

Project no.:
218868

Project Acronym:
ECCO

Project title:
European value chain for CO₂

Instrument: Collaborative Project
Small to medium scale integrated project

Start date of project: 2008-09-01
Duration: 3 years

D3.1.1

Review of existing tools and relevant experience

Revision: Final

Due date of delivery: 2008-11-30d
Actual submission date: 2009-03-13

Organisation name of lead contractor for this deliverable:
SINTEF Energiforskning AS

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Deliverable number:	D3.1.1
Deliverable title:	Review of existing tools and relevant experience
Work package:	WP3.1 CO ₂ value chain assessment tool
Lead contractor:	01 SINTEF-ER

Status of deliverable		
Action	By	Date
Submitted (Author(s))	Per Eilif Wahl, SINTEF-ER	2009-03-13
Verified (WP-leader)	Per Eilif Wahl, SINTEF-ER	2009-03-13
Approved (SP-leader)	Christian Bos, TNO	2009-03-17

Author(s)		
Name	Organisation	E-mail
Jana Poplsteinova Jakobsen	SINTEF-ER	JanaPoplsteinova.Jakobsen@sintef.no
Bartosz Kus	SINTEF-ER	
Per Eilif Wahl	SINTEF-ER	Per.E.Wahl@sintef.no
Christian Bos	TNO	Christian.Bos@tno.nl
Filip Neele	TNO	filip.neele@tno.nl
Asgeir Tomasgard	NTNU	Asgeir.Tomasgard@sintef.no
Adela Pagès	NTNU	Adela.pages@iot.ntnu.no

Abstract
<p>This deliverable gives a description of some existing tools that are used for evaluation of CO₂ chains or that includes elements that are related to such evaluations. Each tool is described and the relevance of the tool for the ECCO project is further described. The functionality of the existing tools is used as a background for the specification of the ECCO tool.</p>

TABLE OF CONTENTS

1	INTRODUCTION	3
2	LITERATURE REVIEW ON CO ₂ CHAIN ANALYSIS	4
3	EXISTING TOOLS	5
3.1	CASTOR Economic Analysis Tool (CASTOR EA Tool)	5
3.1.1	The tool structure	5
3.1.2	Different modules of CASTOR EA Tool	6
3.1.3	Relevance for the ECCO Tool	9
3.2	Expand (SINTEF-ER)	10
3.2.1	Structure of the model	10
3.2.2	Main input and assumptions	10
3.2.3	EOR Model	11
3.2.4	Other financial elements of EXPAND	13
3.2.5	Relevance for the ECCO Tool	14
3.3	TNO Carbon Capture & Storage integrated model	14
3.3.1	Model output	16
3.3.2	Elements of the model	17
3.3.3	Relevance for the ECCO Tool	20
3.4	NTNU infrastructure model	20
3.4.1	The tool structure	21
3.4.2	EOR model	22
3.4.3	Calculation methods	23
3.4.4	Relevance for the ECCO Tool	24
3.5	IEA GHG tool	24
3.5.1	The tool structure	25
3.5.2	Cost estimation	26
3.5.3	Relevance for the ECCO Tool	27
3.6	Geocapacity tool	28
3.6.1	Outline of the internet Geocapacity application	28
3.6.2	Outline of the local decision support system	30
3.6.3	Outline of the Geocapacity analyses	31
3.6.4	Relevance for the ECCO Tool	35
3.7	Other tools	35
4	SUMMARY	37
5	REFERENCES	39

1 INTRODUCTION

The objective of SP3 is to develop methodology and a tool for CO₂ value chain analysis. As there are many questions and issues related to CCS and they are indeed of very various kinds it is important to first frame the problem we want to focus on and identify by what means the particular problem should be studied. In the ECCO proposal we suggest three basic means to analyse the CCS chain:

- Scenario
- Case study
- Simulation tool

It is necessary to understand the specific functions and characteristics of these as well as the close interconnections between them. Defining the tool functionalities and proposing the tool structure are the first objectives of working package WP3.1.

The purpose of this review is to establish state of the art within CCS analysis, review available published studies and existing tools and map the experience the partners co-operating within ECCO have with CCS analysis. As such this report will become an important starting point for the further work on specification of the tool to be developed within ECCO.

2 LITERATURE REVIEW ON CO₂ CHAIN ANALYSIS

Since 2005, several Norwegian techno-economic studies on selected CO₂ value chains have been published. In the following, four studies are briefly commented, quotation [1].

The OD study [2] documents a business economic analysis of two different CO₂ chains. The analysis is performed in an incremental manner (explained later). The report states that CO₂ for EOR is complicated but technically feasible. Economically a realization is not profitable, due to the large investment costs. The report states that today, there is not enough CO₂ available for EOR. By building new power plants or by CO₂ import more CO₂ may become available, but the long distances between the possible CO₂ sources will cause high transport costs. The study points out that CO₂ injection competes with other methods for enhanced oil recovery (EOR), e.g. alternating water and gas injection (WAG). It is concluded that further research is required to enable cost reductions.

In GASSCO [3], a techno-economic evaluation of 12 possible CO₂ value chains with sequestration in oil fields in the Norwegian continental shelf is presented. In the incremental analysis, none of the 12 identified CO₂ value chains have positive net present value. Injection of CO₂ for EOR in several fields gives more optimistic results, but this option requires yearly increasing amount of available CO₂ to utilize the EOR potential.

Bellona [4] presents a socio-economic analysis of a Norwegian CO₂ infrastructure in which the government participates in the CO₂ value chain development and takes on considerable investment costs. Aspects such as electrification of the Norwegian continental shelf, power plant construction, substitution of natural gas for EOR, reduced CO₂ quota cost, electricity export and increased taxation revenues from the oil companies are included in the analysis. The report concludes that development of the recommended infrastructure will be profitable for all involved parts.

In NVE [5], a techno-economic analysis of seven different CO₂ value chains is presented. The analysis is limited to power plant, CO₂ capture, conditioning and transport. CO₂ is sold offshore to licensees at the Norwegian continental shelf. The report concludes that the profitability of CO₂ capture and storage is too low for CO₂ value chain investments given the present circumstances.

Basically, all these studies on CO₂ value chain conclude that it is technically feasible to build the required CO₂ infrastructure, but the results vary with respect to profitability. This is not surprising, since the different authors chose different viewpoints and strategies in their analyses. Nevertheless, it is challenging to interpret and compare the results due to incomplete documentation of applied parameter values and lacking parameter sensitivity analyses. In addition, varying level of documentation of underlying data and assumptions complicates the evaluation of the results. Hence, the reported studies demonstrate the need for an adequate methodology for CO₂ chain analysis including an increased consciousness regarding presumptions and conditions.

3 EXISTING TOOLS

This section gives a description on some existing tools and also their relevance for the ECCO project.

3.1 CASTOR Economic Analysis Tool (CASTOR EA Tool)

The objective of CASTOR project was to study the final amount of CO₂ emitted to the atmosphere taking into account the captured CO₂ from new power plants equipped with capture technologies and the avoided CO₂. An overview of the related costs (e.g. operating & maintenance and investments costs) and revenues expected (benefits from Enhanced Oil Recovery (EOR)) are computed.

CASTOR Economic Analysis Tool was developed to compare different CO₂ reduction strategies on an economic basis. It is a computation program in Excel. The tool computes the investment costs regarding capture, transport and storage based on input data. Results from the simulation are presented in generated emissions, electric power demand and related cost plots.

3.1.1 The tool structure

Several modules have been developed in the CASTOR EA Tool, each with a specialized task, and operating on the data from the worksheets in Excel.

Four types of worksheets can be distinguished:

- **Input parameters data sheets:**
 - The “ProjectData” sheet groups the general parameters for the simulation. They refer to the number of sources, sinks and capture installations in the corresponding input sheets.
 - The “Sources” sheet describes the initial set of the operating and planned power plants (coordinates, starting year and expected lifetime, estimated CO₂ emission and full load hours of each individual power plant).
 - The “Scenario” sheet contains the electric demand scenario for the thermal power plants. The user may use its own data in this sheet.
 - The “Prices&Taxes” sheet provides the CO₂ tax, price of emitted CO₂ in Euro per tonne and the Enhanced Oil Recovery price in Euro per barrel (bbl) up to 2050.
 - The “Transport” sheet contains the on- and offshore transport distance.
 - The “Sinks” sheet lists the geological storage sites. Parameters like availability of the sink, expected storage capacity, storage type, injectivity, depth of the reservoir, water depth etc.
 - The “Site” sheet describes the expected evaluation and development costs for sinks that are utilized to store the captured and avoided CO₂.
- **Input parameters on the capture side data sheets:**
 - The sheet “NewSourceTypes” lists the various source types that can be generated in the source generation module. It provides the data for the increment of new capture technology and the range of power capacities of the newly generated sources.
 - The “ExistingCaptureTechnologies” sheet groups the details of the capture costs and gives the costs of CO₂ avoided and CO₂ captured for each capture technology.

- **Intermediate results data sheets:**

- The “NewSourcesGenerated” sheet uses The Sources Sheet format and lists the newly generated power plants which are generated after running the program when electricity demands become higher than the available power capacity.
- The “MegaWattProfiles” sheet shows the initial and newly generated power sources and the total power capacity on a yearly basis in TWh.
- The “CO2Emission Profiles sheet” shows the total CO₂ emission, produced by the sources, and the captured, avoided, and emitted CO₂ on a yearly base.
- The “CO₂ Injection sheet” concerns the injection of the emitted CO₂ into the available sinks as defined in the Sink sheet.
- The “Transport” sheet displays the number of ships necessary to transport CO₂, the pipeline diameter and the outlet pressure.

- **Revenues expenditures and cash flow data sheets:**

Revenues and expenditures are calculated for each step of the CO₂ sequestration.

3.1.2 Different modules of CASTOR EA Tool

The source generation module

This module builds a set of new fossil-fuel fired power plants to satisfy the electricity demand up to the year specified by the user in the Project data sheet. The NewSourceType sheet lists the newly generated power plants. Each source type refers to a post combustion capture technology. The number of MWh generated by both the initial and newly generated sources is listed in the MegaWattProfile sheet. As an output from the module we receive power production plot (Figure 1).

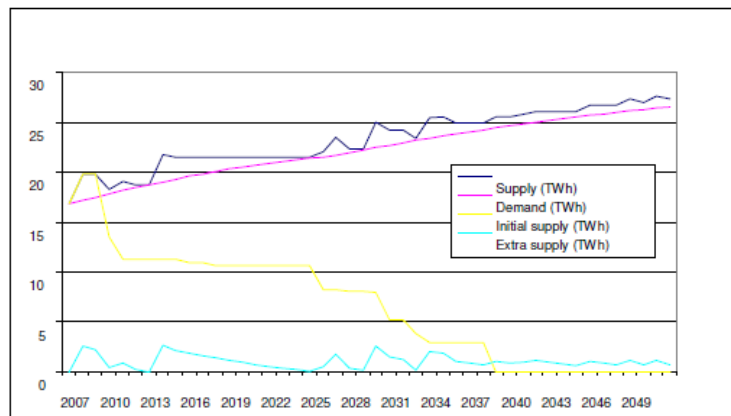


Figure 1: Power production plot from The Source Generation module.

In yellow the initial supply from the existing power plants is illustrated. The ‘extra supply’ curve depicts the extra generation of energy by power plants equipped with capture technology. The deployment of new sources relates to the energy demand curve (pink curve). The blue curve shows the total supply of both initial sources and newly generated sources.

The possible new sources that are generated during a specified period of time have to be defined by the user. A new source type is defined by a series of fields, including:

- the year of availability of the new source
- the power in MW of the source
- the life time of the source type
- the capture technology used per source type

The capture module

The computations are based on the results of the Baseline Economics of the CASTOR project (deliverable D.1.1.2), in which the details of the post-combustion CO₂ capture are described. They include the compression costs inherent to the pipeline transport system, with a CO₂ delivery pressure after capture of 110 bars. The capture module computes the emitted, captured and avoided tonnes of CO₂ and the corresponding investments and O&M costs. The output data sheet will summarize the results for each newly generated source, as well as the total number of newly generated sources on a yearly base. The results depend on the post-capture technology used and are a function of the power capacity, of the operation time and of the lifetime of the source. The additional costs related to CO₂ capture as a result of additional fuel consumption, are a function of the fuel price. The natural gas or bituminous coal prices at the start date of the project are input values of the Prices&Taxes sheet (in €/MWh). An energy costs index is computed from the oil price per barrel (€/bbl) which is a user input in the Prices&Taxes sheet.

The differential investment costs are computed. That means: the investment needed for a new source with CO₂ capture and the investment that would have been necessary for the same new power source without capture technology. The specific investment costs, expressed in M€/kWe, are defined in the ExistingCaptureTechnologies sheet. The capture investment for a new source is obtained by multiplying the differential costs of a specific investment with the power capacity of the new source.

The operating & maintenance costs are expressed in percent of the investment, which is a function of the power capacity.

The distinction between the captured, avoided and emitted CO₂ before and after a capture technology is introduced. The amount of CO₂ emitted, captured and avoided (in kg) are functions of the full load hours of the source. As the time increment is one year, no variation of electricity consumption between seasons can be taken into account.

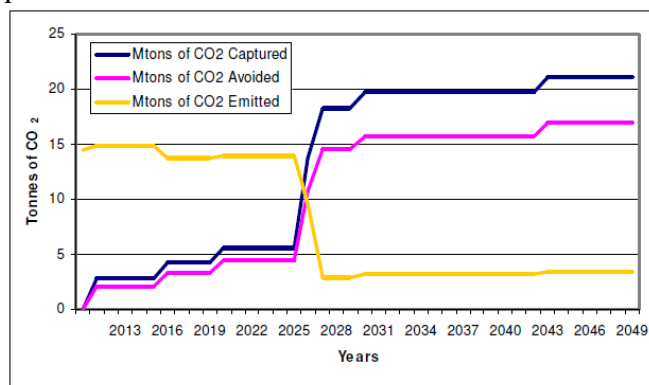


Figure 2: CO₂ emitted, captured and avoided.

Figure 2 represents the profiles in time of the CO₂ emitted, captured and avoided. These values are obtained by summing up the values of the operating sources for each year.

Transport module

Pipeline investment costs: The diameter of the pipeline depends on the maximum emission rate. It is calculated as a function of the flow rate, the velocity and the density of CO₂.

Booster Station Investment Costs: The investment costs for booster stations, that are used to recompress the CO₂ during long distance transport, is assumed constant and incorporated as costs per kilometer. The booster station costs are assumed to be 7 M€ for onshore stations and 14 M€ for offshore stations.

O&M costs of the pipeline transport are split into two groups of costs, namely variable costs (pumping energy) and fixed costs (O&M costs). Assuming an average pressure difference per booster station of $\Delta p = 4$ MPa, CO₂ density of 800 kg/m³, and pumping efficiency of 75%, the energy consumption amounts to 6.7 kJ/kg (1.9 kWh/tonneCO₂) per 200 km.

The O&M costs are calculated by taking a fixed percentage of the total investment costs.

Storage module

The costs of an individual storage facility will depend on the area, the type of reservoir and its local physical properties (flow rate) and the amount of (exploration) work necessary to access the reservoir (e.g. depth and number of wells). Based on lifetime, the well injection capacity and the storage capacity, the number of wells necessary to fill the sink is calculated. It is assumed that CO₂ is delivered by pipeline or by ship at the storage facilities and is pressurized to 8 MPa. No injection pumps are necessary. The pipeline is directly connected to the well head. Pressure monitoring and safety valves are part of the wellhead equipment.

A division in 4 classes of capital investment costs (CAPEX) is made:

- Site evaluation costs
- Site development costs
- Drilling costs
- Monitoring costs

One of the purposes of the EA tool is to show when, how much and in which sink CO₂ is injected. The injection volumes are shown for each individual source with the total amount of CO₂ that should be injected into the sinks, and the total emission that is present. The availability of sinks is sometimes not in line with the captured CO₂.

Cash flow module

Costs and revenues related to storage correspond to the taxes, the incomes, the investments and the O&M costs of the sequestration chain. Results are summarized on a yearly base in the Cash-flow sheet per sink and will be plotted along with the capture and transport costs for analysis. All these items are regrouped and printed for each source, for the transport infrastructure and for the storage of the captured CO₂ in crude values as well as in discounted values in the Cash-flow sheet.

The revenues from oil recovery during CO₂ storage are taken into account. The costs of the sequestration chain are:

- The CO₂ tax in Euro per tonne of CO₂ emitted
- The investment costs for capture, transport, buffer and storage steps
- The O&M costs of the capture, transport, buffer and storage steps.

All costs and revenues are displayed in crude values and in Net Present Values. The total Net Present Value is obtained by summing all the discounted values of the project.

The CASTOR Economic Analysis Tool was developed to be utilized as a strategic support tool for developing CO₂ reduction strategies. The economic feasibility of CCS projects is analyzed in an integrated approach. For each part of the CCS process varying input data is utilized, e.g. type of fuel use of the source, full load hours, coordinates of sources and sinks, well injection capacity, etc. Also, different databases are used to construct the background of the calculations in the tool, e.g. costs for developing a transport infrastructure, costs of the capture technology. The output data is visualized in Excel worksheets. With these results a comparison can be made between different CCS projects, especially when varying projects have been computed with the use of this tool.

3.1.3 Relevance for the ECCO Tool

The CASTOR EA Tool is implemented as an Excel workbook with additional VBA (Visual Basic for Applications) code. Most of the calculations are performed by the VBA code. Some calculations are also performed by the cells (some simplified calculations on the ExistingCapture Technologies worksheet due to different type of information stored in different units and the calculation of well injection capacity on the Sinks worksheet). All other values are either specified by the user or calculated by the VBA code. There also exists a set of named elements that are references to other worksheets that are not available. It is not known whether some of these names are in use. There is one command button for the actual calculation of the worksheets. Except for this button all user interactions are performed on the cells in the worksheet. All charts that are created are embedded in the worksheets.

The VBA code is based on fixed locations for most of the cells having input values. The number of cells for the calculated values is dependent on the input parameters and is based on a relative position to some cells that are fixed. This makes sure that there are only cells that have been calculated are displayed, in contrast to systems where a predefined set of cells are created (a set of cells that are large enough to handle all foreseen sizes of the problems). Since the cells that are referenced by their row and column, the user must be careful when modifications are made to the worksheets. The addition of a row or a column where it was not intended will prohibit all calculations. Most likely this is only of minor importance for an experienced user, but could cause problems for a newbie. There is no help system available. The user must be precise in the specification on the ProjectData worksheet. There is no consistency checking for the number of units (sources, sinks etc) and the number of units actually specified. There does not seem to be any checking of values prior to the calculation in order to help the user to give a consistent input specification.

The different modules (sources, sinks and transportation) are easily inserted by adding one row and edit the appropriate cells. All modules are only represented as individual elements; there are no connections between them and no checking for consistency of the chain.

One nice feature is that the specifications of the sources and the sinks are based on an Excel output from the Gestco database. In that way existing elements may be selected. A direct

connection to the Gestco database could perhaps have been implemented in order to further improve the tool.

3.2 Expand (SINTEF-ER)

The EXPAND model is an Excel based economical model that calculates NPV and cash flow from sources, pipes and sinks in a CO₂ value chain. The model uses module set up consisting of source, capture, transportation and storage module. Each module, a source, pipe or sink, has one worksheet each where all calculations concerning the module is done. This makes the calculations easy to follow, as the user can see all calculation and how it changes as the user alters the assumptions.

It is important to remember that the model analyses the incremental effect of CO₂ capture. It will therefore provide the background for decisions regarding the integration or not of a capture process but it should not be used as background for decisions regarding the construction of a power plant, for instance.

Building a case

Making new cases and selecting the data needed is made automatic. In addition a library function has been added. This simplifies and reduces the amount of time needed to construct new case models, and also is a natural place to store information on already developed modules.

3.2.1 Structure of the model

The model is organized in the following worksheets:

- **Sensitivity analysis:** It contains the parameters that are considered as critical for the value chain and the most relevant results. The user can vary these parameters and see immediately the effect on the results. The variations are presented as % of the input values presented in the worksheet “Assumptions”.
- **Assumptions:** It contains all the input values to the financial model and the main assumptions for the calculations.
- **Prices:** It contains price profiles for electricity, gas, oil, CO₂ quotes and CO₂ tax as a function of time. All profiles are built based on two input values in the Assumptions sheet: start value and slope for increase/decrease with time.
- **Source:** It contains the investment and operational costs, possible incomes, gas and electricity consumptions, and CO₂ flows for the post-combustion capture plant as a function of time. It also contains the investment and operational costs, electricity consumption and CO₂ flows for the compression (and impurity removal) plant as a function of time.
- **Transport:** It contains the investment and operational costs for the pipeline as a function of time.
- **Sink:** To complete the module based framework the oil production and the income calculation are stored in this sheet.

3.2.2 Main input and assumptions

This section explains all inputs to the model, as they are shown in the worksheet “Assumptions”. For the sake of clarity, the inputs are organized in sections, mainly corresponding to the modules in the financial model:

Economic basis

- Interest rate: 7%
- Period of analysis: 25 years
- Economic lifetime: 10, 20 or 25 years, depending on operation period
- Operating hours: 330 d/y
- Currency value: 8.00 NOK/EUR, 6.50 NOK/USD
- Annual operator labour cost: 400 000 NOK/y per operator onshore
600 000 NOK/y per operator offshore

3.2.3 EOR Model

The EOR model that is implemented in EXPAND, uses four input parameters to calculate an EOR window. The length of the time window is an input parameter which is chosen for each sink. The model is programmed to start the time window as the sink starts EOR production. The total EOR potential per sink is decided as the product of the total recoverable amount of oil in the field and the EOR potential, which is a percentage of the total recoverable oil. When both the EOR potential and the EOR time window are known a rectangular EOR window is constructed. If the EOR production in one year exceeds the EOR potential the production is set to the potential limit, no matter the size of the CO₂ input.

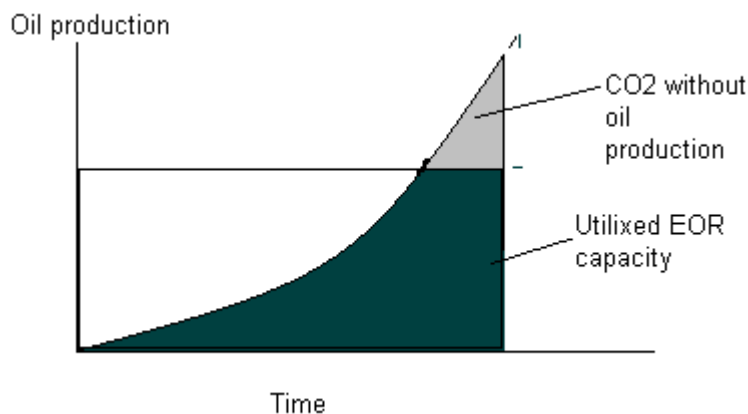


Figure 3: Enhanced oil recovery vs. CO₂ pumping time

Another important part of the model is the EOR yield from each amount of CO₂. The model assumes that ideally each ton of CO₂ inserted gives a fixed amount of oil. This amount of oil is recoverable during the 5 years after the injection and in the same amount each year. If the injection point is closer than 5 years to the production end, the full potential of the injection will not be utilized. The same is the case if the production exceeds the EOR capacity as discussed above.

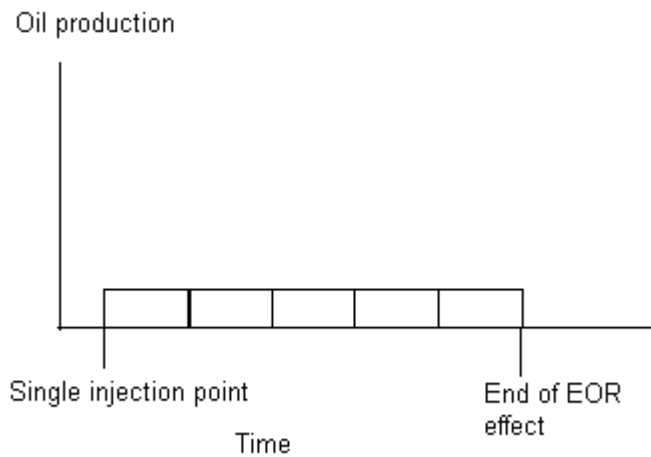


Figure 4: CO₂ injection potential dependent on injection time

This model reflects positively on the EOR effect from the CO₂ injected early in the EOR time window, and negatively on the CO₂ injected late in the EOR window.

The oil income from EOR also includes increased oil production that comes as a consequence of prolonged production, as seen in Figure 5 and named Indirect EOR oil. This oil is not directly related to the CO₂ injection, but is recovered as a result of the increased profitable production life.

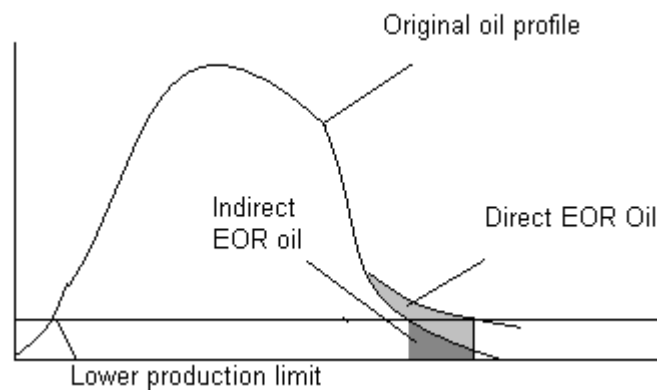


Figure 5: Direct and indirect EOR oil

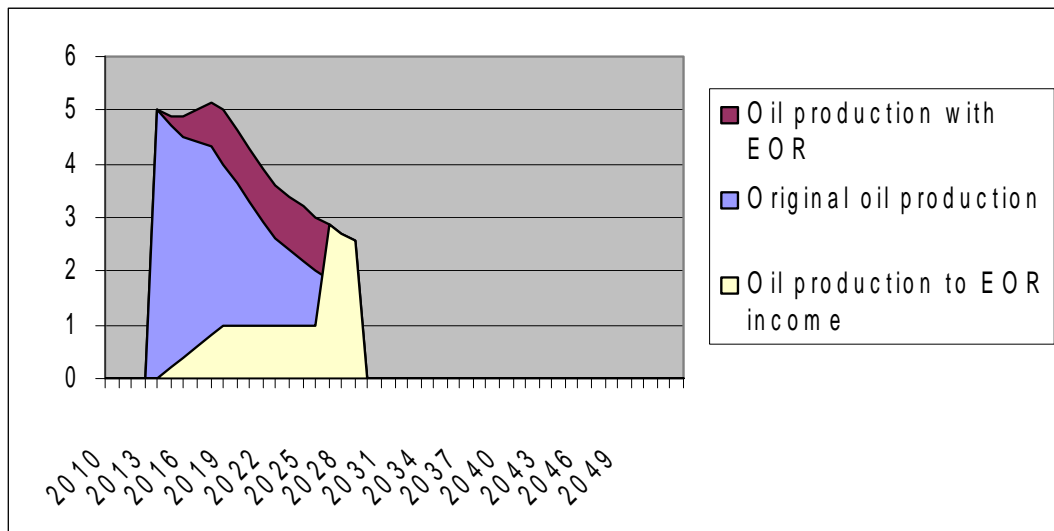


Figure 6: Oil production with EOR in time window.

The EOR capacity, EOR time window and EOR effect per ton CO₂ is field-dependent values in EXPAND, so that the user could choose different EOR properties in the different sinks.

3.2.4 Other financial elements of EXPAND

Delayed decommission cost

As a result of prolonged production, the decommission cost comes at a later date than originally planned. Relative to the EOR project this is an income at the original decommission date, and an expense when the sink is decommissioned with EOR. The cost of decommissioning the sink is assumed to be equal in both years. There is as a consequence no positive net cash flow in the period, but since the negative cash flow comes at a later date the delayed decommission cost has a positive effect on NPV.

Increased OPEX cost

During the first years of EOR production the sink is in regular production, and the EOR project will only have to cover additional OPEX costs directly dependent on the CO₂ injection. However, after the original decommission year the EOR oil production has to cover the entire OPEX costs for the sink, as the sink would be out of commission without EOR. It will also gain some extra income as the EOR project is granted all oil production after the post decommission date as discussed in the EOR model chapter.

CO₂ emission cost

In the EXPAND model the sinks incur a quota cost when they emit CO₂.

Investment profile

In EXPAND the investment is paid at once with a large negative cash flow early in the modules life. This is the same solution chosen in the CASTOR EA Tool. Instead of loan interest, the cost of invested capital is related to the discount rate in the NPV model.

3.2.5 Relevance for the ECCO Tool

EXPAND is a program implemented in Excel using VBA. The VBA code is used for computation, user interactions and maintenance of modules. It is restricted in that few modules are implemented, but the network itself is conveniently represented. Like all Excel applications it is best suited for a simple chain with few modules that will not be modified except for numerical values. Each module is clearly a separate unit and the calculations are performed within each module. It is also assumed that the economic parameters for each module have been established before the unit is added to the chain. In that way modifications of one unit that changes the amounts in the chain will not be reflected in the cost parameters for the other successor units. The only exception is that the amount of CO₂ for the successor units will be recalculated. The user will then have the possibility to check whether the assumptions used for the economic parameters have been violated.

EXPAND also introduces a library of units that have been fully specified. The user may then insert predefined modules into the current chain. Since everything is stored within one workbook, the use usage of this will be limited. Every time a new case is created a new copy of the workbook will be created and both the code and the library may develop within different branches. In addition the representation is also heavily dependent on named cells in Excel. This makes it very difficult to maintain and extend the system.

The tool is dependant on many worksheets. Some of these should have been hidden from the user since they are not intended to be modified by the user. In addition some of the names that are used in the cells are template names that initially are not defined but are only defined when an actual module is created. Since these names are not defined for the templates it looks like the worksheet is full of errors. In order to help the user to navigate between the worksheets a small toolbar has been created for this purpose. For tools relying on many worksheets this is a good idea. Most of the user interactions take place on the “Sensitivity” worksheet where a set of buttons have been put in an unorganized way. The buttons are a mix of ActiveX control buttons and Excel buttons. The motivation for having different types is unknown, but for practical purposes it does not matter which type that are used.

There is some limited help functionality within the tool based on the office assistant. Four specified text strings are sequentially displayed in order to guide the user in how the tool is used. The user will have to go through all of them. The office assistant has been removed in Office 2007 (Office 12). Having help functionality is crucial, but it must be implemented in a different way.

There exists a skeletal for a newer version of Expand (working title Catena) which has a more flexible representation of its structure. It consists of a set of classes and their relations. It is not a tool that is ready to be used, and most of the internal calculations have not been implemented. However the structure is useful as a basis for the tool that is to be implemented in the ECCO project. It is implemented in C#.

3.3 TNO Carbon Capture & Storage integrated model

The model is a tool to support the investment decision-making and planning processes for a single depleted gas field that is to be converted to CO₂ storage operation.

The model is an Excel model that can be run with a statistical plug-in, such as Crystal Ball or @Risk, in order to compute histograms of Key Performance Indicators (KPI). With such

outcome, sensitivity analysis can be easily done (tornado plots, etc.) and risks quantified per decision alternative.

The general philosophy of the model is to provide a tool that integrates uncertainty modelling, physics and planning/economics (Technical-to-Business integration: T2B). Not only in an absolute sense, but also relatively (i.e. when comparing alternative decision options and scenarios) is it important to closely integrate physics, cashflows and planning. Since the physics have an important impact on both timing and quantity of most CAPEX and OPEX items and, hence, also determine the magnitude of the cash-in items, models that correctly incorporate these relationships generally compute forecasts that are significantly different compared to more loosely integrated or simplified models. Obviously, this may come at a cost of technical detail: the spatial and temporal resolution in this CCS XL model is very coarse as only analytical formulas are being used. In our opinion, however, such trade-off is warranted when, for decision-making / planning purposes, a high spatial and temporal resolution is less important than a closely integrated probabilistic T2B model.

A further principle of the tool is that the life-cycle of the asset can be modelled, i.e. including the transition from gas production operations via facility mothballing to CO₂ storage operations and storage site monitoring operations (see Figure 7).

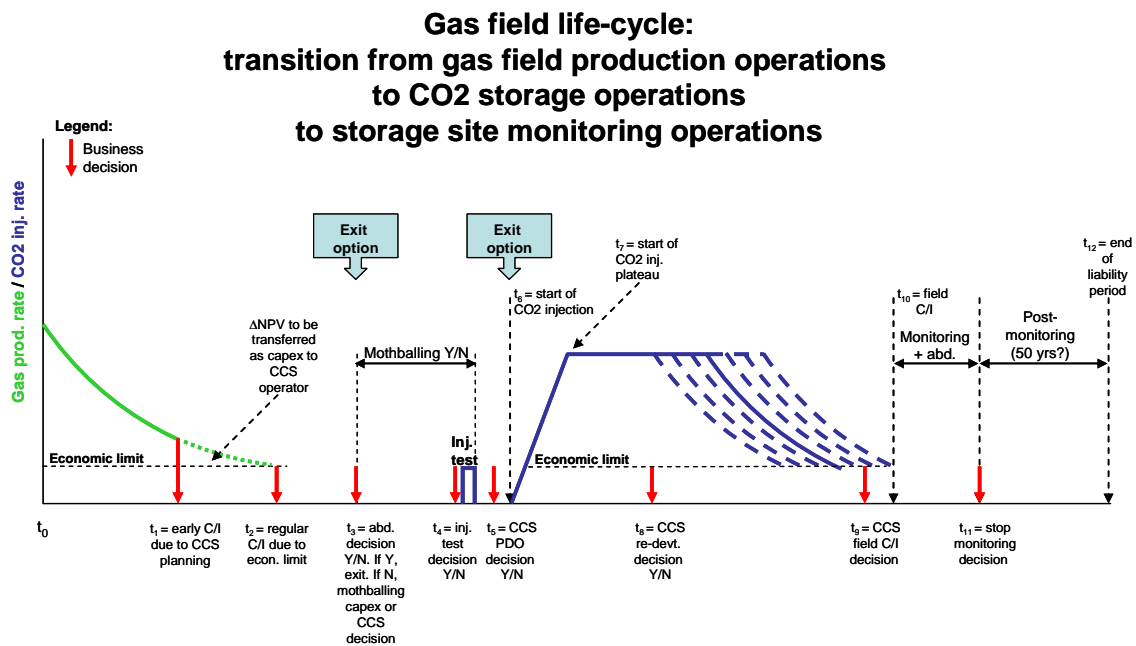


Figure 7: The life-cycle of the asset

A final principle is that the full CCS value chain is calculated: the ETS CO₂ price can be modelled (e.g. by correlating it to an oil price scenario), the capture costs are modelled (e.g. by a cost decline curve assuming a certain technological progress and learning curve), and the transport tariff is calculated (based on a calculated CAPEX and OPEX, and assuming a user-defined post-tax IRR for the transport system operator). This results in the net wellhead CO₂ price remaining for the storage operator. This CO₂ wellhead price is then used to perform the economic calculations for the storage operator.

3.3.1 Model output

Per life-cycle phase (injection phase and, if applicable, post-injection phase) and per stakeholder (according to the equity shares that may change in time), the model computes and plots all relevant time-series and (histograms of) KPIs such as:

- Total CO₂ injected
- PV CO₂ injected
- PV Government Take @PV discount rate%, ref year
- PV subsidies
- NPV@PV discount rate, ref year,
- IRR
- Maximum exposure (undiscounted CF)
- Maximum exposure (discounted CF)
- PIR undiscounted
- PIR discounted
- Unit Technical Cost (undiscounted cost/ton CO₂)
- Unit Technical Cost (PVcost/ton CO₂)
- Break even CO₂ price (with and without subsidies)
- Pay-out time (undiscounted cashflow)
- Pay-out time (discounted cashflow)
- Nr of additional platforms / well clusters constructed
- Nr of injection wells drilled (additional wells, i.e. on top of pre-existing wells)
- Nr of compressor trains installed
- Operational injection years of CCS site

Moreover, per KPI the “risk” can be calculated (= cumulative probability of not meeting a hurdle rate, multiplied by the probability-weighted average value of those samples that do not meet the hurdle rate). Finally, uncertain time-series can be plotted as probabilistic curves (e.g., the P90-P50-P10 etc injection rates, cashflows etc).

An example of graphical output for the storage operator is given below.

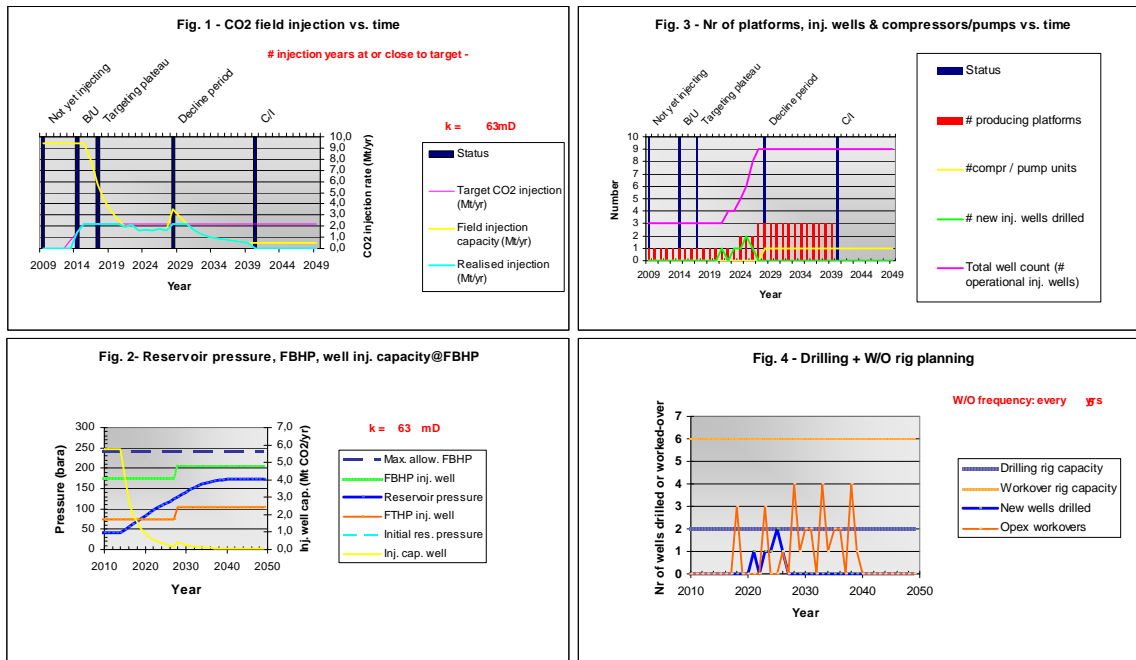


Figure 8: Graphical output for the storage operator

3.3.2 Elements of the model

Integrated CCS field model

The integrated CCS field model is a full-field injection/cashflow model, i.e. individual wells or field-sectors (e.g. fault-blocks) cannot be modelled. For input variables that are heterogeneous in space and/or changing in time, it is assumed that they can be adequately represented by field-wide average values. To establish injection rates the model assumes a targeted CO₂-plateau injection rate, followed by a decline period that is controlled by the increasing reservoir pressure and by the injection well’s tubing head pressures. To achieve the targeted rates, either pre-existing wells are brought on stream (after a workover), additional wells are automatically drilled, or additional compressor trains are installed, taking account of the replenishing field and, hence, gradually reducing well injection capacities.

The targeted rates will only be achieved if the injection wells can deliver it. At a given maximum number of wells or maximum number of compression trains (this is a controllable decision), it is no longer attempted to achieve the targeted rate and the field injection rate declines according to the material balance P/Z graph. All injection is corrected for a constant load factor. All injection is total field injection: individual well performances are not modelled, but the number of new wells required to achieve the targeted total field CO₂ injection rate is calculated from the difference between the total injectivity (installed injection capacity) and the targeted gas injection rate in the previous year (output), and from the individual well injectivity prevailing in the current year.

Therefore, the targeted CO₂ injection rate will not always be met: the trigger to drill new wells or to install a (new) compressor train lags one year behind the deficiency between target and achieved injection rate. The number of injection wells to be drilled each year is then used to calculate the yearly drilling expenditure (DRILLEX) and, hence, depreciation, tax and NCF.

Material balance

The material balance is assumed to be a straight line relationship between P/Z and cumulative remaining gas in place (at the onset of injection into a depleted gas field) + cumulative CO₂ injected (tank model). Pore compressibility and possible active aquifers are ignored. Similarly, compartmentalisation (i.e. restricted, delayed X-flow between the reservoir compartments) and gas in tight streaks (i.e. excluded from the net sand count, although still contributing to the material balance in the longer term) are ignored.

Available pore volume

The Gas Initially in Place (GIIP) of the depleted gas field is calculated from the basic volumetric input parameters (Gross Rock Volume, net-to-gross, porosity, water saturation, initial expansion factor). Each of these parameters may be subject to uncertainty (the expansion factor by giving a distribution to the initial reservoir pressure). The remaining gas in place upon handing over the field from gas production operations to CO₂ injection operations is user-defined, and may also be subject to uncertainty.

Well inflow performance

All wells are assumed to be identical. Their inflow performance is calculated from the semi-steady state inflow equation using pseudo-pressures. This requires the input of CO₂ PVT data (Z-factor, expansion factor and viscosity vs. pressure), reservoir data (permeability, thickness, reservoir temperature), and well / drainage area data (drainage area + shape factor, well radius, mechanical skin factor, non-Darcy flow coefficient). For the Flowing Bottom Hole Pressure (FBHP, or p_{wf}), the user can specify the “ Δp ” (i.e. p_{wf} minus reservoir pressure) as a % of the reservoir pressure prevailing at each time-step. Together with a maximum tubing constraint, this determines the well injection capacity at any point in the reservoir's P/Z vs. cumgas graph.

Vertical Flow Performance and Compression

The FBHP is controlled by the imposed FTHP and the achieved injection rate. A FBHP maximum_constraint can be specified to prevent damage (e.g. caprock fracturing) around the well. The reservoir pressure is allowed to increase until the minimum economic injection rate is achieved, following which injection is discontinued. A vertical flow performance (VFP) relationship is modelled to calculate the FBHP given the imposed FTHP. A minimum FTHP can be specified as a trigger to install compression, or to drill additional wells in order to meet a total field injection rate target. The CAPEX (DRILLEX or compression CAPEX) is automatically inserted at the right time-step using the user-defined costs.

Timing uncertainty

The timing of first injection is an input variable and, therefore, may be subject to uncertainty (by assigning it a pdf).

Plateau injection rate

The field injection rate is constrained by the targeted plateau rate: if the target is achieved, the field will not exceed this target even if it has more total injectivity at that point in time. The capacity of the installed facilities is assumed to be equal to the targeted plateau CO₂ injection rate.

Cash-in items (CO₂ price, subsidies, etc)

The CO₂ price is assumed to be the CO₂ pipeline exit point price, after subtraction of capture and transportation costs. The CO₂ price may be input as a time-series (price-deck), be

modelled as volatile time-series based on its historically observed volatility, or be correlated to other quantities such as the oil price. The oil price is assumed to be either constant over time (model 1), or to evolve in time (models 2, 3, 4). CO₂ price sensitivity analysis may be done by repeating a study at different CO₂ price models (and, if desired, updating CAPEX as a function of the changed oil price, i.e. if the two are correlated). The evolution of the oil price in time can be modelled based on user-defined characteristics (models 2, 3). A stochastic oil price volatility model (model 3) can be switched on. Alternatively, a corporate "price deck" can be entered (model 4). In a later version, the possibility to correlate CAPEX items (e.g. DRILLEX, compressor CAPEX, or new platforms) to the oil price prevailing at any point in time is planned to be included.

Subsidies can be specified as a user-defined time-series, as a function of the yearly CO₂ injected, or as a function of the difference between a target price and the price realised in a particular year.

Tax

The tax regime is based on corporate tax. The project is assumed to be ringfenced. To calculate the fiscal income, CAPEX is depreciated according to a straight line capital allowance formula (SLCA). The number of depreciation years is to be specified by the user. The depreciation schedule starts in the year that the capital was spent and, if applicable, an "uplift" schedule can be specified to compensate companies for the missed fiscal relief in years when the taxable income is negative (when the taxable income < 0, the companies are not in a tax position and, hence, cannot profit from the depreciation mechanism; usually this occurs in the early years).

In a later version, Depreciation At Will (DAW) may be supported.

CAPEX

Early (normally pre-injection) CAPEX items are directly input by the user as time-series. Injection dependent CAPEX items, such as DRILLEX (in order to maintain plateau injection), new platforms (or well clusters) or new compressor trains, are automatically calculated and included in the cashout time-series. New platforms are required when the maximum number of wells per platform is exceeded. Abandonment costs are automatically included a specified number of years after last injection (output) and can be specified either directly or as a % of total CAPEX installed.

OPEX

The fixed OPEX is input by the user as a time-series. Based on the user-specified input, the variable OPEX is automatically calculated for the following components: CO₂ injection OPEX (function of total CO₂ injection rate); compressor OPEX (function of CO₂ injection rate and Δp); CO₂ pipeline tariff; well OPEX (function of total number of injection wells in operation); well workovers (function of cost per workover and workover frequency per well); and scheduled / unscheduled compressor maintenance.

Compressor variable OPEX

Compressor OPEX per time-step is calculated from the achieved injection rates, the Δp from compressor inlet pressure (CO₂ pipeline pressure) to FTHP, the compressor's thermodynamic efficiency and the kWh price (which may be correlated to other prices such as the oil price). Moreover, to achieve supercritical conditions at the wellhead, heating of the CO₂ stream may be required. The OPEX of this heating is calculated as a function of the temperature

difference between compressor outlet temperature and required FTHT. This FTHT is then also used as starting point for the VFP calculation. Finally, scheduled and unscheduled compressor maintenance can be specified.

Equity shares

The equity shares can be input as time-series to obtain cashflows and KPIs per stakeholder / partner.

Post-injection phase

Financial risks associated with the post-injection phase, i.e. after the CCS site has been abandoned and the third party liability has been handed over to some other organisation (e.g. a state company or an agent responsible for monitoring and remedial action that may be required as a result of some residual risk) can be computed explicitly. Residual risk is user-defined as the probability of occurrence of some discrete event (e.g. leakage) at any time-step and the cost of remedial action. The probabilities may be (anti-) correlated or conditional in time (e.g. given an event in year n , the probability of occurrence in year $n+1$, $n+2$, etc is x).

3.3.3 Relevance for the ECCO Tool

The tool is entirely represented as a set of Excel worksheets. Its use of worksheets and charts is very well presented. Some worksheets could have been hidden for the user and some manual operations most likely could have been automated. It relies entirely on the Excel functionality that is accessible through the cells. It includes no additional code, except that the layout of the input and output parameters satisfies the criteria for using additional programs (add-ins) like Crystal Ball. These tools are used for sensitivity analysis. Since such tools already exists, the ECCO tool should be specified in such a way that it will be capable of using similar tools instead of implementing similar functionality within the tool.

The TNO CCS tool is a fairly sophisticated model compared to most of the other modules within the other tools. It includes simplified models for the calculation of the different economic parameters based on physical properties for the injection reservoir and the properties of the inlet CO₂ streams. The functionality of the tool serves very well as a basis for an injection module. The use of simplified models will also be useful as guidelines to how other units may calculate some of their financial parameters. The principles for the financial calculations are also very well suited for bringing into the ECCO tool.

Like all Excel application it will suffer from the lack of flexibility in that similar calculations are implemented in every cell. If a new case is to be used a new workbook is created (at least if the old case is to be stored). One must then keep track of the latest version of the workbooks in order to maintain the code.

3.4 NTNU infrastructure model

The tool is a mathematical optimization model that describes the investment in a CO₂ value chain. Given a set of CO₂ sources and a portfolio of CO₂ drains for plain storage or for EOR, this model seeks to optimize the net present value (NPV) by deciding timing and place for construction of pipelines, application of CO₂ for EOR and deposition of CO₂ in aquifers.

The focus is thus slightly different than other CO₂ value chain studies as we are not considering the profitability of a predetermined CO₂ value chain, but to try to find the optimal decision regarding treatment of captured CO₂ in the case where it cannot be vented.

The model is implemented and solved in Xpress-MP and reads the data from an Excel worksheet. The model has been tested on a base case of the Norwegian Continental Shelf for the period 2016-2040.

By performing a sensitivity analysis of the parameters used, it is possible to evaluate incentives and contract designs in order to secure a sound distribution of risk and profit within the value chain.

3.4.1 The tool structure

Input data

- **CO₂ sources:**
 - Source nodes available at the beginning of the study
 - Expected amount of CO₂ captured each year of the study.
 - Capture cost estimates: CAPEX and OPEX (including drying, cooling and compression of the captured CO₂).
- **CO₂ drains:**
 - Possible drain nodes: EOR fields and plain storage aquifers
 - EOR specification (time window, min and max CO₂ injection rate, starting year of the modification, CO₂ reproduction factor, CAPEX and OPEX per ton injected)
 - Aquifers specification (Yearly storage capacity, CAPEX and OPEX per ton of CO₂ injected)
- **Transportation – pipelines:**
 - Set of possible arcs linking CO₂ source with drain, source with source and drain with drain nodes.
 - Which pipelines can handle flow in both directions in different time periods
 - Set of possible pipe dimensions and cost estimates (the model will choose the cheapest dimension which meets the necessary capacity)
- **Economics:**
 - Expected oil price
 - Expected CO₂ quota (constant for all periods but may be different at each source).
 - Future cash flows are discounted to NPV using two discount rate factors (to ensure a one year delay between an investment is done and when income and operation costs start incurring), with an interest rate of 7%.

Output

- **CO₂ drains:**
 - Which and when drain periods are modified for injection of CO₂
 - Starting period of CO₂ injection for EOR or plain storage
 - Amount of CO₂ sequestered
 - Amount of CO₂ injected
 - Amount of extra barrels of oil recovered.
- **Pipe network:**
 - Most suitable pipelines and required size
 - Construction period of the pipe
 - Size of the pipe
 - Flow dynamics at each year
- **Economics:**

- Total NPV for the CO₂ value chain
- Analysis of the income and cost distribution
- Analysis of the CAPEX and OPEX distribution

Assumptions

- CO₂ production is assumed known and constant (from existing power plants)
- CO₂ can not be vented
- CO₂ capture technology at the source nodes is available at the beginning of the period under study
- Ownership structure is regarded as neutral: socio-economical optimum
- Transportation of CO₂ through pipelines is the chosen option
- The specific pressure levels in the network are not taken into account
- Lost sales from produced gas with high CO₂ contents are not accounted

Graphical representation

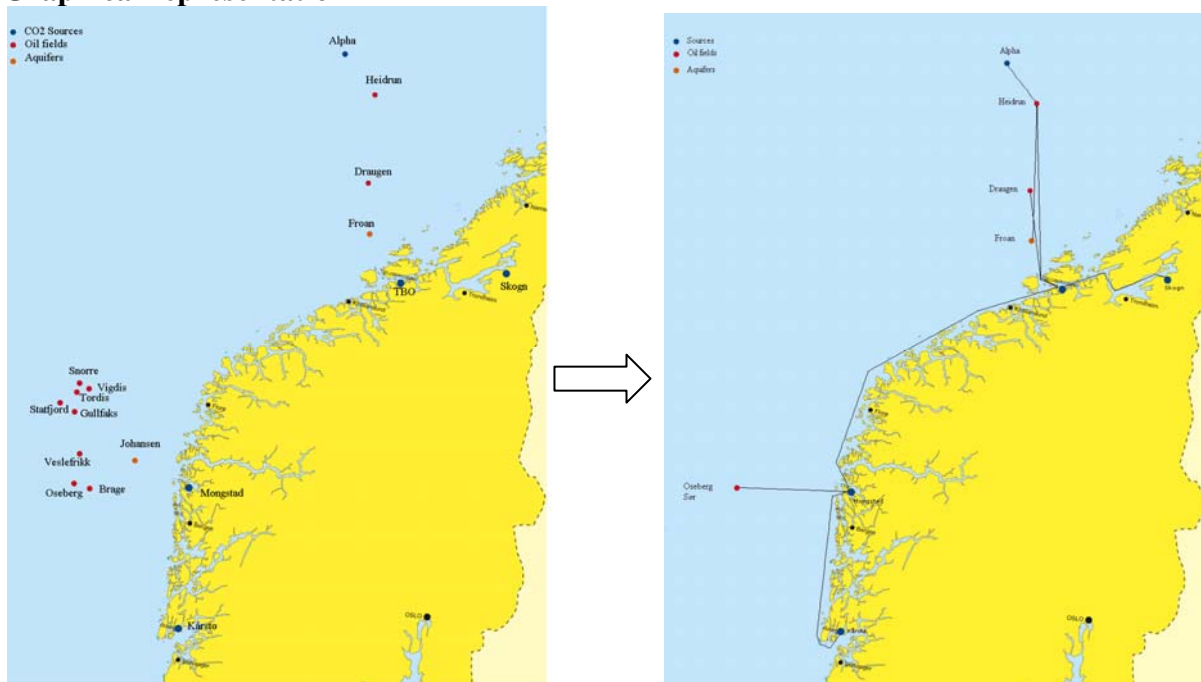


Figure 9: CO₂ sources and candidate drains for CO₂ injection (left) and solution (right).

3.4.2 EOR model

The model uses estimates of EOR potential rate for each oil field for each year. The profile of the extra oil produced versus the amount of CO₂ injected will vary over the injection period. Typically improved oil recovery is low the first year and then peak after two or three years. The CO₂ injection is restricted between a minimum and maximum amount during the injection period.

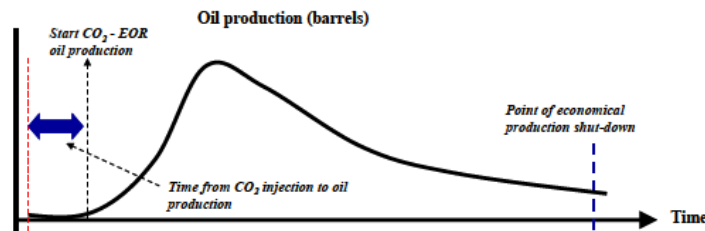


Figure 10: EOR profile

CO₂-EOR is done for fields in tail production, and obviously there will be a specific time window for each field, which means that several fields would start CO₂ injection nearly simultaneously. However, the limited CO₂ supply inhibits this. A late start-up year reduces the technical potential of EOR. Since the starting year of CO₂ injection is a decision variable of the model, the decline is accounted for by discounting EOR income for start-ups postponed after 2020.

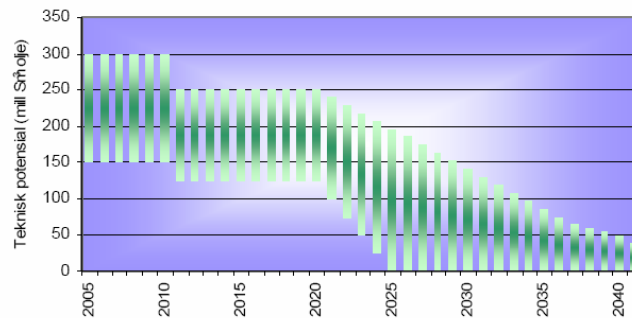


Figure 11: Technical EOR potential in time

3.4.3 Calculation methods

Evaluation / Sensitivity / Optimization / Risk Analysis

The model formulation is coded and optimized in Xpress-Mosel language. Excel was chosen for establishing a database for the input data. Testing different data cases is straightforward.

Solving the base case takes around 8 minutes on a desktop computer. The base case has 5 source nodes, 16 drain nodes (14 oil fields and 2 aquifers), 32 possible arcs, 5 pipe dimension options and 25 time periods.

Although the current version is a deterministic model, the solution to the model with different parameter values can be used to gain inside about the problem structure, and to assess the effect that a parameter has on the objective value. This can reveal coherence within the problem which can be useful to the decision maker.

From the sensitivity analysis we can assess the oil breakeven price according to several parameters, how EOR contributes to make CCS less costly or the NPV change:

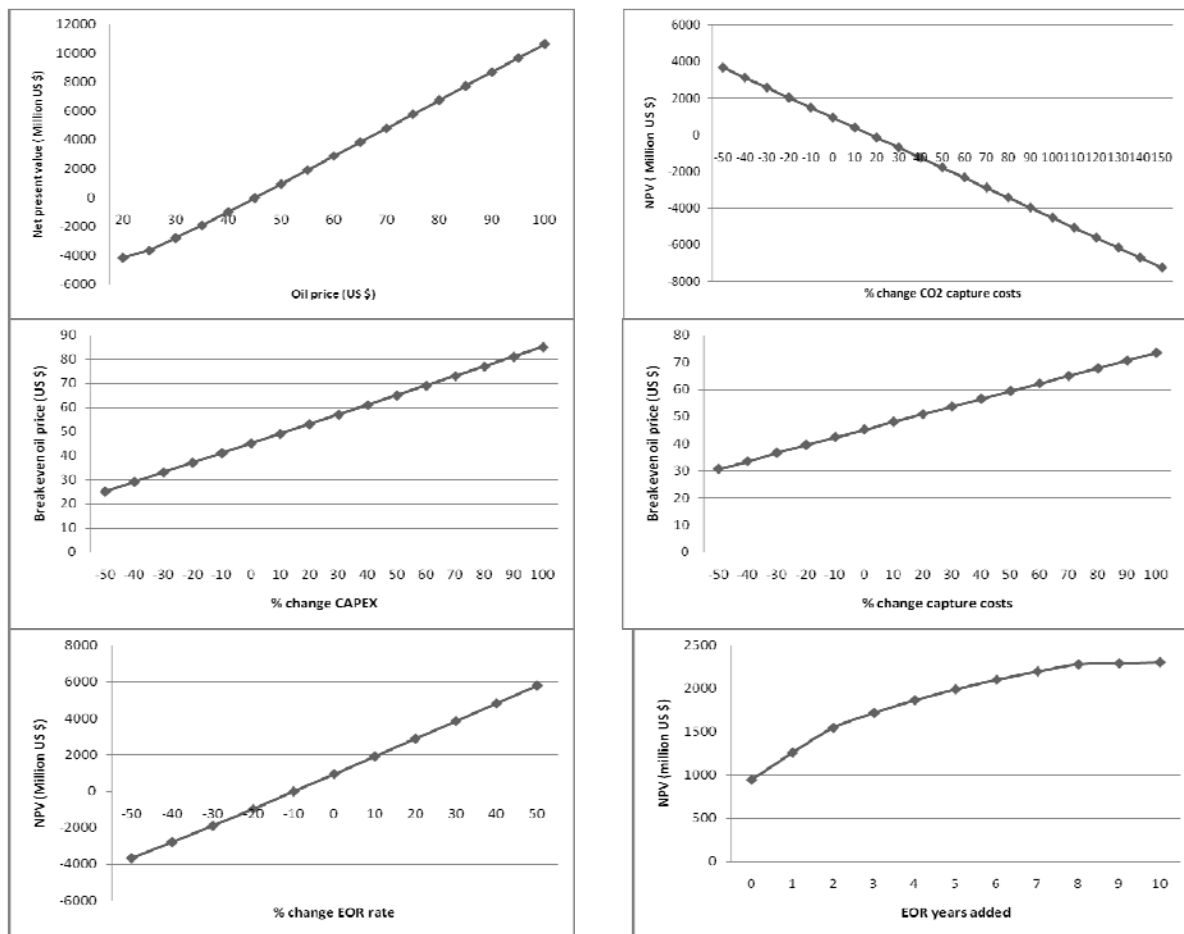


Figure 12: Calculation output from NTNU infrastructure model

3.4.4 Relevance for the ECCO Tool

This tool is different in that the emphasis is more on the optimization of a CO₂ chain including simplified models than on the evaluation of a chain that has the possibility of having more complex models. Like the other tools the specifications are performed within Excel, but the optimization itself is performed with another commercial system. The ECCO project will be mostly focused on the actual evaluation of the chain and not on any type of optimization. Within this context this tool is most likely not so relevant.

3.5 IEA GHG tool

The objective of the tool was to provide initial assessment of the cost and performance of CO₂ and energy transmission systems. Employed model exceeds CCS related activities as it covers pipeline transmission of CO₂, natural gas, hydrogen, methanol and distillate oil and AC and HVDC transmission of electricity. The tool calculates the cost and the performance of onshore and offshore pipelines and assesses the sensitivity to a wide range of factors (e.g. flow rate, pipe diameter, pressure, terrain and location). Different pipeline configuration might be also compared (dedicated single pipelines or pipeline grids including trunk lines). User interface allows specifying up to 10 “assets” which may include pipelines, energy conversion plants and wells for CO₂ underground storage. Then the costs and performance of individual assets are calculated and overall costs, energy consumption and greenhouse gas balances are calculated.

3.5.1 The tool structure

Energy conversion plants

Simple algorithms for calculation of costs and performance of energy conversion plants are employed to model overall energy delivery schemes. The plants types include:

- Combined cycle power plant
- Natural gas-based hydrogen production plant
- Natural gas-based methanol production plant
- Coal fired power plant

CO₂ capture is attached to all above cases except the hydrogen fired combines cycle plants. The user specify the useful energy output from the plant and the software calculates the fuel feed rate and quantity of CO₂ captured.

Pipelines

For the pipelines the user specifies the following information:

- Throughput
- Length
- Onshore or offshore
- Type of the terrain crossed
- Country/region
- Type of fluid
- Pipeline inlet pressure
- Number of booster compressor/pumping stations or minimum distance between booster stations
- Compressor/pumping station inlet and outlet pressures
- Is and inlet booster compressor required
- Pipe diameter

There are two methods for sizing the pipelines. The user can specify the minimum distance between booster stations and the model will select an appropriate diameter, else the user select a pipe diameter and number of booster stations and the model will calculate the pressure drop.

Electricity transmission lines

This part of the model will not be described here as it is beyond the scope of CO₂ value chain.

Underground CO₂ storage

The model includes also underground CO₂ storage asset. The user specifies the following data:

- Depth of the injection walls
- The injection pressure
- Throughput per well

The model calculates the capital cost, fixed operating cost and variable operating cost.

3.5.2 Cost estimation

The main objective of the tool is to determine Capital expenditure (CAPEX) and both fixed and variable Operating Expenditure (OPEX) for each asset.

Project settings

Before running the model the user is asked to define project specific values that will be applied to each case. These settings refer to main model inputs:

- Asset location
- CO₂ storage cost
- Economic Parameters
- Further details

Asset location

The geographical location has an impact on the CAPEX and OPEX. A location factor is applied to take into account the effect on local costs.

CO₂ storage costs

The tool has assigned default CAPEX CO₂ injection costs. They can however adjusted by the user in the project settings, what would be advised due to the time of building the tool (2002). Also fixed OPEX values are set as default and can be adjusted for offshore and onshore well and wellhead platform.

The total offshore storage cost is calculated as follows:

Storage cost = (cost per well x number of wells) + cost of wellhead platform + offshore pipeline cost + booster station cost (in required)

Economic parameters

To determine CAPEX and OPEX of a project the following economic parameters has to be specified:

- Annual Capital charge Factor: a factor applied to the CAPEX to determine an Annual Capital Charge in USD M/year. The default is 1.
- Load Factor: An availability factor applied to the number of hours a year to determine the operating hours a year. The default is 100%.
- Fuel Costs: The variable OPEX of a facility is based on the cost of fuel/feed or electricity consumed by facility. The default costs can be adjusted by the user.

Totalized Asset Costs

The tool calculates the totalized costs for each case is compiled from specific component costs, e.g. an Electrical power Generation asset will comprise the following:

- Power station cost
- Electrical transmission system cost
- CO₂ pipeline with related sending facilities

As an output the tool will create a table with the CAPEX, OPEX and Variable OPEX listed as a function of plant power.

Power station

The CAPEX costs for power stations are based on the natural gas power station with a capital cost factor applied depending on the type of fuel (distillate, methanol, hydrogen). The scaling exponent is 0.835 for all fuels.

Fixed OPEX costs are calculated by the same method used in the CAPEX estimation. The common for all fuels scaling exponent is 0.5.

The variable OPEX costs (excluding fuel) are calculated by the same method used in the CAPEX estimation with fuel factors. Then cost of fuel is added to give the total power plant Variable OPEX.

Transmission pipelines

According to different ANSI piping classes (600#, 900#, 1500#) 3 cost relationships were incorporated to the model. Developed equations give a base CAPEX cost estimation which is further factored based on the terrain choice in case of onshore pipeline. For offshore pipelines the model also provides 3 different cost relationships. Set of equations for offshore pipelines was based on “S-type” pipelay technology, which is typically limited to water depths of 600-800 m.

The OPEX cost of pipelines is calculated from equations developed based on reviewing the OPEX of a number of pipeline scenarios.

Pumping and compression facilities

Estimation of the costs is based on the required power for pumping/compression and take into account both initial and booster facilities. Set of CAPEX equations for different assets can be found in [7].

The fixed OPEX has been developed from the following costs:

- Personnel
- Administration and overheads
- Planned facilities maintenance/inspections
- Spares
- Miscellaneous

The variable OPEX is assumed to be the fuel costs of pumping/compression.

3.5.3 Relevance for the ECCO Tool

Like most other tools described this tool is also implemented in Excel as a set of worksheets and additional VBA code (password protected). In contrast to most of the other tools it has a dedicated menu-bar for most of the commands and also a help system. The help system is based on the old help system using Microsoft Windows Help (winhelp.exe or winhelp32.exe). The file format is now obsolete. It was based on RTF. Current help systems are mainly based on HTML, but the newest help systems are based on XML.

By default the user does not see the tabs for the different worksheets; all maneuvering between the worksheets is either performed by the menus or command buttons on the worksheets. Like Expand it also includes several dialogs for the specifications of the modules.

In contrast to EXPAND almost all data except for the tabular input on the further defaults data are specified in the dialogs. Almost all other tools rely on specification in the worksheets.

It also distinguishes the locations based countries. This is valid for all cases and all assets.

When the tool is executed the user must first define all 5 cases (i.e. either provide the information or explicitly skip every case that is not used). This seems to be quite awkward. For each case the different assets must be specified. It distinguishes between four types of assets which have their own dialogs for adding information. Like many other tools there are no connections between the assets. There is a simplified material balance that checks the amount of CO₂ that is produced and the amount of CO₂ that is stored.

One major question related to the calculations is how the lifetime of the case is supposed to be handled. There seems to be no places where the number of years may be added. The underlying models for each of the modules (assets) seem to be the simplest ones among the different tools reviewed.

3.6 Geocapacity tool

The aim of the EU Geocapacity project was to create an inventory of CO₂ emission levels and CO₂ storage capacity in Europe and to build a CCS feasibility analysis tool. The project was a follow-up of the GESTCO project, which performed a similar task for six north-west European countries. The latter project also produced a software tool for the analysis of the economic feasibility of carbon capture and storage (CCS) projects, by estimating the costs involved in the different elements of a CCS chain. This chain was defined by capture and compression at a single source, storage at a single storage location, plus a connecting pipeline.

The EU Geocapacity project was also tasked to extend the GESTCO project in this aspect, by developing a more advanced CCS analysis tool. The tool that was developed is capable of handling more realistic scenarios, with multiple sources and multiple storage locations. In addition, the tool can clearly show the uncertainties associated with CCS feasibility analyses through a Monte Carlo approach.

The Geocapacity tool, or decision support system (DSS), consists of two parts. The first part is an internet application, to be used for the construction of a CCS scenario; the second part is a local application, which can perform a stochastic analysis of the costs involved. This local application contains modules representing different elements of the CCS chain (capture, storage, etc.), of which some (capture, transport) contain type curves and some (storage) are closer to the physics involved. An important element of its input is made up of the geological properties of the storage reservoirs, which ultimately control the entire CCS chain.

3.6.1 Outline of the internet Geocapacity application

The internet-based part of the DSS is used to construct a CCS scenario. The database compiled in the EU-Geocapacity project is used to select any number of CO₂ emission points and storage locations. A network of pipelines connecting all selected 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 CO₂ produced by performing a simple source-sink match. All data are then downloaded as input for the local application, in the form of a zip file. Figure 13 and Figure 14 show snapshots of the web-based application.

The user must go through a number of steps to construct a CCS scenario.

1. Define the start year and the duration of the CCS project (typically 30 or 40 years).
2. Select CO₂ sources from the collection of sources in the EU Geocapacity database. These are shown on a Google Maps background.
3. Select CO₂ storage locations. The aquifers and hydrocarbon fields in the EU Geocapacity database are shown in different colours on the map; the size of the markers is proportional to the storage capacity.
4. Compute the source – sink match. To make sure that the storage space in the selection of sinks is sufficient, a simple source – sink match must be done, before a network is computed. The user is asked to provide any missing data, after which a simple algorithm is used to compute whether the yearly production of CO₂ can be stored. There is a match only if all CO₂ can be stored throughout the duration of the CCS project.
5. Compute a network of pipelines. When there is a source – sink match, a network connecting sources and sinks can be computed. The network is an efficient network, in terms of total pipeline distance, but not the shortest possible. Due to computing time requirements, no rigorous shortest network algorithm has been implemented. The network is displayed on the Google Maps background (see Figure 14).
6. Network editing. The network algorithm does not take into account land use, again because of computation time considerations. Instead, the user has the option to change the location and shape of any of the pipelines in the network, to avoid obvious obstacles such as cities or steep topography. In addition, the network elements can be made to run parallel to existing pipelines. The user should be aware that the main purpose of editing of the network is to increase the fidelity of the length estimate of the pipelines. The length of the pipeline is increased by 20% in the computation of transport costs, to account for small deviations from the planned route due to local infrastructure. In addition to changing the location of pipeline segments, an onshore / offshore attribute can be set for each element in the network. An example of an edited network is shown in Figure 14.
7. Download data. 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.

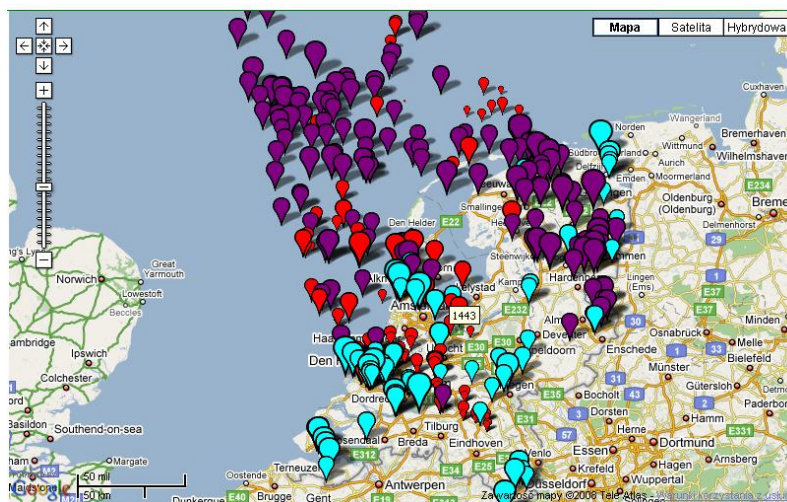


Figure 13: Screen shot of the Google Maps interface showing a map with the locations of sources (light blue) and sinks (purple: hydrocarbon fields; red: aquifers) in the EU Geocapacity database

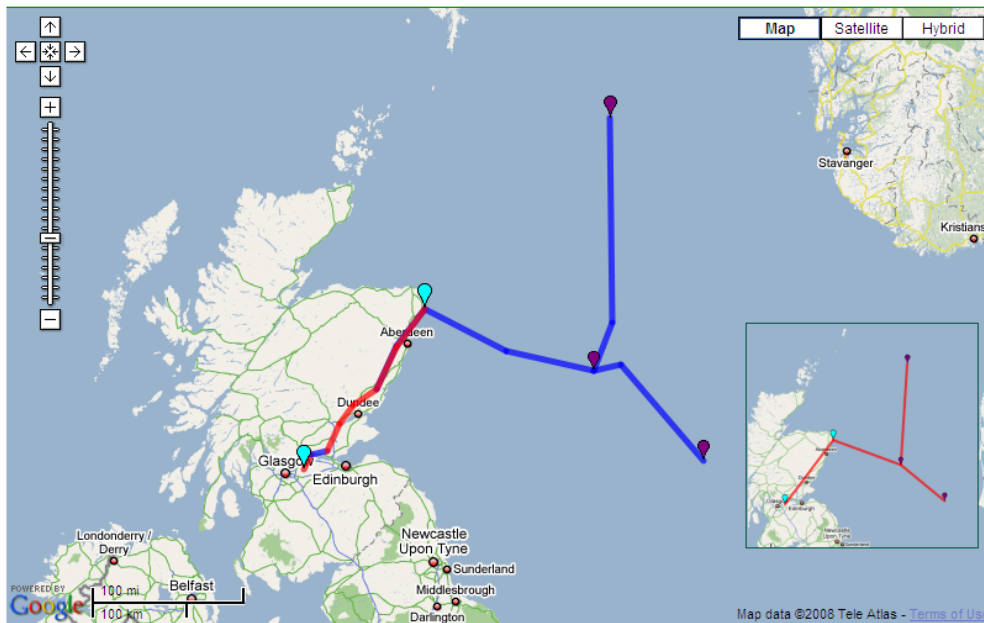


Figure 14: Screen shot of the Geocapacity internet application, with a network superimposed on a Google Maps background. The network was computed by the network algorithm. With the position of sources (light blue) and sinks (dark blue) fixed, the route of the onshore pipeline (in red) has been changed to follow a possibly more realistic (although hypothetical) route; the offshore pipelines (in blue) have been slightly shifted. The inset shows the network as it was computed by the network algorithm, with straight segment, by default onshore.

3.6.2 Outline of the local decision support system

The local Geocapacity tool performs a stochastic analysis of the costs of a CCS project. The data on the sources, sinks and network as downloaded from the web application are the starting point of the analysis.

The Geocapacity economic tool is an extension of the GESTCO tool in several aspects.

1. The tool is capable of handling multiple sources and multiple sinks in a single scenario. The single source – single sink scenarios in the GESTCO tool are now considered not to be realistic, as it is expected that future, large-scale CCS projects will include many sources and many sinks.
2. The tool performs a stochastic analysis of the economic costs. Key technologies for CCS are not yet mature (e.g., capture) and recent years have shown significant increase in price levels (e.g., of pipeline construction costs). Such, and other, uncertainties should be reflected in the economic analysis by computing the band width of the total cost. The EU Geocapacity tool can handle probability distributions for all of the input data, propagating this information to the results.
3. The starting point for the tool is the EU Geocapacity database of CO₂ emission and storage capacity, which contains data on almost all EU member states. In combination with the many – on – many capability mentioned above, this allows for cross-border CCS to be analysed. This is a relevant issue for several EU member states, where insufficient storage capacity is available for national CO₂ capture projects. It is straightforward to replace the Geocapacity data by any other data, as long as the structure of the database is maintained.

The local tool is built in Java, using DSS software developed by TNO in recent years. This software has built-in functionality for performing stochastic analyses and has been successfully applied to such diverse areas as E&P (exploration and production) and power plants using geothermal energy. The stochastic character in the tool lies in its Monte Carlo approach, performing a large number of identical computations, in which the input is varied according to the user-defined stochastic properties of the input data. The architecture of the DSS software makes it easy to add new modules or update existing modules from other applications.

3.6.3 Outline of the Geocapacity analyses

The analysis of economic feasibility of CCS, performed by the application that runs on a local computer, 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, source and sink properties can be different, leading to varying degrees to which the captured CO₂ can be stored in the sinks.
4. Network update. The CO₂ flows vary among the Monte Carlo runs. These variations lead to different pipeline capacity requirements and, hence, to different transport costs. The network layout is fixed throughout the Monte Carlo runs, while the size of each network segment is adjusted to fit the maximum flow in each run and stored.
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.

The results of the analyses are the following:

- Economic parameters. These include NPV, unit technical cost, maximum exposure, and more. As a result of the Monte Carlo approach, the uncertainty in any of the input parameters is propagated into the results. Figure 15 shows two graphs of NPV of a hypothetical CCS project, in the form of an expectation curve (left graph) and a probability distribution function (right graph). These graphs illustrate the strength of the Monte Carlo approach in visualising the uncertainty inherent to feasibility analyses.
- Technical parameters. These parameters related to the sinks, parameters related to the capture process for the sources, etc.

These results can be single-valued (like NPV), while many results are presented as time series. Where single-valued results can be plotted as shown in Figure 15, time series are plotted as shown in Figure 16, with all curves from the Monte Carlo runs plotted on top of each other. For this particular parameter, storage investment costs for one sink in a scenario with several other sinks, such results show the uncertainty in both the magnitude and the timing of the costs. The uncertainty in timing is due to the properties of the other sinks in the scenario, leading to variations in when this sinks needs to be developed.

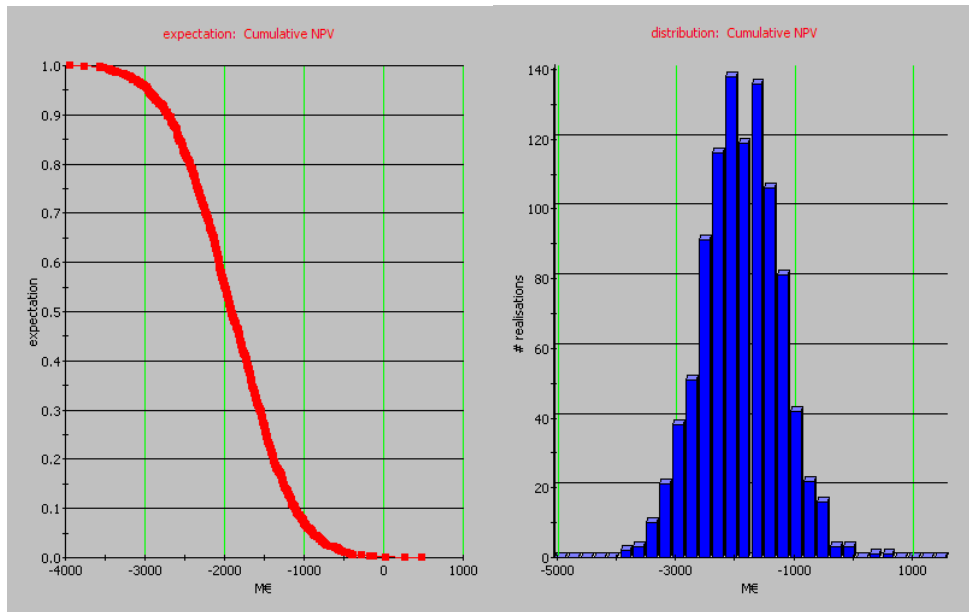


Figure 15: Examples of output from the local application: NPV for a hypothetical CCS project. Left: results presented in the form of an expectation curve; each red dot represents the outcome of a single Monte Carlo run. Right: results presented as a histogram.

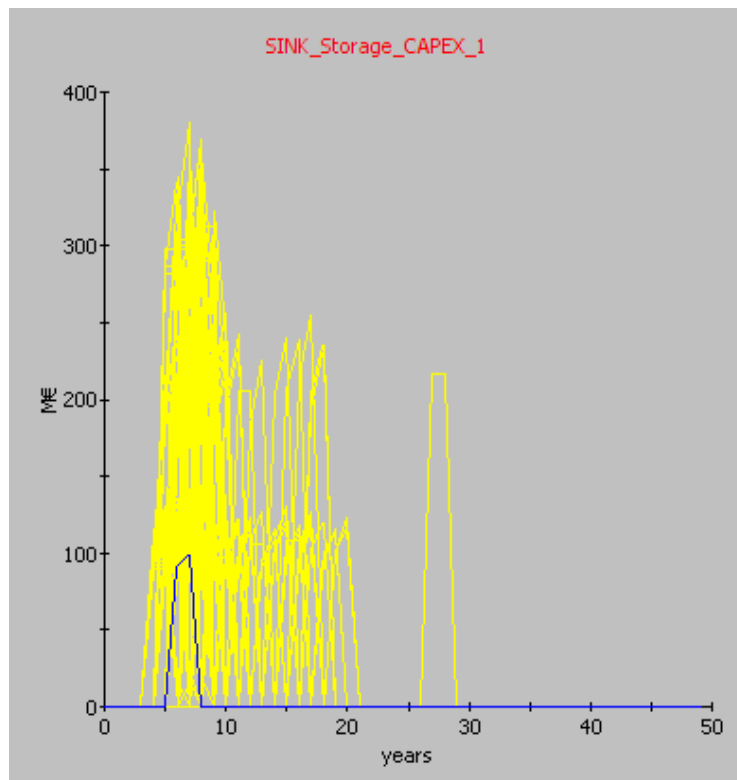


Figure 16: Examples of time series output from the local application: investment costs for a storage site. The Monte Carlo analysis resulted in 1000 curves that are all plotted in the frame above. The blue curve represents the mean.

The different elements of the chain are discussed in some detail below.

Sources

For each industrial source selected by the user, the DSS calculates capture and compression parameters. To this end, the DSS takes parameters from the source database as input for calculations of capture and compression variables. The type of CO₂ emitter determines which data will be used in the calculations. Some important variables are:

- type of plant (power and non-power installations, including a wide range of industries)
- new vs. existing (retrofit) plant
- plant technology class (e.g. gas turbine, combined cycle, etc.)
- type of fuel (divided in gaseous, liquid and solid fuels)

Combinations of the first three variables mentioned result in the definition of several ‘Sourcetypes’. An example: one of the source types is a power plant with an existing steam turbine or boiler. For each sourcetype, parameters are determined for different fuels and different capture technologies. The parameters are input for the capture and compression modules.

All required data for the different source types in combination with fuels and capture technologies are readily available in the DSS and the attendant databases. However, if desired, users can change any input data on, for instance, fuel use for the capture process, volume of flue gas to be treated for capture, percentage of CO₂ captured, fuel emission factors or costs of fuel and electricity.

Capture

Users can select from a range of capture technologies for isolating the CO₂ at the source. Capture technologies included are: post-combustion (capture of CO₂ from flue gases), pre-combustion (CO₂ capture by fuel conversion), oxy-fuel combustion (capture by fuel combustion using pure oxygen), or high-purity (capture from sources that emit (nearly) pure CO₂). The capture module calculates amongst others the energy requirement for the capture process, the amount of CO₂ captured per year, any additional CO₂ generated by the process itself, resulting CO₂ emissions, and the economics of the capture process.

Compression

The compression module calculates the energy required to compress the flow of CO₂ from the capture unit to the required transport pressure. The module can then determine the energy use for compression, the associated CO₂ emissions and the economics of the compression step.

Storage capacity and injectivity

A significant part of the uncertainty in CCS projects is associated with the properties of the subsurface reservoirs. Whereas depleted gas fields are generally well studied and have a relatively well-defined storage capacity (although end of production times remain uncertain), aquifer storage is associated with highly uncertain reservoir properties.

Storage modules have been developed for CO₂ injection into aquifers and abandoned oil and gas reservoirs under supercritical conditions. These compute the injection rate (Mt/yr) and storage capacity (Mt), using reservoir properties (such as pressure, temperature, maximum pressure, permeability) as input. Injectivity calculations are based on a mass balance equation and a pressure model that incorporates the development of a growing CO₂ zone around the wells with different mobility than the original fluid in place.

As data on subsurface reservoirs can be difficult to obtain, which is the case for aquifers, the user has the option to use less complex algorithms to compute storage capacity and injectivity.

EOR is not included.

Source – sink matching

This is an essential element of any many – on – many CCS scenario, that can not be done through interaction with the user. In each Monte Carlo run and each year in a CCS scenario¹, the captured CO₂ must be distributed over the sinks. The user has two options of prioritising sinks: by distance over the network, or by size. This way, the trade off between pipeline costs (use nearby sinks first) and site development and operational costs (use larger sinks first) can be studied. Other prioritisation schemes (such as schemes based on unit storage costs or on requirements related to EOR) are possible, but have not yet been implemented.

The algorithms perform a yearly update of the amount of CO₂ captured and stored, at each source and sink, taking into account start and end years of capture, and the availability of sinks. One of the input parameters for the sinks is the earliest possible year of CO₂ storage.

The result of the source – sink matching is the following, for each Monte Carlo run:

- the maximum expected flow through each network segment (this defines the segment's size);
- the start and end year of operation of each network segment (this defines when investments and operational costs are incurred);
- the start and end year of injection for each sink (this defines the timing of sink development and operational costs);
- the number of wells used throughout the scenario lifetime for each sink (this determines the number of injection sites required);
- the year of first use for each well, for each sink (this determines the timing of drilling costs);
- the injection rates, cumulative stored volume for each sink;
- the amount of CO₂ not stored (if any) throughout the scenario lifetime (this occurs if the total injection rate is insufficient for the total captured yearly volume of CO₂, due to unavailable, (nearly) full or tight storage reservoirs).

As indicated in the list, these parameters are essential for the calculation of transport and storage CAPEX and OPEX. It is to be stressed that the ultimate drivers for these costs are the geological properties of the subsurface reservoirs.

Network (transportation)

The network is fixed throughout the Monte Carlo runs. In each run, the results from the source – sink matching algorithm is used to compute the cost (CAPEX, OPEX) of each network segment, from the size required to accommodate the maximum expected flow. The start and end year of operation of the segment are used to correctly position the costs in time.

¹ A CCS scenario is defined as a number of sources and sinks; it has a lifetime of typically 30 or 40 years. In each Monte Carlo run, the CO₂ flows are computed throughout this lifetime.

Cost data

A cost module reads data on the cost of wells, platform (offshore) or site (onshore) development. Cost data include the cost of drilling, platform (offshore) or site (onshore) development and operation and maintenance cost estimates.

Economics

The economic module combines the cost estimates of all previous modules to produce the net present value (NPV) of the CCS project. Other economic parameters include the internal rate of return (minimum discount value), the maximum exposure and unit cost. The latter parameter has units of €/tCO₂ and is often used in CCS literature as an indicator for the cost of a specific CCS project.

3.6.4 Relevance for the ECCO Tool

In contrast to the other tools this is not an Excel application. It consists of two applications:

- One internet application where the network (sources, pipelines and sinks) are shown
- One standalone Java application that uses information generated by the internet application

The internet application is very nice in the way that it uses rather new technologies that the users most likely are familiar with for other applications. The architecture of the DSS software makes it easy to add new modules or include modules from other applications. The software has built-in functionality for sensitivity analysis that automatically adapts to changes in the list of input and output parameters.

The internet application is in essence a scenario building tool and could as such be useful to the ECCO project. The standalone tool covers the entire CCS chain, in ways that differ from other tools discussed here. The source – sink matching algorithm provides the framework for the modeling of a developing CCS infrastructure, which will also be studied in the ECCO project. The network generation algorithm may also prove relevant in many – on – many scenarios. The flexible software backbone architecture that was used in the Geocapacity tool helped developing the software in a very short time frame, offering built-in stochastic analysis features, rapid extension of the chain of modules and allowing user-defined workflows. The latter feature allows the user to choose from a range of algorithms for a specific CCS module, to fit the level of complexity in the calculations to the amount of data available.

Taken together, these characteristics of the Geocapacity tool render it highly relevant to the ECCO project.

3.7 Other tools

There are also some other tools that have been mentioned. No documentation is available for any of these.

The Gestco (European potential for geological storage of CO₂ from fossil fuel combustion) project has created a database of existing sources, pipelines and sinks for CO₂. The content and the format of this database are unknown. It also includes the calculation of the most cost efficient route from one single source to one single sink. The model itself is not considered to be useful for the ECCO project, but the database itself may be interesting.

There is a new project EU-Europipe that is too start in a few months. Some issues are related and some cooperation could be useful for both projects. It includes multi sources and multi sinks and is thus more relevant than one source – one sink. It has not been decided whether Europipe will develop a new tool or use existing tools.

The TNO-ENETSIM is an “agent-based” tool to model the full value chain of liberalised gas markets. It includes explicit actor competition, contracts and decision algorithms per actor, and calculates security of supply and spot market prices. For the time being, these principles are not yet applicable for early CCS developments and not useful for the early ECCO tool.

TNO E&P – DSS is a decision support system which is used and refined within the GeoCapacity project.

4 SUMMARY

At present, there exist several software tools for CO₂ value chain analysis. Some of them embrace only some parts of the chain whereas the others analyse all parts from sources to the sinks. Description of existing tools included in this work gives an overview of experience gained up to date in the field of CCS economics. This report identifies structure of existing tools, lists issues taken into account and suggests these worth considering in the tool which is to be developed in the project.

In this report the tools have been analysed regarding general functionalities, economical and techno-economical criterions, type of software and user interface employed and additional functionalities.

The existing tools differ in many aspects. The differences pertain to system input (number of sources, amount of CO₂, power demand, power generation technology, capture technology, pipeline distances, type of sink, etc.), system assumptions (oil and CO₂ quota price, price profile, legal incentives, etc.), method of analysis (economical measures, sensitivity analysis, optimisation, etc.) and output (economics, amounts of EOR, CO₂ sequestered, pipeline networks, presentation of results, etc.). The existing tools also differ in terms of how physics, planning and economics have been integrated. The phasing and sizing of CAPEX and OPEX items are a function of the physics involved and of the planning targets and constraints. The NPV and other KPIs are very sensitive to this type of integration. ECCO scenarios to be modelled will in our opinion have to take this into account.

To develop a comprehensive tool for CO₂ value chain evaluation many factors have to be taken into account. Based on existing experience in CO₂ value chain and the first ECCO workshop the issues and question have been grouped into 4 main categories: market and regulations, infrastructure and logistics, economical, technological and others which were difficult to assign to the precedent. There are many uncertainties both on the decisive and technological part of the value chain. Hence, we will need to develop a flexible tool that will allow for future modification and adjustments.

A key requirement for the ECCO tool is that it should be detailed enough to capture those parameters to which the investment decision-making process, as done by individual actors who depend on other actors to close the CCS value chain, is most sensitive. The tool should give insight on how to make all actors, relevant to closing the value chain, move into the same direction. For understanding individual actor behaviour and understanding how to align the different actors, a level of detail is required, which is not represented in the tools discussed in this report. For the storage operator, the TNO XL tool comes perhaps closest to this required level of detail.

The future ECCO tool is supposed to take up a new, as yet unrepresented, position in the landscape of existing tools. Whereas other, existing tools are aimed essentially at providing some high-level, first order scenario definition tool for policy makers, the ECCO tool is aimed at individual decision-makers who need to understand how their individual investment options fit in the overall CCS value chain and, hence, depend on other actors in the value chain. The ECCO tool should be complemented with other, more detailed tools to study a specific component more in detail and underpin an actor's Final Investment Decision.

The ECCO tool to be developed will most likely be inspired by several of the described tools. For this purpose it may be distinguished between the functionality of the tool as seen from the user (what the tool will do) and the representation as seen from the programmers (how the tool will accomplish this). The functionality will most likely be inspired by the TNO XL tool and partly the Geocapacity tool. The level of detail of the calculations for the implemented modules in the TNO XL tool will most likely be closest to the level of detail in the ECCO tool. Likely the types of financial calculations will also be similar. Both the TNO XL tools and the Geocapacity tool handle stochastic simulations; the first with an add-in while the second has this functionality built in. However Catena (next version of Expand) has a much more flexible structure than any of the others (not including the Geocapacity tool). This is to a large extent due to its object oriented implementation in C# in contrast to the very static representations one will achieve in Excel based tools. It may serve as a basis for the structure of the tool and also as the selection of implementation language. However Catena is not a complete tool; the structure is not complete and most of the methods have not been implemented. The TNO XL tool has a lot of the functionality ECCO needs and thus serves well as a starting point for the types of evaluations performed. It will therefore be very useful to incorporate the types of calculations performed within the TNO XL tool into Catena. In addition there will be other modifications to the tool which results from internal discussions in the ECCO consortium.

5 REFERENCES

- [1] Jakobsen, J.P., Tangen, G., Nordbø, Ø., Mølnvik, M. 2008, Methodology for CO₂ Chain Analysis. Special issue (for 4TCCS) of International Journal of Greenhouse Gas Control
- [2] OD, (2005). CO₂ for økt oljeutvinning på norsk kontinentalsokkel.
http://www.npd.no/NR/rdonlyres/87FE5D85-8E20-46A1-9C07-4CC7BECEC7EF/0/CO2_rapport_norsk.pdf
- [3] GASSCO, (2006) GASSCO, 2006. Innledende forhandlinger mellom de kommersielle aktørene i en CO₂-kjede. Dokumentnr.: ØKKU-RA-6004.
http://www.regjeringen.no/upload/kilde/oed/rap/2006/0005/ddd/pdfv/282990-gassco_co2_verdikjede_oed_7_juni_06.pdf
- [4] Bellona, (2005). CO₂ for EOR on the Norwegian shelf.
http://www.bellona.no/filearchive/fil_CO2_report_English_Ver_1B-06022006.pdf
- [5] NVE, (2005) Norges vassdrags og energidirektorat, 2005. Gasskraft med CO₂-håndtering, Verdikjedevurderinger. Rapport nr.: 20-2005. ISBN: 82-410-0567-9.
http://www.nve.no/FileArchive/337/Rapp%2020_2005c.pdf
- [6] CASTOR, Project no. SES6-2004-CT-502586, CO₂, From Capture to Storage, Deliverable D1.1.3B, Economic Analysis Tool, Sylvain Sebutoviez IFP, Paula Coussy IFP, Ad Lokhorst TNO, Frank Keppel TNO, Paul Egberts TNO, Leslie Kramers TNO, Muriel van der Kuip TNO.
- [7] IEA Greenhouse Gas R&D Programme, Pipeline Transmission of CO₂ and energy transmission study – report, by Woodhill Engineering Consultants, 28.02.2001