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Geocapacity: economic feasibility of CCS in networked systems

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Abstract

A Decision Support System (DSS) has been developed to evaluate the technical and economical feasibility of CO_2 storage in the subsurface. The DSS performs a detailed, stochastic analysis of the technical and economical aspects of a CCS project, which consists of any number of CO_2 sources and sinks plus the connecting pipeline network. The DSS uses the database of CO_2 emission points and storage locations in Europe that has been compiled in the EU Geocapacity project. The system is a combination of an internet application, which visualises the database and allows the user to select sources and sinks and create a pipeline network, and 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. The DSS provides not only an estimate of the total CCS cost, but also an analysis of the elements in the CCS chain (capture, compression, transport and storage), enabling a feasibility analysis on several levels.

Keywords: CCS; economic feasibility CCS chain.

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1. Introduction

The aim of the EU Geocapacity project, Vangkilde-Pedersen et al. [1], is to assess the European capacity for geological storage of CO_2 in deep saline aquifers, oil and gas structures and coal beds. Other priorities are further development of methods for capacity assessment, economic modelling and site selection as well as international cooperation, especially with China. This paper presents the tool that was developed within the framework of the EU Geocapacity project to model and assess the economic feasibility of CCS projects.

The Geocapacity project will result in an update and extension of the data produced by the earlier EU GESTCO project, which performed a similar task for eight 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, and the connecting pipeline. The EU Geocapacity project was tasked to extend the GESTCO project in this aspect, by developing a more advanced CCS analysis tool, capable of

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handling more realistic scenarios, with multiple sources and multiple storage locations. In addition, the tool should be able to clearly show the uncertainties associated with the analysis of the economic feasibility of CCS projects. As CCS initiatives are being developed in Europe, the uncertainties at various levels in the CCS chain become apparent; it is essential that an feasibility assessment takes into account these uncertainties. The updated and extended database of CO_2 emission and storage capacity provides the basis for CCS feasibility analyses.

2. Economic tool

The economic tool was developed with a number of requirements:

- The tool must be able to handle multiple sources and multiple sinks (storage locations). CCS projects that are currently being planned are more complex than one-on-one configurations. Storing the CO_2 of even a single coal-fired power plant typically requires of the order of 2-5 $MtCO_2$ to be stored each year, over the expected lifetime of the power plant, which is typically 30 or 40 years. This requires a total storage of up to about 200 Mt. Although this could be stored in a single (large) aquifer or depleted gas field, it is reasonable to assume that multiple fields will be used. For the case of The Netherlands, storing this amount of CO_2 will require a cluster of depleted gas fields. On the source side, current plans assume some sort of network, linking multiple sources to a cluster of storage locations.
- The uncertainty inherent in economic feasibility studies must be represented in the results of the tool. In the case of CCS projects, uncertainty not only exists in the economic parameters, but also in the calculation of capture, transport and storage costs. The geological properties of the storage locations can be highly uncertain, especially in the case of storage in saline aquifers. A stochastic approach is required to propagate uncertainty in input parameters to the results.
- The level of detail in the computations must be appropriate for the purpose, which is feasibility analysis at an early stage in the development of CCS projects. Although it can be used in a later stage, when more detailed plans are made, its main use will lie in planning at a relatively high level of abstraction.

These requirements led to a tool consisting of two elements. The first part of the tool is web-based and serves as a window on the Geocapacity database. It serves to select sources and sinks from the database and create the connecting pipeline network. The second part of the tool is an application running on a local computer, using data downloaded from the web-based part as input. This local application performs a Monte Carlo analysis of the CCS project, both at a technical and economical level, and provides the user with an estimate of the economic costs of the CCS project.

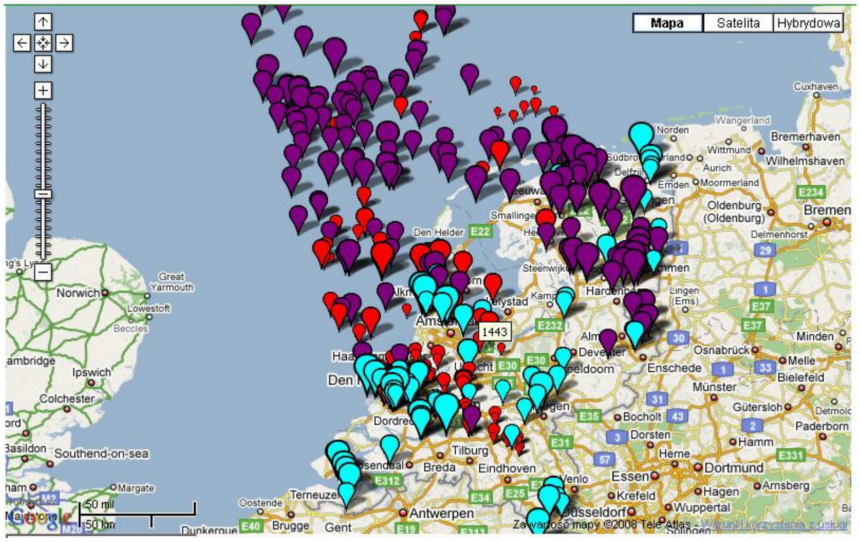

Figure 1. Screen shot of the Google Maps interface showing Netherlands sources (blue), aquifers (red) and hydrocarbon fields (purple) from the Geocapacity database. Symbol size is proportional to CO_2 production (sources) or storage potential (aquifers and hydrocarbon fields).

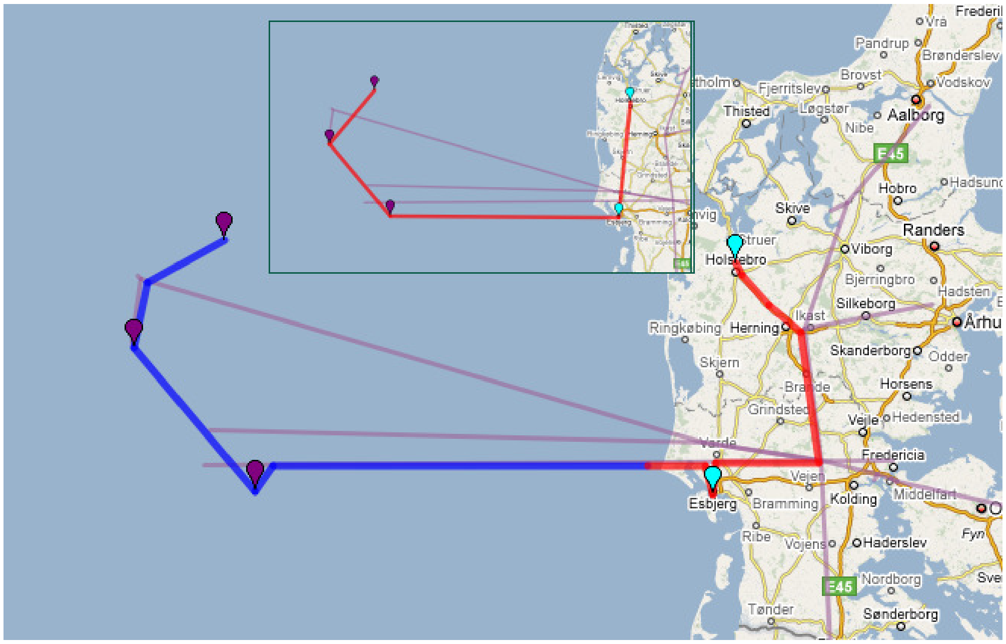

Figure 2. Hypothetical example of a CO_2 network, before (inset) and after aligning the network produced by the economic tool transport algorithm with existing pipelines (in purple) and roads (for the onshore part). All segments of the original network were given the label ‘onshore’ (indicated by the red colour), while the offshore part of the adapted network has been given the label offshore (indicated by the blue colour).

2.1. Web-based part of economic tool

The web-based part of the economic tool provides the user with a graphic view of the Geocapacity database (see Figure 1). In a Google Maps window, sources and sinks are shown for all participating countries. Once sources and storage locations are selected, the tool shows the available data, for the user to change or supplement. When sufficient data are available, the total storage capacity in the sink(s) can be compared with the total production (capture) of CO_2 during the lifetime of the CCS scenario, which can be chosen to be equal to the expected economic lifetime of the capture installations (typically 30 or 40 years).

When the total storage capacity in the CCS scenario is sufficient, a network connecting all sources and sinks can be computed. This network is computed on the basis of shortest distances, but does not necessarily represent the shortest possible network. For a detailed description of the network algorithm, see Kazmierczak et al. [2]. The GESTCO tool uses land use as a cost driver to compute the best (cheapest) pipeline route between a single source and single sink, but a similar approach was considered too time consuming to be applied here. Instead, the network algorithm computes a network consisting of straight segments, which can be edited by the user to take into account existing pipeline corridors, topography and land use. As noted above, the aim of the tool is not to perform detailed planning, but rather to provide a realistic estimate of the economic feasibility of a CCS project. Building a schematic, but realistic, network is part of that approach. Figure 2 shows a hypothetical network that links two sources and three offshore storage sites, before and after editing, using existing pipeline locations and land use to find a more reliable routing.

After editing the computed network, i.e., changing the route of the segments of the network, all data can be downloaded to the local computer, as input to the local application.

2.2. Local part of the economic tool

The stochastic analysis of the economic costs of a CCS project is performed by an application running on a local computer. This tool is an application of decision support software developed at TNO. A series of modules represents the entire CCS chain, to compute the costs associated with capture, compression, transport and storage. As the timing of costs strongly affects the net present value (NPV) of a project, all costs must be placed at the correct position in time in the lifetime of the project. The key driver here is the behaviour of the sinks, which determine if and when each sink is developed and activated, in turn requiring parts of the network to be constructed. The modules representing the elements of the CCS chain are briefly discussed here, in the order in which they are executed in the code.

2.2.1. Capture

The capture module estimates capture parameters and cost for a variety of sources types and capture technologies. The latter include post-combustion (capture of CO_2 from flue gases), pre-combustion (capture by fuel conversion), oxyfuel combustion (capture by fuel combustion using pure oxygen) and high-purity CO_2 (sources that emit almost pure CO_2). Important parameters are plant type (both power and non-power plants), new versus existing (retrofit) installations, plant technology (e.g., gas turbine, combined cycle, etc.), the type of fuel (gaseous or liquid). Additional data to be provided include CO_2 concentration in the flue gases, the volume of flue gases to be treated and the emission factor for fuel and electricity used for the capture process and the electricity.

The capture module calculates among other results the energy requirement for the capture process, the amount of CO_2 captured per year, any additional CO_2 generated by the process itself, remaining CO_2 emissions, and the economics of the capture process.

2.2.2. Compression

The compression module calculates among other results the energy requirement for the compression process, the amount of CO_2 produced additionally per year due to compressing the captured CO_2, and the costs (investment and operational costs).

2.2.3. Storage

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 current increasing oil prices result in highly uncertain production end times), saline aquifer storage is associated with highly uncertain reservoir properties.

The storage module was developed for injection of supercritical CO_2 into aquifers and abandoned oil and gas reservoirs and computes storage capacity and injection rates. The storage capacity of a reservoir is listed in the Geocapacity database, but the capacity calculation can be redone using data on the reservoirs that is also listed. This allows for a consistent computation of reservoir storage capacity for all sinks in a scenario. For depleted gas fields, the capacity estimation for these reservoirs is straightforward, assuming that CO_2 can replace the original fluids and that the reservoir can be brought back to its original pressure. Saline aquifer storage is treated differently, as that implies bringing an uncertain reservoir volume to a pressure above its initial pressure. For a detailed description of aquifer storage, see Van der Meer & Yafuz [3] and Van der Meer & Egberts [4]. Two methods are provided for the computation of storage potential. The first assumes a fixed percentage of available (i.e., hydraulically linked) aquifer volume that can be created by increasing aquifer pressure. This percentage is not the same as the sweep efficiency used by the IEA (see, e.g., Bachu et al, [5]), but applies to the entire affected space. The volume of injected CO_2 is to be stored in a trap structure, which should be large enough. The second method computes the storage potential from the physical properties of the aquifer and can be used when sufficient data on reservoir properties are available. Important parameters include maximum overpressure, porosity, aquifer thickness and area (e.g., the area bounded by sealing faults).

Apart from the total storage potential, the feasibility of storing CO_2 in a reservoir depends on the storage rates that can be achieved. Storage rates (in Mt/yr) can be computed from data in the database (such as permeability, reservoir thickness and temperature). The model is based on a mass balance equation and a pressure model that incorporates the development of a growing CO_2 zone around the wells with different mobility than the original fluid in place. At the basis of the algorithm is the assumption that injection pressure can not exceed a user-specified maximum pressure. The result of the injection rate module is the maximum feasible injection rate as a function of fill fraction of the reservoir, for one to three injection wells. This information is used in the source – sink match algorithm.

EOR is not included yet.

2.2.4. Transport, source – sink matching

When the volume of captured CO_2 (throughout the lifetime of the scenario) is known and the reservoir properties (storage capacity and injection rates) available, the flow of CO_2 through the network can be computed. Whereas the network structure is computed by the web-based tool, the size of the pipeline segments is not known, nor is the year in which each of the sinks in the scenario is to be developed for injection. Both these data are required for the computation and timing of transport and storage costs.

The source – sink match algorithm determines where the captured CO_2 is stored. A choice can be made to use the closest available sink, or the largest available sink. The former option minimizes the total length of pipeline used at any given time during the lifetime of the scenario, while the latter option delays the development of any additional sinks. In both cases, investment costs are delayed, which decreases the net present value of the CCS project.

During the scenario lifetime, the injection rate of an active sink is adjusted (lowered) as its storage capacity is used up. When the maximum possible injection rate becomes insufficient to store the yearly volume of CO_2, additional wells are developed when appropriate. (For ‘good’ reservoirs, with sufficient permeability and thickness, developing additional wells does not in general significantly increase the injection rate. The additional well will affect the pressure field of the first well(s), reducing its (their) injection rate. Additional wells only help in the case of tight reservoirs, which would perhaps not qualify for storage as they require a (too) large number of wells to obtain useful injection rates.) When additional wells do not solve the problem, new storage locations in the network are developed.

The result of the source – sink match algorithm is the time interval in the scenario that each segment of the network is active. This is used to compute the investment and O&M (operation and maintenance) cost curves for the entire network.

2.2.5. Economy

The economic module adds the cost of all elements in the CCS chain. Its main results are the NPV of the CCS project. Additional results include the NPV broken down into the capture, compression, transport and storage elements, as well as the total costs for each source and each sink in the project. This helps identifying any dominant cost factor. An important aspect of the results produced by the tool is the estimate of the uncertainty associated with each cost result. All results are given in terms of a probability distribution function (pdf), or, more concisely, as a mean plus standard deviation. The Monte Carlo approach is encoded in each of the modules described above and takes into account the pdf of each input parameter and propagates it into the results.

3. Example of results

A hypothetical CCS scenario was created to show the results produced by the Geocapacity economic tool. The scenario includes two sources and four sinks (two depleted gas fields and two aquifers). The most relevant properties of the sources and sinks are shown in Table 1 (sources) and Table 2 (sinks). The total volume of CO_2 to

Table 1. Emission source parameters, for the hypothetical CCS scenario described in section 3.

Source 1	Existing power plant Gas turbine, 1000 MW Load hours 7500 ± 200 hr/yr CO_2 emission 5.0 ± 0.5 $MtCO_2$/yr Capture period 2015 – 2045	Capture technology Post-combustion, retrofit Captured fraction 75 ± 2 % Total captured CO_2 in scenario 128 ± 6 $MtCO_2$
Source 2	Existing cement plant Gas fired Load hours 7500 ± 200 hr/yr CO_2 emission 3.0 ± 0.2 $MtCO_2$/yr Capture period 2015 - 2055	Capture technology Post-combustion, retrofit Captured fraction 75 ± 2 % Total captured CO_2 in scenario 100 ± 6 $MtCO_2$

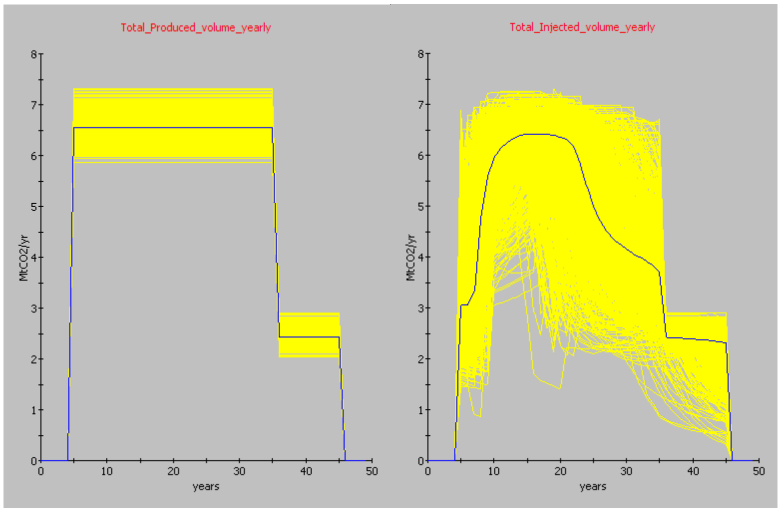

Figure 3. Total volume of CO_2 captured at the two sources (left) and total volume of CO_2 injected in the four sinks in the project (right). Although the storage potential in the project is large enough, problem arise immediately, due to insufficient injection rates. The volume not injected is subtracted from the volume of CO_2 avoided in the scenario.

be stored during the project is about 230 $MtCO_2$; the total storage potential in the sinks is about 275 $MtCO_2$, about 120% of the required storage potential. These numbers suggest that storage problems may occur towards the end of the lifetime of the CCS project, when CO_2 levels in the sinks begin to approach their limits.

Figure 3 shows the volume of CO_2 produced (captured) throughout the lifetime of the CCS project (left panel). The figure shows the results from all Monte Carlo runs (1000, in this case), plus the mean (blue curve), giving a clear view of the variability of the result, due to uncertainties in the source parameters. On average, about 6.5 $MtCO_2$/yr is captured in the first part of the project, decreasing to about 2 $MtCO_2$/yr when the power plant is taken out of production. The second panel in the figure shows the volume of CO_2 stored during the CCS project. Although storage capacity is sufficient, in the first years of the project the combined injection rates of the saline aquifers is insufficient and full storage is only possible when the gas fields are also available. On average, however, the sinks in this project are unlikely to provide sufficient capacity to store the 6.5 $MtCO_2$/yr produced by the two sources.

Figure 4 shows an illustration of the source – sink match algorithms. The first panel shows network length used throughout the CCS project, using the algorithm that uses the largest sink available at a given time, while the second panel shows network length resulting from the algorithm that connects to the closest available sink. The latter results in delaying network construction costs, apparent from the shorter network. Whether this effect is larger than delaying site development costs, which is the aim of the former algorithm, depends on the layout of the network. The setup of the economic tool allows this trade-off to be studied.

Table 2. Storage site parameters, for the hypothetical CCS scenario described in section 3. The start data of injection in the gas fields is uncertain, but will not be available at the start of capture. The saline aquifers are available.

Sink 1	Sink 2	Sink 3	Sink 4
Depleted gas field	Depleted gas field	Saline aquifer	Saline aquifer
Capacity 51 ± 9 Mt	Capacity 68 ± 13 Mt	Capacity 109 ± 51 Mt	Capacity 45 ± 22 Mt
Depth 1200 m	Depth 1200 m	Depth 1500 m	Depth 1500 m
Starts: 2025 - 2033	Starts: 2015 - 2020	Starts: 2015	Starts: 2015
Permeability 40 – 80 mD	Permeability 80 – 140 mD	Permeability 40 – 110 mD	Permeability 40 – 80 mD
Maximum injection rates 1 – 2 $MtCO_2$/yr	Maximum injection rates 2 – 5 $MtCO_2$/yr	Maximum injection rates 1 – 2 $MtCO_2$/yr	Maximum injection rates 1 $MtCO_2$/yr

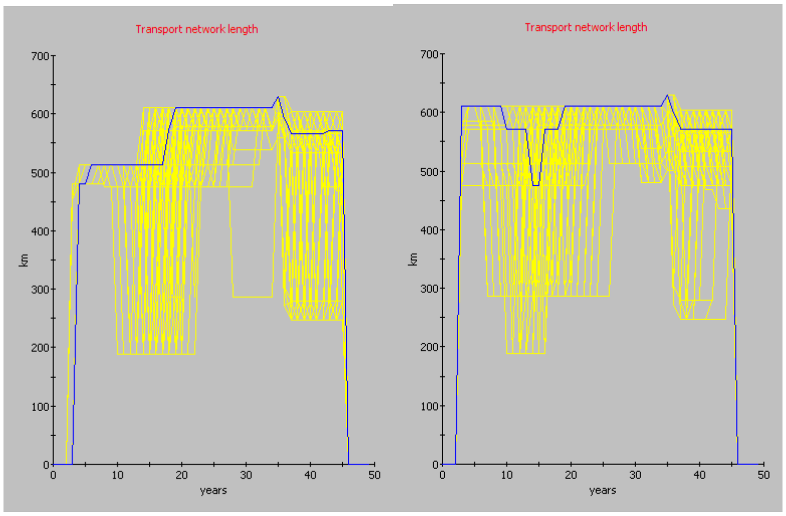

Figure 4. Total length of pipeline used throughout the CCS scenario lifetime. Left: results from the algorithm that uses largest available sink first; right: results from the algorithm that uses nearby sinks first. Yellow curves represent individual realizations in the Monte Carlo run; blue curve represents the average over all (1000) runs.

Figure 5 shows the net present value (NPV) of the hypothetical CCS project, normalized by the total amount of CO_2 avoided in the project. NPV values are shown for the entire project, as well as for the elements of the CCS chain: capture, compression, transport and storage. This breakdown identifies the location of the major costs (capture). Other ways of breaking down costs are also computed, such as NPV for each source and each storage location, to highlight the elements in the CCS project that are most expensive. An important aspect of Figure 5 is the fact that all results, including the NPV values shown, are given in terms of a probability distribution function. In the figure, the pdf has been simplified by a mean and 10 – 90% confidence interval (indicated by the error bars). The economic tool allows for a simple and straightforward sensitivity analysis, to find those parameters or uncertainties in the input that most strongly affect the result.

Investment (CAPEX) and operation and maintenance (OPEX) costs are shown in Figure 6. These results were obtained for a discount percentage of zero. Again, the yellow curves represent the different Monte Carlo realizations and provide a graphical representation of the uncertainty in the results, in this case in the timing of investment costs incurred later in the CCS project, when additional storage sites need to be developed.

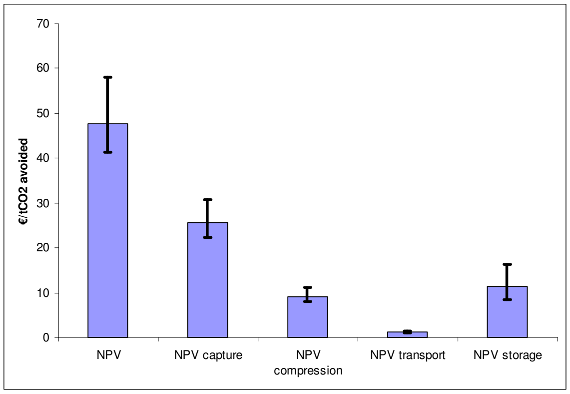

Figure 5. Representation of net present value for the hypothetical CCS project described in section 3, normalized by the total amount of avoided CO_2 (in this case the same as unit cost). Shown is the NPV for the entire project, as well as for capture, compression, transport and storage elements in the CCS chain. The columns represent the median values, while the errors bars indicate the 10% and 90% probability values. The unit is €/tCO_2 avoided, taking into account any CO_2 produced as a result of capture and compression and any CO_2 captured but not stored.

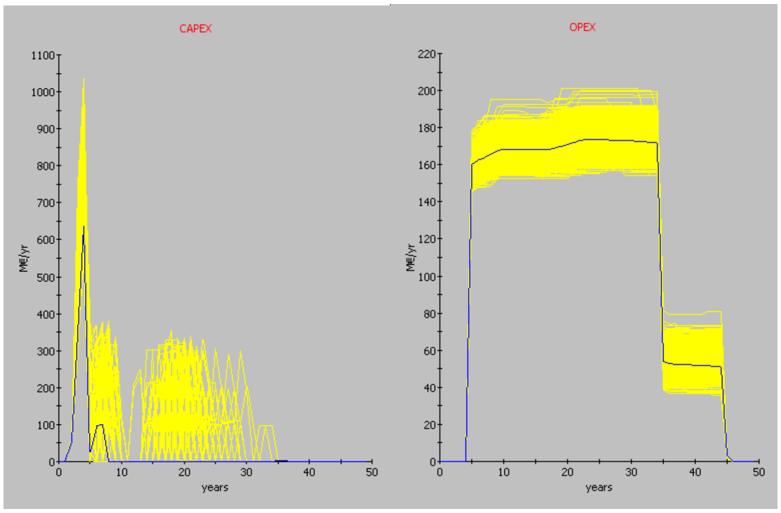

Figure 6. Investment costs (CAPEX, left) during the lifetime of the CCS project, and operation and maintenance cost (OPEX, right), in M€/yr. The high investment costs at the start of the project are due to capture installations, construction of the first elements of the network and development of the first sinks. Investments required between about 15 and 30 years into the projects are due to additional network construction and site development.

4. Conclusions

A tool has been developed, in the framework of the EU Geocapacity project that can be used to estimate the economic feasibility of a CCS project, which includes any number of CO_2 sources and sinks and a connecting network of pipelines. Given the location of the sources and sinks, the tool computes the network of pipelines and the total cost (net present value) of the CCS project, using a Monte Carlo approach to propagate the uncertainty in any of the input variables into the results. The tool covers the entire CCS chain, producing results that can be used to test in detail the capture, compression, transport and storage aspects of a CCS project.

5. References

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