.2.2. PARAMETERS

The following are the parameters used:

\[ CR_{\text{min}} \] – Minimum targeted overall CO\(_2\) reduction (tonnes per annum)
\[ CS_i \] – Total CO\(_2\) emissions from each source i (tonnes per annum)
\[ F_i \] – Total feed flue gas flowrate from each source i (moles per second)
\[ XS_i \] – CO\(_2\) composition in the flue gas emissions from Source i (mol%)
\[ XL_j \] – Lower composition processing limit for capture plant j (mol%)
\[ XH_j \] – Higher composition processing limit for capture plant j (mol%)
\[ C_{k}^{\text{max}} \] – Maximum storage capacity at the storage site k (tonnes)

2.2.3. VARIABLES

The following 0-1 binary variable is used to determine the selection of a specific source, capture plant (with various technology material combination) and the storage site:

\[ X_{i,j,k} = \begin{cases} 
1, & \text{If CO}_2 \text{ from source ‘i’ is captured using technology-material combination in capture} \\
& \text{plant ‘j’ and stored in Storage site ‘k’} \\
0, & \text{otherwise} 
\end{cases} \]

\((i, j, k) \in (I, J, K)\)
We use a 0-1 continuous variable to determine the quantity that is going to be captured from each source:

\[ FR_{i,j,k} = \begin{cases} 
0-1 \text{ continuous variable represents the fraction of the total CO}_2 \text{ captured from source } \ 'i' \text{ using capture plant 'j' and sent to storage site 'k'} \\
(i, j, k) \in (I, J, K) 
\end{cases} \]

2.2.4. MODEL

2.3. Objective Function

Equation (1) shows the objective function, the total CCS costs \( C \) as the sum of capture and compression costs (which includes the flue gas dehydration costs), transportation costs and storage costs.

\[
\text{Minimize } C = \sum_{i,j,k} (CC_{i,j,k} + TC_{i,j,k} + SC_k) \quad (i, j, k) \in (I, J, K) \tag{1}
\]

Where, sources are given by \( i \in 1, ..., I \), capture plants are represented by \( j \in 1, ..., J \), storage sites are shown by \( j \in 1, ..., k \), \( CC_{i,j,k} \) - Capture and Compression Costs, \( TC_{i,j,k} \) - Transportation Costs, \( SC_k \) - Storage Costs

2.4. Constraints

To ensure that at most only one capture technology - material combination and one geological storage site is chosen for each selected source, equation (2) is introduced.

\[
\sum_{(j,k) \in (J,K)} X_{i,j,k} \leq 1 \quad \forall \ i \in I \tag{2}
\]

\[ X_{i,j,k} = \begin{cases} 
1, & \text{If CO}_2 \text{ from source 'i' is captured using technology-material combination in capture plant 'j' and stored in Storage site 'k'} \\
0, & \text{otherwise}
\end{cases} \]

This equation also ensures that CO\(_2\) captured from each source does not get distributed to multiple storage sites. In addition, this also facilitates the one to one coupling assumption between sources and capture system. Each storage site has a maximum capacity limit for injecting CO\(_2\). For keeping track on the maximum injection limit of each storage site and ensuring that it does not exceed that maximum storage capacity, we use equation (3)

\[
\sum_{(i,j) \in (I,J)} CS_i \ast FR_{i,j,k} \leq \frac{C_{k}^{max}}{Years} \quad \forall \ k \in K \tag{3}
\]

\[ FR_{i,j,k} = \begin{cases} 
0-1 \text{ continuous variable represents the fraction of the total CO}_2 \text{ captured from source } \ 'i' \text{ using capture plant 'j' and sent to storage site 'k'} \\
(i, j, k) \in (I, J, K) 
\end{cases} \]

Where, \( CS_i \) - total CO\(_2\) emissions from each source 'i' (tonnes per annum), \( C_{k}^{max} \) - maximum storage capacity of the storage site 'k' (tonnes) and Years represent the number of years of operation. To make
sure that a source is connected to a storage site and it stays the same way throughout the 25 years, we divide the total capacity of each storage site by 25, as the emissions from each source \((CS_i)\) is given per annum. This equation allows more than one source to connect to a single storage site, but still maintain the capacity restriction. To ensure that a minimum targeted \(CO_2\) emission reduction is achieved, equation \(4\) is introduced.

\[
\sum_{(i,j,k) \in (I,J,K)} CS_i \cdot FR_{i,j,k} \geq CR^{min}
\]  

In our case the minimum targeted emission \(CO_2\) reduction \((CR^{min})\) is 54 Mtpa. To make sure that when a source is selected, no more than 90% of \(CO_2\) is captured from that source equation \(5\) is introduced and that is also the reason for using a constant 0.9 in this constraint.

\[
0 \leq FR_{i,j,k} \leq 0.9 \cdot X_{i,j,k} \quad \forall \ (i,j,k) \in (I,J,K)
\]  

This is based on the assumption used in the economic model for the capture and compression cost, where the capture technologies are chosen to facilitate a minimum of 90% capture from the source. This will be explained in the the section. 2.5. The additional benefit, in terms of modelling, is the avoidance of the multiplication of variables \(FR_{i,j,k}\) and \(X_{i,j,k}\) and thereby linearizing the model reported by Hasan et al. (2014) [11]. All the technologies considered cannot be used to capture \(CO_2\) from all the sources as some of them are not capable to remove 90% of \(CO_2\) from the feed flue gas with a product purity of 90% \(CO_2\). This depends on the composition of \(CO_2\) in the feed and with equation \(6\) this can be facilitated.

\[
\sum_{(k) \in (K)} (XH_j - XS_i) \cdot (XS_i - XL_j) \cdot X_{i,j,k} \geq 0 \quad \forall \ (i,j) \in (I,J)
\]  

Where, \(XS_i\) - \(CO_2\) composition in the flue gas emissions from Source \(i\) (mol%), \(XL_j\) - Lower composition processing limit for capture plant \(j\) (mol%), \(XH_j\) - Higher composition processing limit for capture plant \(j\) (mol%).

The main benefit of our model to the model used by Hasan et al. [11] is that, \(FR_{i,j,k}\) is considered as a variable in our model, whereas it is considered a parameter in Hasan et al.’s model. But, our linear model can choose the amount or fraction \((FR_{i,j,k})\) (that has to be captured from each source) freely. In the model by Hasan et al., the \(FR_{i,j,k}\) as a variable, makes the model non-linear and the optimum is not a guaranteed one because of the non-convexity.

2.5. ECONOMIC MODEL

Two widely used economic criteria to compare the cost effectiveness of a capture process are: (i) the cost of 1 ton of \(CO_2\) captured and (ii) the cost of 1 ton of \(CO_2\) avoided. The IECM framework as summarized
by Rao and Rubin [30], presents the cost of CO₂ avoided as shown in the equation. 7

\[
\text{Cost of CO}_2 \text{ avoided} = \frac{(\mathcal{E}/kWh)_{\text{capture}} - (\mathcal{E}/kWh)_{\text{reference}}}{(\text{tonne CO}_2/kWh)_{\text{reference}} - (\text{tonne CO}_2/kWh)_{\text{capture}}}
\]  

(7)

Where, \((\mathcal{E}/kWh)_{\text{capture}}\) and \((\mathcal{E}/kWh)_{\text{reference}}\) is the cost of electricity in a plant with the capture facility and the cost of electricity without the capture facility (reference plant) respectively and \(\text{tonne CO}_2/kWh\)\(_{\text{reference}}\) and \(\text{tonne CO}_2/kWh\)\(_{\text{capture}}\) is the CO₂ emitted in the reference plant and the CO₂ emitted in a plant with the capture facility. The main difference between the two criteria is that, cost per ton of CO₂ captured does not give the true overall reduction with respect to the reference plant. Though Rao and Rubin provide useful information, the capture costs for each plant vary according to the composition of CO₂ in the flue gas and the flue gas flowrate itself. Thus, in this work, we use the cost of 1 ton of CO₂ captured and the model presented by Hasan et al. [11]. Based on maturity and total readiness level, four leading capture and compression technologies are selected: absorption, Pressure Swing Adsorption (PSA), Vacuum Swing Adsorption (VSA) and membrane separation [11] [18]. The materials for each technology chosen are based on the literature [10] [11]. Hasan et al. [31] [32] [11] in their work have optimized various capture and compression technologies and materials and reported the costs for the technologies and material combinations that we have considered in terms of CO₂ composition and feed flue gas flowrates. The important assumptions and the basis considered for this cost model are that the technology-material combination is able to capture at least 90% of CO₂ in the feed flue gas with the product purity of 90% CO₂ and a 150 bar pressure of CO₂ product. Other assumptions such as assumptions for the investment and operating costs parameters and the reason for choosing the investment cost per annum can be found in their work.

The capture and compression costs are given as follows:

\[
CC_{i,j,k} = CDC_{i,j,k} + CIC_{i,j,k} + COC_{i,j,k} \quad \forall \ (i,j,k) \in (I,J,K)
\]

(8)

Where, \(CDC_{i,j,k}\) is the flue gas dehydration costs, \(CIC_{i,j,k}\) is the capture investment costs and \(COC_{i,j,k}\) is the capture operating costs. All the saturated flue gases are dehydrated using a Tri-Ethylene Glycol (TEG) absorption. The costs of TEG absorption are \(\mathcal{E}9.28/\text{ton of CO}_2\) and includes the investment and operating costs for dehydration according to Hasan et al. [11].

\[
CIC_{i,j,k} \left(\mathcal{E}/\text{yr}\right) = \alpha_j \ast X_{i,j,k} + \left(\beta_j X_S^{m_j} + \gamma_j\right) \ast F_i^{m_j} \ast (m_{11,j} \ast FR_{i,j,k} + m_{12,j} \ast X_{i,j,k})
\]

(9)

\[
COC_{i,j,k} \left(\mathcal{E}/\text{yr}\right) = \alpha_{o_j} \ast X_{i,j,k} + \left(\beta_{o_j} X_S^{m_{o_j}} + \gamma_{o_j}\right) \ast Fc^{m_{o_j}} \ast (m_{21,j} \ast FR_{i,j,k} + m_{22,j} \ast X_{i,j,k})
\]

(10)

\((i,j,k) \in (I,J,K)\)

Equations [9] and [10] show the linearized version of the cost models presented by Hasan et al. [31] [32] [11] for the investment and operating costs per year of capture and compression costs. \(F_i\) is the flow rate of
flue gas in moles per second. Their model becomes non-linear as a result of the exponent in $FR_{i,j,k}$. For each of the 13 technology/material combinations considered, the costs are linearized by us with less than 5% overall relative error compared to the original model. Linearization also allows us to choose the $FR_{i,j,k}$ freely, rather than assuming it constant as considered by Hasan et al. [11]. Fig. 3 shows the capture and compression costs as a function of composition of $CO_2$ in the flue gas, for a constant flue gas flowrate of 10 kmol/s and $FR_{i,j,k} = 0.9$. The figure is very similar to that provided by Hasan et al. [11], showing that the applied linearization does not significantly change the costs compared to the original model. It can also be seen that absorption is preferred for cases with very low $CO_2$ compositions in the flue gas, whereas adsorption is preferred for cases with higher compositions.

![Figure 3: The Capture and Compression costs (€/ton) for various technology material combination (flue gas flow rate = 10 kmol/s)](image)

Modeling of the transportation node(s) has also received a significant attention. The review by Knoope et al. [33] gives a good overview of all the available models. In this work, the model presented by Serpa et al. [12] is used, as it provides us with a linear model and the costs as a function of the quantity transported. There is no distinction made between transportation costs in land and sea. The distance between the source and the storage site ($D_{i,k}$), is calculated based on its latitude and longitude and they are not the actual distances. The terrain factor, $F_T$, for off-shore is generally lesser than that of onshore (though, in reality, the investment and operating costs are higher than Onshore), and onshore, $F_T$ for populated place is 1.4 and $F_T$ for remote place is 1. Hence, on an average, a terrain factor, $F_T$ of 1.2 [34] is considered. However, this can also be taken as correction for the distances (as actual distances are not used). 16 kms is added to the distance ($D_{i,k}$) for access to a suitable injection site within storage formation [35]. The yearly operation and maintenance costs ($OM_t$) for pipelines are taken as 4% of the investment costs [33].
$$T_{CI,i,j,k} = \begin{cases} 
TIC_{i,j,k} = (\alpha_t * CS_i * FR_{i,j,k} + \beta_t * X_{i,j,k}) * F_T * (D_{i,k} + 16) \\
+ \end{cases}$$

$$TOC_{i,j,k} \left( \frac{\epsilon}{yr} \right) = OM_t * TIC_{i,j,k}. \tag{11}$$

For the storage and injection costs, Jansen et al. [36] give an average investment ($I_{well}$) and operating costs ($OM_{well}$) per well and to calculate the number of wells, a parameter maximum injection capacity per well ($IC_{max}$) used by Hasan et al. [11], is also used in this model. 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.), it is assumed to be a constant. Equation. 12 shows the storage and injection cost that is used in this model.

$$SC_k = \begin{cases} 
SIC_k = I_{well} * n_{well_k} \\
+ \\
SOC_k \left( \frac{\epsilon}{yr} \right) = OM_{well} * n_{well_k}. \tag{12} 
\end{cases}$$

Number of wells required,

$$n_{well_k} = \frac{\sum_{(i,j) \in (I,J)} CS_i * FR_{i,j,k}}{IC_{max}} \tag{13}$$

Parameters used for the cost functions can be found in the supplementary file.

### 3. DATA ANALYSIS

In this section, the data of the sources and storage sites in the Netherlands is introduced and analysed. The data analysis is also expected to pave the way for the scenarios that are studied in the next sections.

#### 3.1. SOURCES

Data for the sources are obtained from the Netherlands Government’s pollutant release and transfer register database [8] and the “central bureau voor de statistiek” for the year of 2013 [3]. The database categorizes sources into different levels of detailing according to locations (nation, province level, community (municipality) level and individual location) and industrial activities (sector level, sub-sector level, and individual activity level). To decide at which detail the case study needs to be conducted, initially, the data at province-subsector combination is analysed as the other combinations are either too less detailed or too much detailed. Out of the total emissions of 180 Mtpa, 242 large stationary sources (neglecting smaller sources like emissions from universities, educational centres, recreations clubs, etc.), account for 109 Mtpa (approx. 60% of the total emissions). Out of these 242 sources, only the top 35 sources (all ≥ 0.5 Mtpa), account for approximately 98.5 Mtpa. This means that the other 207 sources, account for only approximately
10 Mtpa of the total CO$_2$ emissions. This also shows that, solving this problem with only those 35 sources can be much more efficient. Defining the same criteria, four different combinations can be proposed: (i) Province-subsector (P and S), (ii) Province-individual activity (P and I), (iii) Community-subsector (C and S) and (iv) Community -individual activity (C and I).

![Figure 4: Comparison of sources at different combinations](image)

The number of sources and the total emissions vary going into various levels of detail and fig. 4 shows how they vary going further into details and with different combinations. From left to right in the fig. 4, the higher the level of detail. It can be seen that the number of sources are almost a constant (varies only between 33 and 35) whereas, the emissions decrease initially as a result of getting into the details of locations and industrial activity, as expected and become almost a constant at the community (municipality) level. This data analysis shows that the community - individual activity level of detail is sufficient.

Fig. 5a shows the location of sources spread across the Netherlands at the community - individual activity combination. The majority of the sources come from the energy industry (electricity production, gas processing and distribution, gas production, etc.) and the chemical industry. Regarding the location, the western and the south western part of Netherlands are the major emitters of CO$_2$. The Netherlands map was divided into four quadrants (fig. 5b). It is obvious that, the majority of the sources and emissions are from Q1 and Q3, (25 out of 35 sources and approximately 71 out of 86 Mtpa of emissions). This demonstrates that, as a government or as a deciding body, the focus has to be in those quadrants to achieve a major reduction of CO$_2$. 
Fig. 5: Locations of various sources

(a) Top 35 sources at Community - Individual Activity combination
(b) Comparison of sources in Community - Individual Activity combination at different quadrants

Figure 6: The composition distribution of sources in Community-Individual activity level

Fig. 6 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 compositions greater than 20%. This is because most of the sources are assumed to have a concentration of 11%, as the exact compositions of most of the sources are unknown. As explained in the economic model of capture and compression (Section 2.5), compositions play a major role in the capture of CO₂ - lower the composition of CO₂ in the flue gas, tougher and costlier it is to remove from the flue gas and vice versa.
3.2. STORAGE SITES

The three main storage types in Netherlands considered in this work are: depleted oil & gas fields, un-mineable coal seams and saline aquifers (deep underground porous reservoir rocks saturated with brackish water or brine). The storage data for the Netherlands were obtained from TNO [22], Ramirez et al. [37], Damen et al. [38] and Neele et al. [39]. There are more than a hundred storage sites individually and considering all of them individually is going to make the model larger. Thus, the individual geographical locations of storage sites represented in the above publications [22, 37, 38, 39] on the map of Netherlands (clusters of storage sites) were grouped manually to reduce the overall problem size. The storage sites are reduced to 47 cluster groups out of which 31 are oil & gas groups, 12 are saline aquifer groups and 4 are groups of coal seams. Although, the realistic values for individual storage capacities are not easily found, the total storage capacities for each type of storage is estimated as presented by Damen et al. [38] and Ramirez et al. [37]. The total storage estimation of 47 groups summed to approximately 11 Gt, out of which, 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. From the 15 storage sites chosen, 11 are oil & gas sites, 3 are saline aquifers and 1 of them is an un-mineable coal seam.

Figure 7: Netherlands map locating the top 15 storage sites
Fig. 7 shows the geographical distribution of top 15 grouped storage sites in the map of the Netherlands, where each sphere represents the center of a group and the size of the sphere represents the capacity of the storage group. It can be seen that most of the big storage groups are in the northern and the north western part of the Netherlands. Only the Groningen site (biggest sphere in fig. 7) contributes to 7.35 Gt of storage capacity. An important assumption is that, all the storage sites are free, ready and available for the CO$_2$ storage and the CO$_2$ injection platform is going to be built from scratch. In addition, no costs related to delay by public protests for injection in these storage clusters are considered.

3.3. Data selection

Fig. 8 shows the change in objective (total costs) with the different combinations of sources considered. It is noted that the objective function becomes almost constant at community level, similar to the trend noticed in total emissions of the sources at various levels and this proves that further detail is not necessary. For this reason, various scenarios are studied at community - individual activity combination with 35 sources and 15 largest storage cluster groups (the details of the individual sources and storage sites with their capacities, locations and other information can be found in the supporting information).
The following cases are going to be considered:

1. All sources & storage sites can be freely selected
2. Only Groningen as the storage site is considered
3. Select only sources from Q1 & Q3 and select Groningen as the only storage site
4. Select only sources from Q1 & Q3 and collect the captured CO$_2$ in a common point and transport it in bulk to Groningen

For the first case, a broader scenario is worked out, where the model is allowed to select the sources and storage site freely and narrow it down on going further. For the second case, a constraint in the model is introduced to select only Groningen as the storage site and case 3 further reduces the scope by selecting sources only from quadrant 1 (Q1) and quadrant 3 (Q3) as the majority of the emissions are from that region. However, as the Q1 and Q3 and Groningen storage sites are in the opposite part of the Netherlands, in case 4, a common collection point for all the captured CO$_2$ is considered, which will be the centre point of all the sources in Q1 and Q3 and then transport it to Groningen storage site is selected. In all the cases except case 1, a constraint is introduced in the model to select only Groningen as the storage site. In case 3 and case 4, an additional constraint is introduced in the model to select sources only from Q1 and Q3. For case 4, the transportation cost is altered by adding a term for bulk transportation from central collection unit to the Groningen storage site.

4. RESULTS & DISCUSSIONS

35 sources, 13 technology-material combinations for capture & compression and 15 grouped storage sites to inject CO$_2$ are considered. The total number of discrete variables are 6825 (35 X 13 X 15). If all the 242 sources and 47 storage sites (as in the province-sub-sector combination) are considered, instead of reducing it, there will be 147862 discrete variables (242 X 13 X 47). This shows that the analysis of data to reduce the number of sources and storage sites helps in decreasing the size of the model and turn it into easier implementation and interpretation of the problem. Reduction of the number of sources also enabled us in moving into more detail in terms of location and the industrial activity, making the results more accurate.

The General Algebraic Modeling System (GAMS - version 24.4.6) is used in this work to solve the MILP supply chain model presented in Section. 2. CPLEX 12.6.2 is the optimization package used to solve the given MILP optimization problem. The total execution time is 7 seconds in a i7 2.4 GHz CPU processor and a 64-bit windows operating system.

Table 1 gives the optimized costs of the CCS network in the Netherlands for different cases. The total costs for 25 years of operation and 54 Mtpa CO$_2$ emission reduction is between €47.8 billion and €52.4 billion for different cases. The main difference between the four cases is in the transportation costs which increases considerably for case 2 and case 3, where the CO$_2$ captured in each site is sent individually to the
Groningen storage site. But an enormous decrease in costs is seen for case 4 because of the collection of CO₂ in a common point and transporting it in bulk to Groningen. Transportation costs are also higher because, most of the CO₂ emissions in Netherlands are from the Q1 and Q3 quadrant but the Groningen site is in the wrong corner of Q2, making the CO₂ travel all the way across the Netherlands. The overall costs per ton of CO₂ captured is between €35.43 per year and €38.8 per year (fig. 9). The costs per ton of CO₂ is very much comparable to the one reported by TNO and Ecofys in their report to Netherlands ministry [40]. To validate the cost models used by us, the costs were compared to the costs obtained by Hasan et al. [11] and the cost proportions are similar despite using different cost functions for storage injection and transportation costs.

Table 1: Total costs for the optimal CCS network in the Netherlands

<table>
<thead>
<tr>
<th>Costs (€ billion)</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total costs</td>
<td>47.8</td>
<td>50.6</td>
<td>52.4</td>
<td>49.0</td>
</tr>
<tr>
<td>FG Dehydration</td>
<td>12.5</td>
<td>12.5</td>
<td>12.5</td>
<td>12.5</td>
</tr>
<tr>
<td>Capture and compression</td>
<td>30.70</td>
<td>30.69</td>
<td>31.39</td>
<td>31.03</td>
</tr>
<tr>
<td>Storage injection</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Transport</td>
<td>1.9</td>
<td>4.7</td>
<td>5.8</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Figure 9: Costs per ton of CO₂ for the optimal CCS network in the Netherlands

It is noted for the costs that, though, dehydration, storage and transportation add to the total costs, the costs of capture and compression, as expected, is the highest contributor. The storage injection costs account for only €2/ton/annum (or €2.7 billion) and, are constant for all the cases because of the linear model that was considered, which does not take into effect the scale of the storage. Another observation on
the storage and injection costs used is that it considers only the amount of CO₂ injected and not the well characteristics. According to the assessment of TNO, most of the storage sites in Netherlands have a depth between 2 and 4 km [22]. But the costs, based on a model that is a function of both the depth of the well and the capacity injected taken from Ogden et al. [41], proves to be lower than the costs used in this work (based on Jansen et al. [36]) (fig. 10).

![Figure 10: Comparison for storage costs](image)

The total transportation costs are between €1.9 billion (€1.42/ton/annum) and €5.8 billion (€4.3/ton/annum) for the 4 cases. According to Knoope et al. 2013 [33], the pipeline costs are mostly underestimated as most of the models keep the cost of natural gas pipelines constructed before 10 to 15 years as basis, whereas the CO₂ pipelines generally operate at higher pressures. Even if the storage injection and transportation costs are considered to be underrated, say 3 or 4 times lower, the capture and compression costs with approximately €23/ton/annum will remain the largest among all the costs for CO₂ reduction. Few reasons, other than the underestimation of the storage injection and transportation costs, may be the compositions of CO₂ in various flue gas sources used might have been inaccurate which can affect the costs considerably (as shown in fig. 3) or the model used for the capture and compression cost itself may not be accurate enough. However, literature also supports the fact that the capture and compression costs are the major contributor to the CCS costs [10, 12, 14]. The main takeaway 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 for different cases are shown in the Fig. 11. The thinner end shows the source and the thicker end shows the storage site. The thickness of the lines is also proportional to the quantity captured from each source, transported and injected in each storage site.
In case 1, for the optimal design, 18 sources and 9 storage sites are selected. Only 4 of the 18 sources come from Q2 and Q4 part of the Netherlands. Out of the selected 9 storage sites, 5 storage sites are oil & gas sites, 3 are saline aquifers and 1 of them is an unmineable coal seam. From the storage occupancy
perspective, there still exists more than 85% of the CO$_2$ storage even after the 25 years of operation to reduce 54 Mtpa. Largest site of all; the Groningen gas field, still has almost a 100% storage capacity left. It may be because of the linear relation for storage injection costs which does not take into account the scale effect of the storage. Furthermore, as mentioned earlier, it maybe 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. Looking at the other cases, where the model only allows Groningen as the storage site, the number of sources selected does not see a major difference, as all of them rally around 18 sources. In case 2, one additional source from quadrant 2 (near Groningen storage site) is selected. In case 3 and case 4, the scope is still narrowed down to select only the sources from Q1 and Q3. Case 4, where it was decided to transport in bulk, proved to be vital in reducing the transportation costs by less than a half (from €4.3 per ton per annum to €2 per ton per annum). Based on the analysis of all the scenarios, it can be concluded that, the scenario where the sources and storage sites are allowed to be chosen freely proved to be the best one. Although, this was proved the optimal, case 4 was not far away from being the optimal scenario and more accurate modelling of transport costs and storage costs might lead this scenario to be optimal.

![Figure 12: Technology preference and comparison](image-url)

In the technology selection to carry out the capture and compression, out of the 13 technology-material combinations, only 3 are chosen - 17 of the 18 selected sources use pressure swing adsorption and only 1 use absorption (fig. 12a). In the material feature, MVY zeolite based adsorption is strongly preferred over the WEI zeolite based one (15 times to two times). This may be because most of the sources have 11 mol% CO$_2$ composition in flue gas and at this composition MVY based adsorption is cheaper than WEI based adsorption. WEI based adsorption is chosen when the CO$_2$ composition in flue gas is greater than 30-35
mol%. It was also noticed that if only absorption is chosen for capture, then the costs are 15-20% higher (fig. 12b). 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. 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$_2$ [42]. In all the cases, only less than 3 sources out of the 18 sources (on an average) selected, have a low CO$_2$ composition in flue gas. This is another reason why adsorption is the most often selected technology in the optimization. It is clear from the fig. 3 and the economic model for capture and compression that, absorption is preferred when the concentrations are below 8 mol% 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 13: Costs of top four technologies for CO$_2$ composition of 11 mol%](image)

As the capture and compression costs are the largest contributor to the overall costs, the possibility of having a central capture unit was studied as the capture and compression costs decrease with an increase in flow rate of flue gas (and CO$_2$). A central capture unit is a capture unit that is fixed in a place which is a centre point to which flue gases from all the sources will be transported to this point where the CO$_2$ in flue gases will be captured and from there, captured CO$_2$ will be transported to the storage sites. The important economic aspects of this situation that needs to be considered are: (1) This does not change the dehydration costs, as flue gases need to be dehydrated anyways before it can be transported and (2) Compression and transportation flue gases (a larger volume), which implies that the compression and transportation costs are going to be higher. Despite higher compression and transportation costs, if the capture costs are considerably lower, then the option of having a central capture plant can be considered viable. For this reason, the capture
and compression costs per ton of CO$_2$ for top four technologies were plotted against the CO$_2$ flow rate at a constant CO$_2$ composition of 11 mol% (Fig. 13). It is clear that, although the costs decrease initially a little bit, the overall reduction of just 6-7 € per ton does not provide us with enough reduction to opt for the central capture unit.

Few important points to be discussed are the effects of assumptions and the uncertainties that can affect the results. The main uncertainty being the source emissions, Which are bound to be very uncertain as they depend on the production and various other market factors like demand, pricing, etc. Though the emissions can vary, the emissions is considered to only go down in the coming years and so the given model results give a conservative estimate. The assumption of having the capture plant in the same location as the source plant, though, looks simple, it is also realistic as it is proven that the transportation of flue gases are not recommended because of the economic aspects. Location of the sources and the distances between the source and storage sites, though are not the actual locations and distances, there is a correction factor included in the transportation cost function to accommodate this. In terms of extension of the model, it is recommended to make the model multi-period to check the storage capabilities at various periods. This is quite effective because Groningen storage site is still producing gas and it is expected to be available only after 2040 or 2045, whereas few other sources are already available. So this extension helps in source-sink matching according to the availability at that time period. In the industrial point of view, it is recommended to start initially with a small network and then extend it to the whole country.

5. CONCLUSIONS

An MILP model was developed to minimize the total costs of the supply chain network for CO$_2$ reduction containing sources, capture plants and storage sites. The MILP model presented in this work also has a linearized relation for the estimation of capture and compression costs. This linearization also allowed the model to choose the fraction captured from each source instead of assuming it to be a constant. The MILP model developed was then applied to synthesize a national CCS supply chain network by selecting the appropriate sources, capture processes, transportation connections and CO$_2$ storage sites to minimize the total costs. Results show that the total cost for reducing 54 Mtpa of CO$_2$ in the Netherlands for 25 years of operation for four different scenarios lie between €35.43/ton/annum and €38.8/ton/annum. The case where the model was allowed to freely choose the sources and storage sites was found to be the optimal and for the optimal design 18 sources and 9 storage sites were selected. It was observed 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. In the technology selection for capture and compression of CO$_2$, Pressure Swing Adsorption (PSA) was significantly preferred over the heuristic choice of absorption and the difference in costs were also noted to be considerable. Choice of connecting the regions of largest sources and largest storage site did not work may be because of the linear economic model considered for storage costs and that the costs of transportation are comparable to the costs of storage. Another clear conclusion that can be drawn from the
relative contribution to the total costs is that the capture & compression cost is the major contributor to the total costs. To consider an option of having a central capture plant, the amount of reduction in the costs of capture the top four technologies showed much lower than the expected increase in the costs because of the need to transport and compress larger volumes than in the base cases and thus, one of the earlier scenarios was still proved to be the optimal.

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