CCS ECONOMIC EVALUATION TOOL – INCLUDING RIJNMOND CASE STUDY

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Content

1 Introduction

Recent research showed that in the Netherlands over 2500 million tonnes of storage capacity is available in gas and oil reservoirs. Including the Slochteren gas field this will increase to close to 10,000 million tonne, roughly enough to store more than 50 years total current CO_2 emissions in the Netherlands. The storage capacity is divided in many small, medium and large-sized storage locations, which are or will become available mainly in the next 10 to 20 years. The location of the potential storage reservoirs are mainly in the North of the Netherlands and in the North Sea. Figure 1 gives an overview of the location of storage reservoirs.

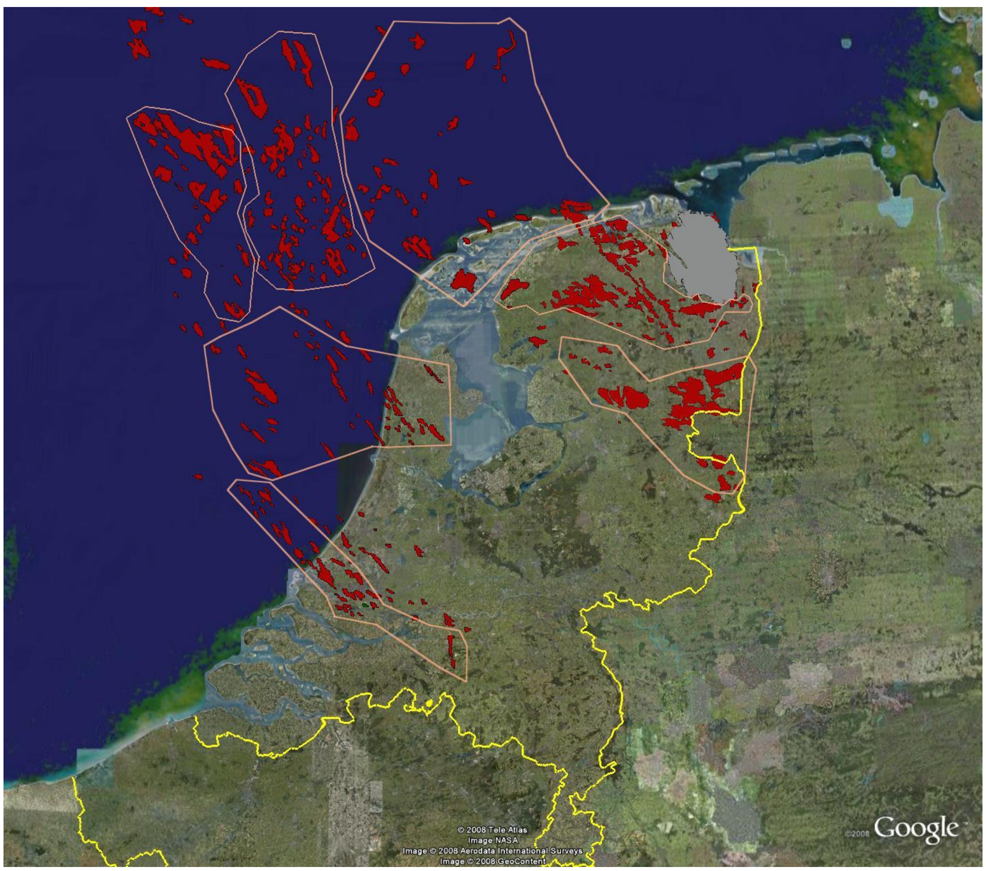


Figure 1. Location and shapes of potential storage reservoirs of CO_2 in the Netherlands

There are about 35 sources of CO_2 each emitting over 500 kt per year in the Netherlands. The largest concentration of these sources is situated in the Rijnmond area. Figure 2 gives an overview of the position and size of CO_2 sources in the Netherlands, as well as in Belgium and Ruhr area in Germany.

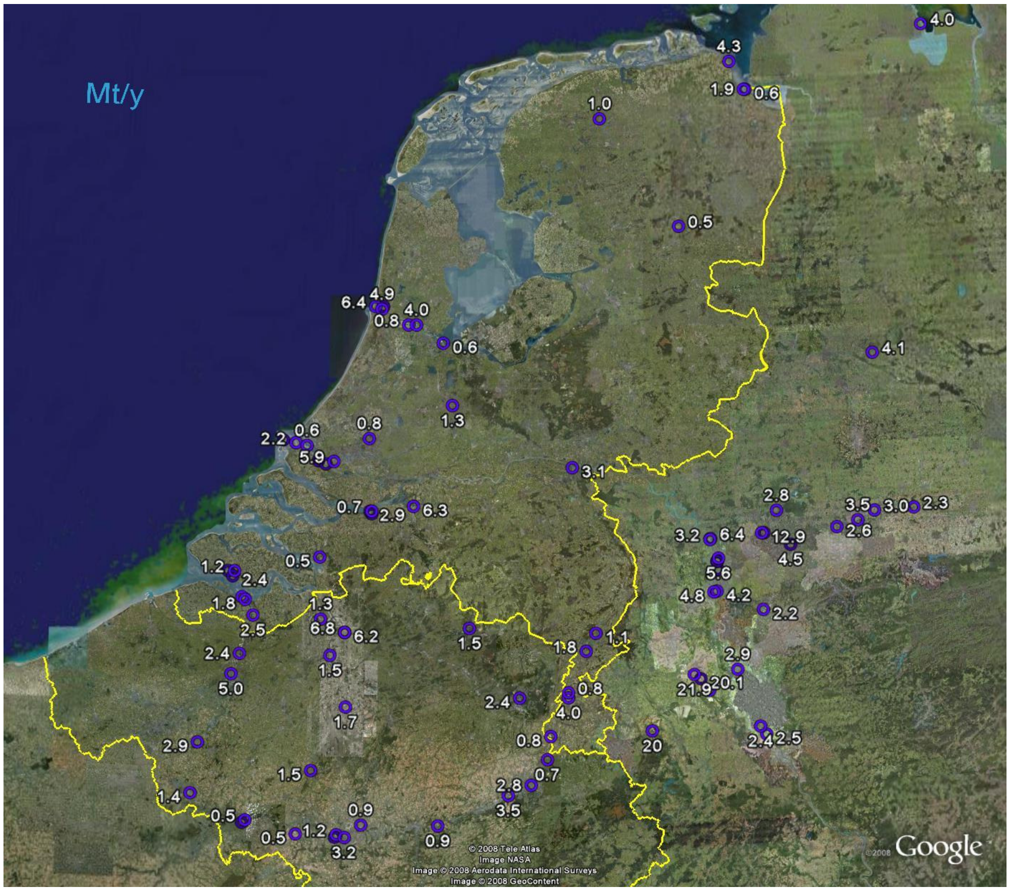


Figure 2. *Location and size of sources of CO_2 in the Netherlands, Belgium and Ruhr area*

In former studies it has been investigated whether there is sufficient storage capacity for the foreseeable future and the relation between amount of captured CO_2 and the availability of storage reservoir capacity. However, there has been less focus on a generic calculation tool for the technical-economic evaluation of specific capture-storage systems, comprising of actual (multiple) sources of CO_2 and storage locations. In the GeoCapacity project [Neele et. al., 2008] Ecofys and TNO developed a decision support system (DSS) to easily evaluate (complex) capture-storage systems. In section 2 a brief description is presented about the structure and development of the DSS system. Section 3 gives an example of such evaluation of CCS system in the Rijnmond area in the Netherlands. Unfortunately, due to time constraints, a thorough analysis of various capture-storage systems in the Netherlands could not have been performed before the end of CATO project. Nevertheless, the DDS tool will be used further in analysing such systems in the $CATO_2$ programme which will start in spring 2009.

2 Description of the DSS System

2.1 Outline of the internet Geocapacity application

The Decision Support System (DSS) has been developed to evaluate the technical and economic feasibility of CO_2 storage in the subsurface. The system can be used to define CO_2 capture, transport and storage systems, consisting of a selection of CO_2 sources and sinks and the connecting pipeline network. It consists of two parts. The first part is an internet application which visualises the data and allows the user to select sources and sinks and create a pipeline network. The other part is an application to be run on a local computer, which performs a stochastic analysis of the costs of a CO_2 capture, transport and storage system. In this section we describe the most fundamental elements of the DSS. A more elaborated description can be found in Neele et al. [2008].

The internet-based part of the DSS[1] is used to construct a CCS scenario. The database compiled in the EU-Geocapacity project is used to select any number of CO_2 emission points and storage locations. A network of pipelines connecting sources and sinks can be computed and edited. The amount of storage space in the sinks in the CCS scenario can be compared with the amount of CO_2 produced by performing a simple source-sink match. The calculated network is displayed on a Google Maps background. The user has the option to change manually the location and shape of any of the pipelines in the network, to avoid obvious obstacles such as cities or steep topography (see Figure 3).

[1]At the time this report was compiled the address where the DSS can be reached was http://dinolab51.nitg.tno.nl/GeocapTrinidaddinolab51_edisonSmallapp/faces/index.jspx.

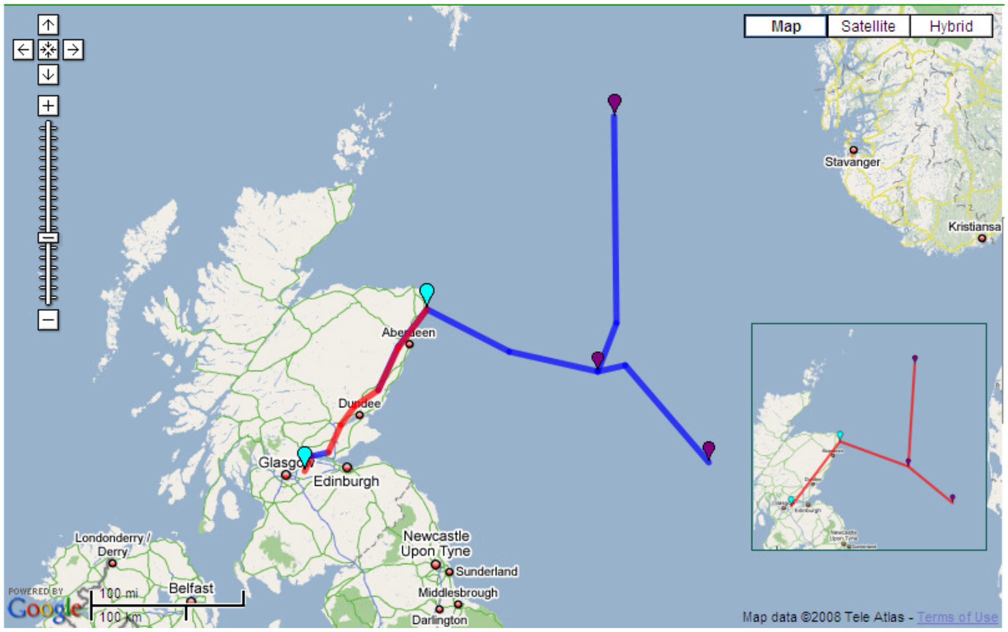


Figure 3. Screen shot of the Geocapacity internet application, with a network superimposed on a Google Maps background

2.2 Outline of the local decision support system

Once the network is ready, all available data can be assembled in a zip file and downloaded, to serve as input for the local DSS.

The local tool performs a stochastic analysis of the costs of a CCS project. The stochastic character in the tool lies in its Monte Carlo approach, in which the input is varied according to user-defined stochastic properties of the input data. The tool is capable of handling multiple sources and multiple sinks in a single scenario and it contains data for the Netherlands and for almost all other EU member states which allows for cross-border CCS to be analysed. An example of output from the local application is shown in Figure 4.

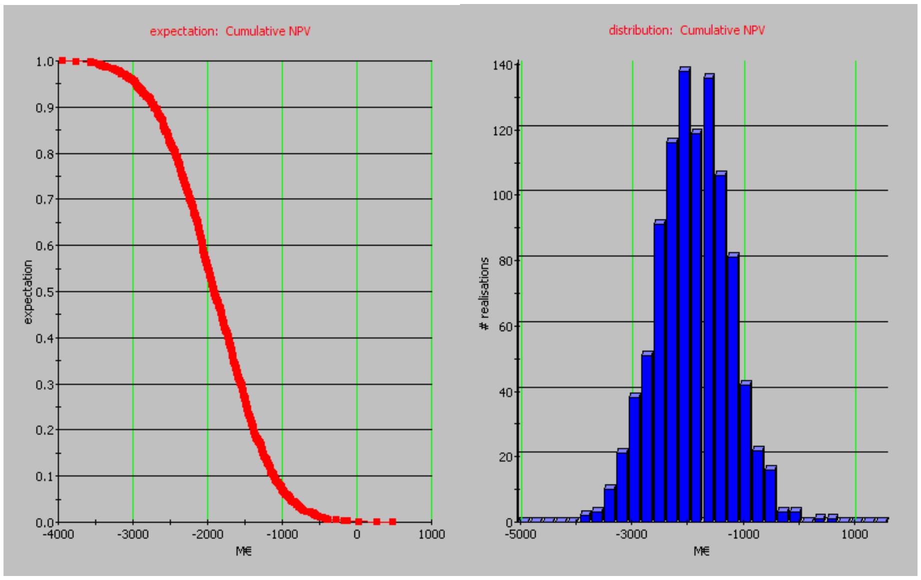


Figure 4. Examples of output from the local application: NPV for a hypothetical CCS project. Left: results presented in the form of an expectation curve; each red dot represents the outcome of a single Monte Carlo run. Right: results presented as a histogram

The analysis of economic feasibility of CCS is split up into several parts that are executed consecutively. This chain of computations is performed many times, once for each Monte Carlo run.

1. Sources. Capture and compression modules compute the performance and cost of capture and compression systems for each source in the project.
2. Sinks. Storage capacity and injection rates are computed for each sink in the project.
3. Source – sink match. In each Monte Carlo run, sink properties can be different, leading to varying degrees to which the captured CO_2 can be stored in the sinks.
4. Network update. The CO_2 flows from the sources and to the sinks vary among the Monte Carlo runs. These variations lead to different pipeline capacity requirements and, hence, to different transport costs.
5. Economic analysis. The costs of all elements of the CCS chain are accumulated, taking into account investments, maintenance costs, tax, etc., to arrive at the net present value (NPV) of the project.

2.3 Database

2.3.1 Emission sources

The DSS uses the database of CO_2 emission sources that was compiled in the Geocapacity project. The reader is referred to Kirk et al. [2009] for a description of the database fields and for a brief outline of the emission points in the Netherlands and of the other participating countries. The database contains all information on the emission points that is required for the DSS input.

2.3.2 Storage locations

Storage locations are taken from the database collected in the EU Geocapacity project. Aquifers and hydrocarbon fields (gas fields, oil fields) are used as potential storage reservoirs for CO_2. All information in the database that is relevant for the computations of (elements of) the CCS chain are used, as a starting point. To allow new information to be added in CCS projects analysed with the economic tool, the database information can be edited, before it is entered into the different modules. Data editing does not result in changes in the original database.

2.3.3 Existing pipeline locations

A database of the location of existing pipeline networks has been compiled. As noted above, the computation of the new network does not take into account the location of existing networks. Instead, the user has the option of aligning the new network with existing infrastructure, to increase both the reliability of the estimated length for the new pipelines and the visual appearance of the new network.

2.4 Modules

2.4.1 Capture

The capture module calculates energy use, emission characteristics - as resulting emission and emission avoided - and economics of the capture process, depending on the main characteristics of the selected sources of carbon dioxide and the capture technologies applied. For instance for the capture of carbon dioxide extra energy is required. The way the energy is supplied depends on the CO_2 source and the capture process. In addition, energy use for the capture of CO_2 will lead to additional production of carbon dioxide. This additional carbon dioxide can be produced on-site at the selected plant or elsewhere (external). In the module calculations, the additional CO_2 produced on-site due will be captured with the same rate as the original produced carbon dioxide within the selected plant. Externally produced CO_2 is not subject to capture on-site, but will be taken into account in the overall calculation of the percentage CO_2 avoided. Relevant information from the capture module is transferred to the modules Compression and Economics.

In the next sections, a description is given for each capture technology on the main conditions taken into account in the calculation module.

Post-combustion capture from flue gases of industrial processes

For post-combustion capture from industrial flue gases it is assumed that the capture technology is based on chemical absorption. The main conditions that determine energy use, CO_2 emissions and capture, and economics are (1) concentration of CO_2 in the flue gases; (2) pressure of the flue gases; (3) energy use of the capture process; (4) availability of waste heat; (5) associated produced CO_2; (6) start and duration of the capture; (7) investment and annual costs of the equipment.

Energy use. As an example, the energy use of the capture process depends on the CO_2 concentration of the flue gases. Figure 5 depicts the heat requirement versus carbon dioxide concentration. This fit is constructed for capture installations, which are well integrated with the basic plant operations (the heat requirement varies from about 4 MJ/kg at low concentrations to about 2.8 MJ/kg in the flue gases of 20% and higher). When the capture installation is constructed in an existing plant (retrofit), normally a less heat efficient system can be implemented. In the case of retrofit, we assume that the heat requirement increases with about 30% compared to an optimal integration.

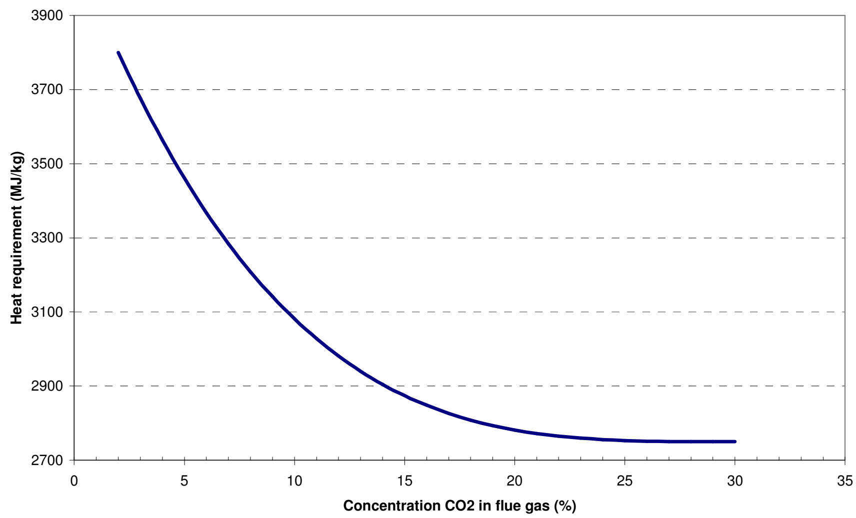


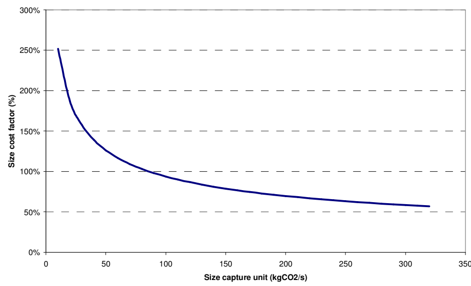
Figure 5. Heat requirement fit for amine-based capture process of carbon dioxide from flue gases for maximum heat integrated systems

Power consumption is related to the concentration of the carbon dioxide in the flue gases (lower concentrations results in higher amounts of flue gas compression) and to the amount of solvent to be pumped. Specific electricity consumption is modelled as:

Specific electricity consumption = 20 + 400/(%CO_2 in flue gas) [kJe/kg CO_2]

Waste heat availability: The availability of waste heat varies per type of industry and per industrial site. The standard availability percentages of waste heat per industry is tabulated, but can be adjusted if more specific information is available.

Investment costs capture unit: The investment costs are dependent on the size of the equipment, the concentration of CO_2 in the flue gas, and the learning rate. Figure 6 depicts the modelled relationships for capture unit size versus specific capital investment, and CO_2 concentration in flue gas versus specific capital investment, respectively. Generally speaking, for large chemical installations doubling plant size may lead to increase of capital investment between up to 70%.



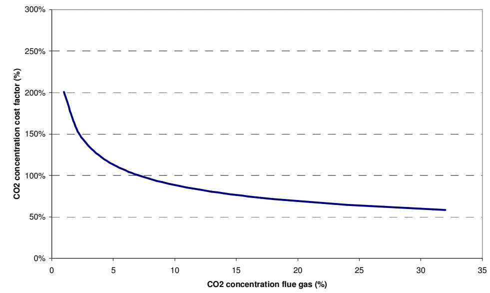


Figure 6. Relationship between capture unit size and relative specific capital costs (left figure), and relationship between CO2 concentration in flue gas and relative specific capital costs (right figure)

O&M costs and energy costs: The operation and maintenance costs consist of labour costs and material costs (solvent and additives consumption, disposal of spent materials). The fixed O&M costs are estimated at 3% of the initial investment costs. In addition a variable O&M costs factor can be used. This factor takes the operational time into account. This factor varies from 4 to 6% of investment costs (on full capacity) and depends on the type of installation.

The user of the DSS can alter the default values when they believe that better information on the selected capture process are available, or wants to execute a sensitivity calculation.

Post-combustion capture from flue gases of power plants

For the post-combustion capture from flue gases from power plants, it is assumed that the capture technique is based on the chemical absorption process using amines. This capture technology uses proven technology (on a commercial scale) and is economically attractive. Main issues are:

Integration and investment costs: A CO_2 capture unit can be added to a power plant without major changes in the design of the plant. However, it might lead to a decrease of the net efficiency of the power plant, due to less steam available in the low-pressure turbine to produce electricity and a negative impact on plant efficiency resulting from removing of SO_x/NO_x. An estimate of energy efficiency decrease of power plants and the specific investment costs are presented in Table 1.

Table 1. Loss in efficiency by capturing carbon dioxide (at 100% capture base) and investment cost capture unit for 500 MWe power plant using amine-based capture technology for various type of power plants. Retrofit efficiency loss values are assumed to be 2% higher than new values reported in this table. Retrofit investment costs are assumed to be 30% higher than new values reported in this table

Type of power plant	Efficiency loss post-combustion capture (%)	Investment capture unit (M€/(kg/s))
Steam turbine or boiler (solid fuels)	10.0%	3.4
Steam turbine or boiler (gaseous fuels)	6.5%	2.7
CHP (solid fuels)	10.0%	3.4
CHP (gaseous fuels)	8.0%	2.7
Combined cycle (solid fuels)	9.0%	3.7
Combined cycle (gaseous fuels)	8.0%	3.7
Internal combustion (all fuels)	2.5%	7.9
Gas turbine (all fuels)	2.0%	6.7

O&M costs: The operation and maintenance costs consist of labour costs and material costs . For chemical absorption unit these fixed O&M costs are estimated at 4% of the initial investment costs. In addition a variable O&M costs factor can be used. This factor takes the operational time into account. Default this factor is 2%, 3%, and 4% for natural gas-fired, oil-fired and coal-fired power plants, respectively.

Pre-combustion capture from power plants

Table 2 shows the loss in efficiency by capturing carbon dioxide (at 100% capture base) and investment cost capture unit for 500 MWe power plant using pre-combustion capture technology for various type of power. Retrofit efficiency loss values are assumed to be 2% higher than new values reported in this table. Retrofit investment costs are assumed to be 30% higher than new values.

Table 2. Loss in efficiency by capturing carbon dioxide (at 100% capture base) and investment cost capture unit for 500 MWe power plant using pre-combustion capture technology for various type of power plants. Retrofit efficiency loss values are assumed to be 2% higher than new values reported in this table. Retrofit investment costs are assumed to be 30% higher than new values reported in this table

Type of power plant	Efficiency loss pre-combustion capture (%)	Investment capture unit (M€/(kg/s))
Steam turbine or boiler (solid fuels)	9.0%	2.7
Steam turbine or boiler (gaseous fuels)	9.0%	4.7
CHP (solid fuels)	9.0%	2.7
CHP (gaseous fuels)	11.0%	4.7
Combined cycle (solid fuels)	9.0%	3.3
Combined cycle (gaseous fuels)	11.0%	4.9

Oxy-fuel combustion capture from power plants

Table 3 shows the loss in efficiency by capturing carbon dioxide (at 100% capture base) and investment cost capture unit for 500 MWe power plant using pre-combustion capture technology for various type of power. Retrofit efficiency loss values are assumed to be 2% higher than new values reported in this table. Retrofit investment costs are assumed to be 30% higher than new values.

Table 3. Loss in efficiency by capturing carbon dioxide (at 100% capture base) and investment cost capture unit for 500 MWe power plant using oxy-fuel capture technology for various type of power plants. Retrofit efficiency loss values are assumed to be 2% higher than new values reported in this table. Retrofit investment costs are assumed to be 30% higher than new values reported in this table

Type of power plant	Efficiency loss oxy-fuel capture (%)	Investment capture unit (M€/(kg/s))
Steam turbine (solid fuels)	10.0%	3.4
Steam turbine (gaseous fuels)	6.5%	2.7
CHP (solid fuels)	10.0%	3.4
CHP (gaseous fuels)	8.0%	2.7
Combined cycle (solid fuels)	9.0%	3.7
Combined cycle (gaseous fuels)	8.0%	3.7
Internal combustion (all fuels)	2.5%	7.9
Gas turbine (all fuels)	2.0%	6.7

Parameter files for capture module

A number of data files contain all parameters needed by the capture module.

Capture at power plants: Parameters pertaining to capture processes at power plants are stored on the file ‘captureParametersPower.dat’. Parameters are given for each combination

(72 combinations in total), for which all parameters for a specific combination of conversion technology (steam turbine, CHP, combined cycle, internal combustion, gas turbine, and fuel cell), capture technology (postcombustion, precombustion, oxyfuel, high-purity CO_2), plant type (new, retrofit) and fuel type (solid, gaseous) are given.

Capture at non-power plants: The capture parameters for non-power plants are stored in a file 'captureParametersNonPower.dat'. This covers 48 combinations of industry (ammonia, cement, chemicals (other), ethylene, ethylene oxide, hydrogen, iron & steel, non-iron metals, oil & gas processing, paper & pulp, refineries, other), CO_2 capture technology (post-combustion, high-purity CO_2) and plant type (new, retrofit).

Energy parameters: Energy parameters are stored in the file 'energyParameters.dat'. This file contains emission factors and price of the fuel types, as well as specific electricity costs and electricity grid emission factors for the EU27.

2.4.2 Compression

The compressor module calculates energy use, emission characteristics and economics of the compression unit. Calculation of electricity use and investment costs is based on (relative) difference in pressure (in-out) and flow. The module receives its input information from the capture module, from the databases with default values and (optional) from user input.

The captured carbon dioxide needs to be compressed to transport it to a pre-defined storage location. The transport is done by pipelines. The default inlet pressure of the pipeline is 120 bars. A centrifugal compressor unit pressurises the carbon dioxide. It is assumed that the compressor unit is a stand-alone unit, which obtains power from the grid (or an alternative power production source). The electricity use contributes to additional emissions of carbon dioxide, and costs are involved. Depending on inlet pressure, required outlet pressure and flow, the compression module calculates the electricity use, additional carbon dioxide emissions and associated costs (investment costs, O&M costs and energy costs).

The main conditions that determine these parameters in the compressor module calculations are:

- Size of the captured carbon dioxide stream (retrieved from the capture module)
- Compression is done by a four-step centrifugal compressor. Water is removed during the first compression stages.
- Electricity is taken from the grid. Power consumption is calculated by formula (left) below.
- Investment costs are calculated by formula (right) below.
- Operation and maintenance costs are 5% of the investment costs.

$$E = C_{e1} \ln\left(\frac{P_{outlet}}{P_{Inlet}}\right) F \quad (1)$$

with:

E electricity use (kJe/kg)

P_{outlet} outlet pressure (Pa)

P_{inlet} inlet pressure (Pa)

C_{e1} constant (87.85 kJe/kg)

F CO_2 flow (kg/s)

$$I = \left(C_1 F^{C_2} + C_3 \ln\left(\frac{P_{outlet}}{P_{inlet}}\right) F^{C_4}\right) F \quad (2)$$

with:

I total investment costs (M€)

C_1 constant (0.1 10^6 €/(kg/s))

C_2 constant (-0.71)

C_3 constant (1.1 10^6 €/(kg/s))

C_4 constant (-0.60)

Investment costs compressors: Investment costs for compression depend on the compression ratio and the (peak) flow. Reported costs on compression of carbon dioxide vary significantly. Figure 7 gives an impression of the range of the specific investment costs reported.

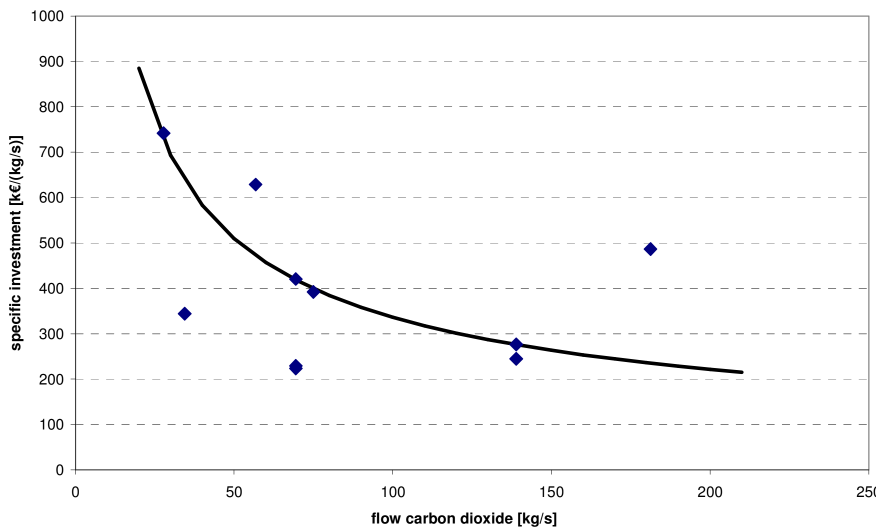


Figure 7. Compression costs from literature (dots) and the relation used in the DSS for compression from 1 to 120 bars (solid line)

2.4.3 Storage

Storage capacity: The storage capacity is listed in the database and can be used directly in the economic tool. For depleted gas or oil fields, the method of computing CO_2 storage capacity is straightforward: it is assumed that the volume of CO_2 that can be injected is given by the extracted volume of oil or gas. The database contains additional fields that allow the relation between produced volumes and CO_2 storage capacity to be recomputed, as well as to estimate the associated uncertainty. Storage capacity calculations use the total proven production, the volume factor and the density of CO_2 to recompute the storage capacity. Pressure and temperature values determine the CO_2 density, using the data given by Span and Wagner [1996].

For aquifers, the method of computing the quantity of CO_2 that can be injected was established after the database was filled. As a result, the aquifer capacity values reported by different countries differ in the underlying algorithm and are, in general, too optimistic. In the case of aquifers, the database contains parameters that allow a more exact capacity computation. It is advised, when sufficient data is available, to recompute the storage capacity for all aquifers in the CCS scenario with the more exact algorithm.

Three algorithms are provided for the estimation of aquifer storage capacity, with increasing level of complexity.

- Use the capacity value listed in the database. As mentioned above, this may lead to optimistic capacity estimates and inconsistencies in the underlying approach.
- Use a fixed percentage of the available pore volume.
- To compute the storage space created for CO_2 through compression of the pore fluids.

Injection rates: As far as the geological properties of a reservoir are concerned, the storage volume and injection rate are the key parameters that determine whether a reservoir is useful for CO_2 storage. Similar to the computation of storage volume, two algorithms are provided for the computation of injection rates.

- The first option is to use fixed rates that are input by the user. Typical values for injection rates are 0.5 – 1 $MtCO_2$/yr for depleted gas fields and lower values for aquifers (0.2 – 0.4 $MtCO_2$/yr). These values are used for a single well, independent of the CO_2 level inside the reservoir. In the source – sink match algorithm, the maximum number of wells is input by the user.
- The second option allows a more exact estimate of injection rates to be obtained. The injection rate depends on the level of CO_2 in the reservoir and, hence on time; it is calculated in the capture module and passed through to the storage module.

Cost calculations: The calculation of storage cost includes site development (for onshore locations) or platform construction (for offshore storage locations) and drilling cost. Additional costs, such as site surveying cost, feasibility studies or monitoring costs can be included either in the site development or platform construction cost, or in the operation and maintenance cost. The construction period of a platform or of an onshore site is used to spread the total cost over the specified number of years. Wells are assumed to be drilled and completed in one year. The source(s) – sink(s) matching algorithms (see next section), provide the start year for each storage location; the site development costs are incurred in the year prior to the start year.

2.4.4 Source - sink matching

Although the user has performed a (simple) source – sink match in the web application, the match must be repeated in each Monte Carlo run. The match algorithm computes the flow of CO_2 from the sources to the sinks: it determines the order in which the sinks are used and computes the CO_2 fluxes for each of the sinks throughout the lifetime of the scenario. The capacities, injection rates and start years of the sinks determine whether all CO_2 captured at the sources can be stored.

The user has the choice between two algorithms for the selection of sinks: sink size and sink distance. In both algorithms, sinks are ordered first by the year they become available. As a second step, in a given year the available sinks are sorted by their storage capacity or by the distance from a particular source.

1. Sink size. In this algorithm, available sinks are ordered by their storage capacity. When a new sink is needed, the largest sink is chosen. This is reasonable from the point of view of minimising site development costs, but may lead to large, remote sinks being developed earlier than smaller, nearby sinks, generating high transportation costs early in the CCS project. In each year of the scenario, the total volume of captured CO_2 is distributed over the sinks, regardless of source – sink distance.
2. Sink distance. This algorithm orders sinks by the distance from a given source, measured along the network. This algorithm may lead to nearby, relatively small sinks being developed first, leading to new sinks to be developed soon after that. In general, this algorithm results in lower transport costs, as the construction of the longer pipelines is delayed. In this algorithm sources are connected to a number of sinks, which are chosen on the basis of source – sink distance.

2.4.5 Transportation

The CO_2 is transported from sources to sinks through a network of pipelines. The network is generated using an algorithm that finds the shortest connections between every source and every sink. The connections can be either direct or indirect, i.e. connections that use already existing pipelines.

Once the network is generated, the size of the pipeline segments can be adjusted (or changed, during the network update process) to the maximum expected flow of CO_2. When the pipe diameter is known, the costs of the network can be calculated. The pipeline costs are accumulated to determine the total cost of the network (the investment, and the operational costs), for each year of the scenario.

Route selection: The network is generated using a stepwise approach – every source-sink connection is created in a single step (it is the shortest connection from all the possibilites examined within the step). The first connection is created quite simple – the algorithm iterates through all sources and for every source it iterates through all sinks, checking which direct connection is the shortest. Once there is at least a single direct connection, next connections can be created using the already generated pipelines – the algorithm looks for a shortest one including the direct ones and those which use existing pipelines. The indirect connections are determined by connecting to some existing pipeline (again, all the pipelines are checked) and recursively searching the destination sink.

*Cost optimisation of the pipeline***:** The cost of every pipeline is based on several physical and economical factors. First of all, the *diameter* of the pipeline has to be calculated. It depends on how much CO_2 has to be transported in a time unit. While modifying the network (setting the size of pipelines in order to make it possible to transport the CO_2) it is possible to determine costs of different configurations of the thicknesses (as the topological structure doesn't change once it has been generated). The costs of those configurations are compared and the cheapest one is chosen.

Network updata: The lay-out of the network is fixed in the Monte Carlo runs. Allowing each Monte Carlo run to generate a new network would result in long computation times, as either the user would have to edit each network manually, or an automatic algorithm would have to solve the complex many-on-many network optimisation problem. The solution chosen here is to update only the size (diameter) of the pipelines in each Monte Carlo, using the flow rates that follow from the source – sink match algorithm.

2.4.6 Economics

The economic module combines the cost results from the source, sink, transport and storage modules into a number of economic parameters, such as the net present value (NPV) and unit cost (in units of € per tonne of CO_2 avoided).

For each element of the CCS chain (capture, compression, transport, storage), the NPV is computed, which is the sum of the discounted investments and operation and maintenance costs.

For scenarios where income from CO_2 credits is taken into account, cash flow and tax is computed. In addition, the program computes pay-out time, internal rate of return (IRR) and maximum exposure. The tax is applied to the taxable income, which is equal to the income from CO_2 credits, minus the investments in that year. When investments over past years can also be deducted, if uplift is larger than one (uplift is a tax measure to allow investments not to be profitable during a given number of years), these are included. The taxable income can not be negative.

Cash flow *in* is computed as the CO_2 credits minus tax; cash flow *out* is defined as the sum of CAPEX and OPEX. The net cash flow is the difference between cash flow *in* and cash flow *out*. Discounted cash flow is cash flow corrected for a discount rate.

The unit cost of CCS is equal to the cumulative discounted cash flow, divided by the cumulative amount of CO_2 avoided, with the latter corrected for the effect of discounting. Unit cost has units of €/t$CO_{2,\ avoided}$. Unit cost is only computed for the complete CCS project.

Maximum exposure is defined as the maximum negative discounted cash flow Pay-out time is defined as the first zero crossing of the cumulative discounted cash flow. The internal rate of return (*irr*) is the discount rate for which the NPV of the project becomes zero. A positive NPV is obtained for higher discount rates, while lower discount rates will result in a negative NPV.

2.4.7 Input data

The local application uses the data on the sources and sinks selected with the internet application, supplemented with data on energy, prices and economics that are mostly to be added in the local application.

The data on sources and sinks is taken from the database, either directly or by combining database fields. The Geocapacity database is incomplete, in the sense that some database fields have not been specified for some sources and sinks (missing data) and not always consistent (database fields with varying units). This will lead to unexpected results when the database content is used without a final consistency check by the user.

3 Case study –Rijnmond area

The DSS has been tested for a CCS system in the Netherlands. The CCS system, however, has not been optimised neither is based on existing plans for capturing from these plants or storing CO_2 in the chosen storage locations.

3.1 Main characteristics of CCS system

The sources and sinks for the case study are located near Rotterdam, the Netherlands. CO_2 is captured from two existing power generation plants and stored in three nearby almost depleted gas fields. Two of the sinks are onshore and one is offshore. The start year of scenario was set to 2003 and it presumed that capture of CO_2 activities starts in 2008, for a period of 30 years.

3.2 Sources and sinks systems

The two power plants run with steam turbines and the combustion fuel for both plants is natural gas. During capture process, it is assumed that post combustion technology is used to capture the CO_2. It is assumed that 100% of the flue gases will be treated with a capture rate of 90%. Data of emission sources are listed in Table 4.

Table 4. Summary of the sources' input parameters in the GeoCapacity Model

Source Name	RoCa (E.on)	Galileistraat (E.on)
Type of industry (sector)	CHP	CHP; peak load
Plant name	RoCa	Galileistraat
City	Rotterdam	Rotterdam
Country	the Netherlands	the Netherlands
Longitude	4.56 E	4.43 E
Latitude	51.97 N	51.91 N
Production (unit/y)	2050 (GWh/y)	1568 (GWh/y)
In operation since	1995	1988
Peak CO_2 emission (kg/s)	29.63	18.52
Yearly CO_2 emission without CCS (Mt/y)	0.8	0.5
Type of capture process	Post-combustion	Post-combustion
First year of capture	2008	2008
Last year of capture	2038	2038
Load hours (hr/yr)	7500	7500
CO_2 capture fraction (%)	90%	90%
Fuel type	Natural gas	Natural gas
New / existing	existing	existing
Power type	power plant steam turbine	power plant steam turbine

As mentioned above, three nearby almost depleted gas fields are selected for storage. The storage capacity of the two onshore sinks is estimated to be around 9 million tonne and

8.5 million tonne, respectively, and the capacity of the offshore sink is around 13 million tonne. The reservoirs are assumed available from 2008. In this Rijnmond case study the maximum reservoir pressure was set to 100 bars. More data related to the sinks are shown in Table 5.

Table 5. Summary of storage sinks' input parameters in the GeoCapacity Model

Sink Name	Maasdijk	Wassenaar	P18-2
Sink type	Natural gas field	Natural gas field	Natural gas field
Depth (m)	1000	1000	1000
Year sink is available (assumed in calculation)	2008	2008	2008
Onshore / offshore	onshore	onshore	offshore
'Exact calculation'			
Current reservoir pressure (bar)	30	30	30
Maximum reservoir pressure (bar)	100	100	100
Rock compressibility (bar^{-1})	0.0	0.0	0.0
Reservoir radius (km)	1.63	1.16	5
Trap radius (km)	1	1	1
Reservoir thickness (m)	25	25	25
Porosity (%)	20	20	20
Volume factor *(gas or oil fields only)*	0.0052	0.0052	0.0041
Proven production *Gas fields: bcm ($10^9 m^3$)* *Oil fields: Mm^3 (10^6 m^3)*	2.2 bcm	2.0 bcm	4.0 bcm
Reservoir temperature (°C)	60	60	90
Permeability (mD)	316	31.6	10
Well radius (m)	0.15	0.15	0.15
'Rough calculation'			
Storage capacity ($MtCO_2$) *Value in Geocapacity database*	7.9	7.2	11.4
Well injection rate (Mt/yr)	0.5	0.5	0.5

3.3 Transport

The internet application computes network of pipelines. The network generated is an efficient network, in terms of capacity and total pipeline distance, as shown in Figure 8.

Figure 8. Pipelines network computed by the network algorithm

However, this network algorithm does not take into account land use. For example, the network should try to avoid cities, freeway crossings and should be constructed as much as possible along existing pipelines corridors and freeways. To improve it, here the route of the pipeline sections was altered, to create a more realistic pipeline routing. The colour of pipelines was changed as well, to make it more distinguishable between onshore (red) and offshore (blue) segment (see Figure 9).

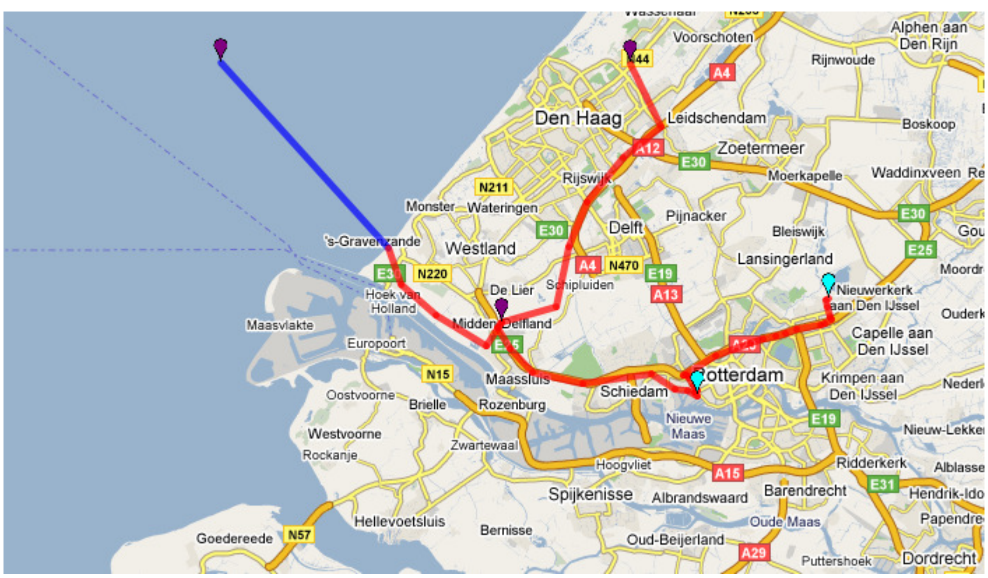


Figure 9. Realistic pipeline network after adjustment by the user

3.4 Results

3.4.1 Source/sink match

When running the web-based tool, s simple source-sink match is computed, to see whether the yearly production of CO_2 can be stored throughout the duration of the CCS project. This matching algorithm does not prioritise sinks by distance or volume; its use is to show whether the total storage capacity is sufficient for the captured CO_2. The outcome of the source/sink match is shown in Figure 10. From this figure it can be seen that from the start year of injection in 2008 until year 2033, there is no ‘injected gap, which means all captured CO_2 can be stored in the selected sinks. After that the ‘injected gap increases since the storage capacity is used up (shown in Figure 11). This implies that during the last 5 years of the CCS project, no storage capacity is available.

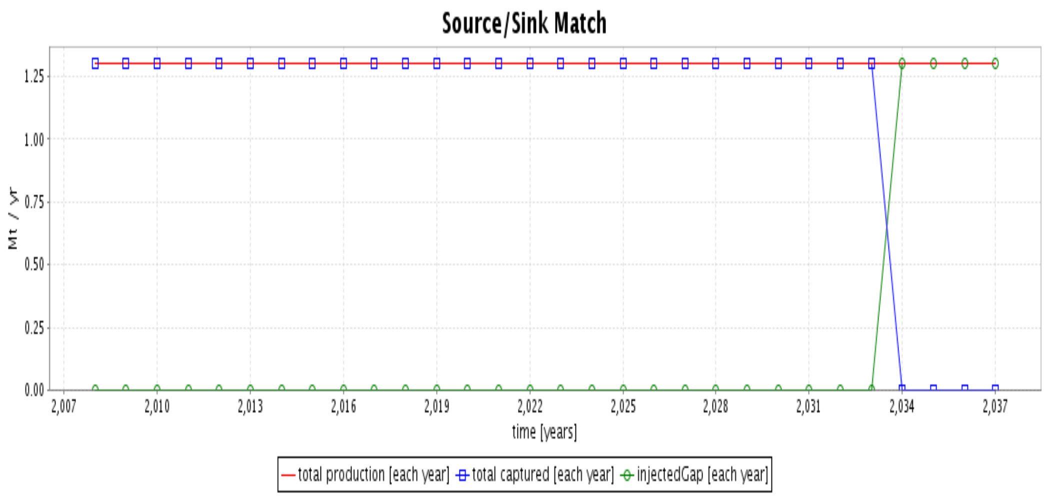


Figure 10. Source/sink match scenario

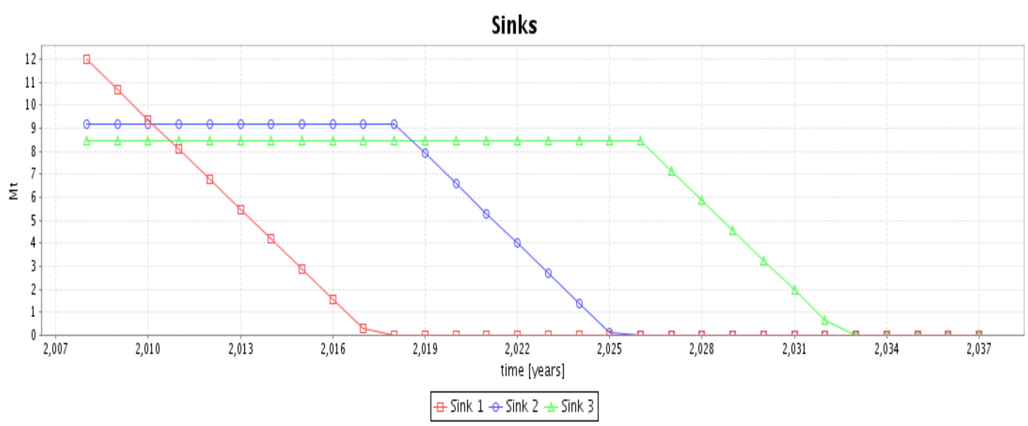


Figure 11. Sinks’ storage capacity scenario

3.5 Economic analysis

Scenario parameters, source data, sink data, capture and compression parameters as well as network data are downloaded to local computer for an analysis of economic feasibility of CCS. For this part the tool performs a Monte Carlo analysis, to provide the users with an estimate of the costs of the CCS project.

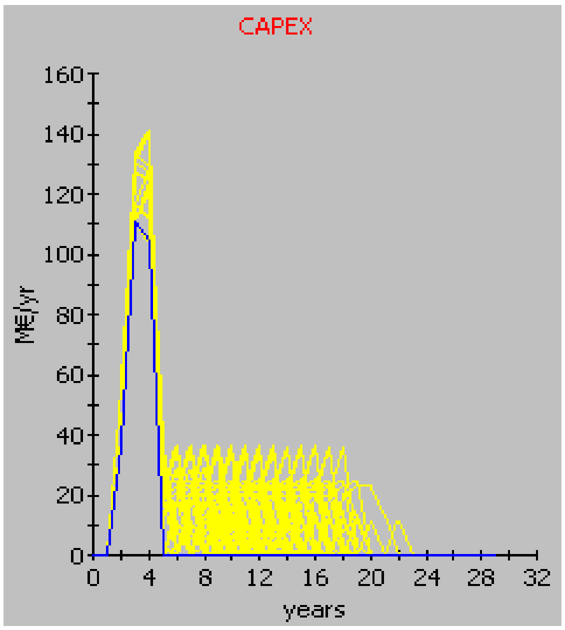


Figure 12. Investment costs (CAPEX) during the lifetime of the CCS project

Figure 12 shows, as an example of the results from the DSS calculations, the total investment costs in the CCS project, during the lifetime of the project. The yellow curves represent the results from individual Monte Carlo runs, while the blue curve shows the average. The figure shows that majority of investment costs occurs at the start of the project, due to huge cost of capture installations, construction of the initial elements of the networks and development of the sinks.

Figure 13 shows the total length of pipeline used in a given year in the scenario. In the Monte Carlo runs the network layout doesn't change. The pipe segment diameter changes, as well as the period each segment is used. The latter depends on the start and end of capture at each source site and the start and end of storage at each sink. There are as many curves in the graph as there are Monte Carlo runs. A total length of pipeline located at 20 km level indicates only one or a few sources and sinks are active while 80 km indicates that the entire network is being used.. There is a yellow line at 50 km level, which indicates that in some scenarios source(s) – sink(s) connections are possible with a total length of about 50 km, i.e. not all storage reservoirs are required. As the possibilities of activating part of the network are limited when two or three sinks are being used, after all curves collapse to either about 50 km of total pipeline length (two sinks active), or about 80 km of pipeline length (three sinks active).

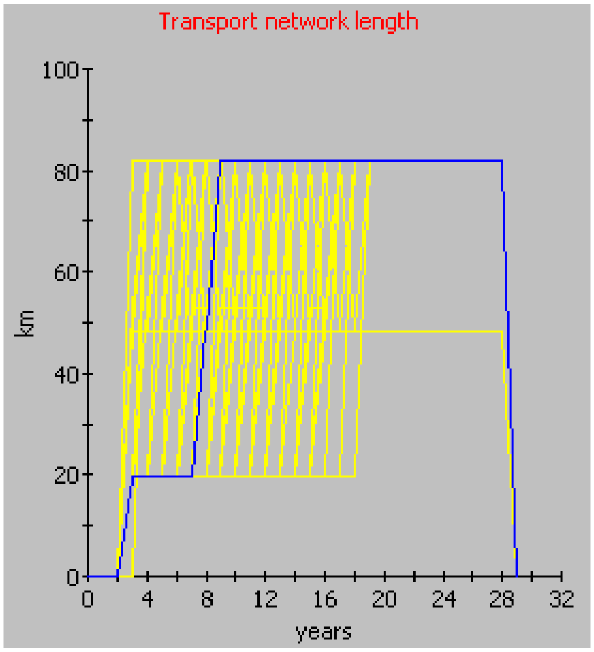
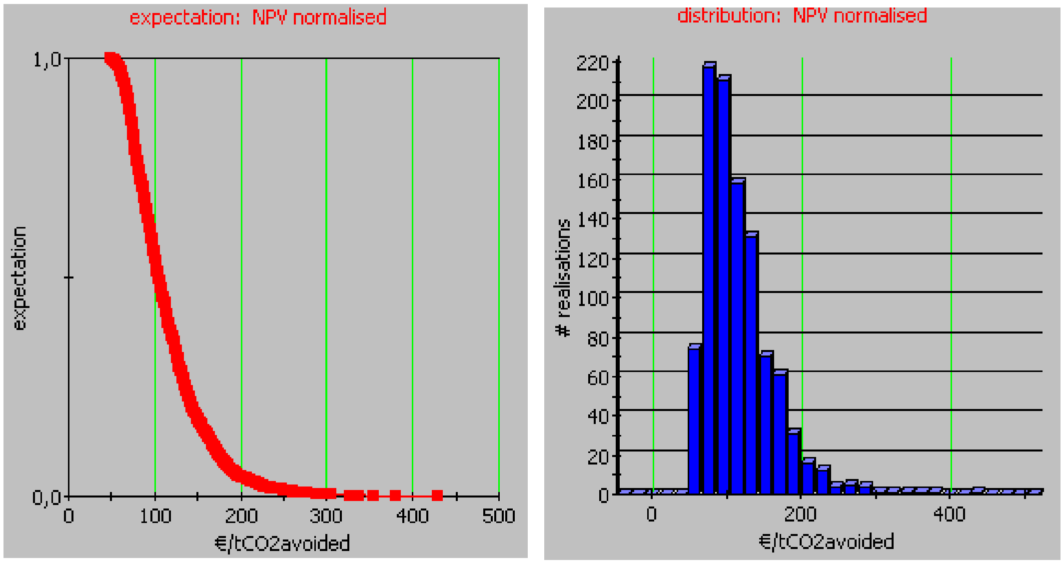


Figure 13. Total length of pipeline used throughout the CCS scenario lifetime

Figure 14 shows the probability distribution of the simulated values of CO_2 capture and storage unit costs per tonne of CO_2 avoided. The result can be presented in either form of expectation curve (left) or histogram bar chart (right). From the charts it is seen that majority of CO_2 capture and storage unit costs per tonne of CO_2 avoided distributes around 100 €/t $CO_{2avoided}$. The user-defined stochastic properties of the input data makes the cost ranging from 50 €/t $CO_{2avoided}$ to 200 €/t $CO_{2avoided}$.



expectation curve **histogram bar chart**

Figure 14. Probability distributions of the simulated values of CO_2 capture and storage unit costs per tonne of CO_2 avoided

Besides the economic analysis output, technical output like total sink injected volume throughout the CCS scenario, sink injected rate, number of wells used, etc are also generated in program. Figure 15 the case of injection rate of sink 1 (Maasdijk). The injection rate decreases after 10 years because it is the filling up.

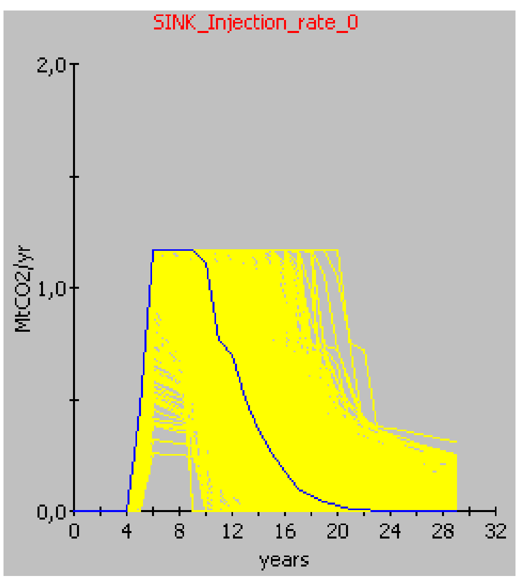


Figure 15. Injection rate of sink 1 (Maasdijk)

Besides charts output, the results of economic analysis are also shown in the form of direct data overview (Table 6).

Table 6. Overview of main results of economic calculations

Indicatortype: Economic

Indicator	p90 value	p50 value	p10 value	mean value	Unit
NPV	863,87	884,66	912,51	886,15	M€
NPV capture	675,07	675,07	675,07	675,07	M€
NPV compression	129,61	129,61	129,61	129,61	M€
NPV transport	4,84	6,59	9,53	6,83	M€
NPV storage	54,36	73,16	98,19	74,64	M€
NPV normalised	69,10	104,29	173,94	114,63	€/tCO2avoided
NPV capture normalised	53,05	79,61	132,02	87,11	€/tCO2avoided
NPV compression normalised	10,18	15,28	25,35	16,72	€/tCO2avoided
NPV transport normalised	0,41	0,82	1,50	0,91	€/tCO2avoided
NPV storage normalised	4,57	8,95	15,94	9,89	€/tCO2avoided
Internal Rate of Return	-99,00	-99,00	-99,00	-99,00	%
Unit technical cost	169,24	225,59	333,22	241,88	€/tCO2
Pay out time	30,00	30,00	30,00	30,00	yr
Maximum exposure	-794,37	-751,54	-707,85	-751,41	M€
SRC NPV capture 0	411,05	411,05	411,05	411,05	M€
SRC NPV compression 0	64,80	64,80	64,80	64,80	M€
SRC NPV capture 1	264,01	264,01	264,01	264,01	M€
SRC NPV compression 1	64,80	64,80	64,80	64,80	M€
SINK NPV storage 0	12,20	14,74	15,50	14,23	M€
SINK NPV storage 1	6,53	9,82	15,42	10,09	M€
SINK NPV storage 2	33,38	49,73	68,97	50,33	M€

From the Table 6 it can be seen that total cost (NPV) was calculated at 886 million € (mean value). The cost of capture process takes a majority percent share (76%) of total cost while compression, transport and storage take only 15%, 0.7% and 8.5% respectively. For the net present value (NPV) normalised it is about 115 €/t$CO_{2\text{-avoided}}$. Compared with the ETS market price which is around 10-15 €/tCO_2, this CCS project is not yet economically feasible.

4 Conclusions

The Decision Support System for CCS systems is able to analyse in a very flexible way potential capture and storage projects. These projects may consists of one source and one sink, but the DDS is also able to handle multiple sources and multiple sinks. Most of the required information for the evaluation is present in the database of the DSS, but depending on the exact formulation of the CCS system some additional information needs to be gathered by the user. On the other hand, any essential information available may be incorporated by the user, thus overriding default values present.

The DSS has been successfully tested to a Dutch CCS system around the Rijnmond area. The system, comprises of two sources (existing power plants with post-combustion capture) and three sinks of (nearly) empty natural gas fields. The DSS checks whether storage capacities are sufficient and designs automatically the optimal transport system. Routing can be adjusted easily to avoid obvious obstacles, when possible.

The DSS calculates economics and technical aspects of the system, together with emission characteristics. As the system incorporates probability ranges in the input data, via monte-carlo runs, distribution ranges of possible outcomes are generated. For the analysed system, the mean value of the costs are around 100 euro per tonne of CO_2 avoided, ranging from 50 to 100 euro/t. It was also shown that the chosen storage reservoirs were able to store captured CO_2 for 25 years instead of the requested 30 years.

The DSS has shown to be a valuable tool to analyse CCS systems. The tool will therefore be improved and used in the $CATO_2$ programme to analyse CCS systems, e.g. around the locations Rijnmond / North Sea and North-East of the Netherlands.

5 References

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