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A techno-economic Analysis Tool for Regional CO_2 Capture, Transport, Use and Storage Scenarios

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Abstract

Carbon capture from industrial, high concentration CO_2 sources, combined with CO_2 transport, utilization and storage (CCUS) is a way to reduce greenhouse gas emissions. CCUS will play an important role in our transition into, and, also beyond the green shift, as CCUS both significantly reduces emissions from industrial processes and offsets emissions from hard-to-remove sectors – leading to the global net-zero society. We study here how the deployment of CCUS networks and commonly shared infrastructure could be evaluated using a dedicated techno-economic analysis tool presented here.

A scenario-approach was taken in the development of CCUS network to decarbonize industrialized regions. In this context, a scenario is defined as a planned deployment of capture, transport, utilization and storage units – each at a given location and at given time between now and 2050. The Excel-based tool presented in this paper, allows for both the design and technical-economic analysis at regional scale. It allowed to define scenarios in a time-dependent spatial network connecting capture points to CO_2-utilization factories and storage locations via transport by pipelines, or via trains, trucks, or vessels/barges.

To set up different scenarios, and to ensure both their internal consistency and comparability with each other, a dedicated tool was developed in the STRATEGY CCUS project funded though EU Horizon 2020 program (grant agreement No 837754). The tool use common input variables shared between different modules of the tool and scenarios which enables comparison between decarbonization of different regions. The tool aims to provide more realistic, and comparable estimates for future energy and

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material use, emissions avoided and negative emissions, revenues created by downstream industries, broken down in discounted and un-discounted costs per ton of CO_2 avoided. The tool allows for future cost reductions due to technology maturation, economy of scale and learning, as well as inflation and energy price outlooks.

This paper describes in more detail the structure of the tool, how it was used, and the lessons learned from its development. Basically, the tool underwent two development stages: The first when the internal logic was developed and the tool itself was put together, and secondly, when eight regional European teams used the tool, its quality and internal consistency significantly improved. Feedback and constructive criticism by users were paramount in the development of the tool.

Keywords: Scenario; Techno-economic; CCUS; Network analysis; pipeline, storage, utilization, ship, train, negative emissions

1. Introduction

Recent world emission outlooks towards 2050 [1-3] have cemented the need for CCUS in the path towards and beyond the green shift into a Net Zero global Society (NZS). To dramatically reduce emissions from industrial regions, CO_2 from point sources must be captured, transported, potentially used for value creation (selling CO_2 and reduce the overall network and storage costs), and then, the remaining CO_2 must be safely stored. To analyze potential time-dependent scenarios for spatially located emission, utilization and storage facilities in the short, medium, and longer term, an Excel based tool was developed. Commonly shared input parameters were defined, and cost and energy use were calculated so that outputs could be generated. The tool was developed in Excel in order to ensure transparent development and easy deployment for all users.

The paper aims at first presenting the logic of the tool before a detailed description of the structure is given. The paper describes how each scenario is designed and presented in time-dependent network graphs, how each unit of the scenario is analyzed at greater depth, and then how the output data is used to obtain regional based Key Performance Indicator (KPI) outputs. The model is jointly owned by the development team and a Joint Ownership Agreement has been signed between IFPEN (France), NORCE (Norway), CSIC (Spain) and University of Evora (Portugal). The authors welcome project initiatives where the tool can be used and further developed.

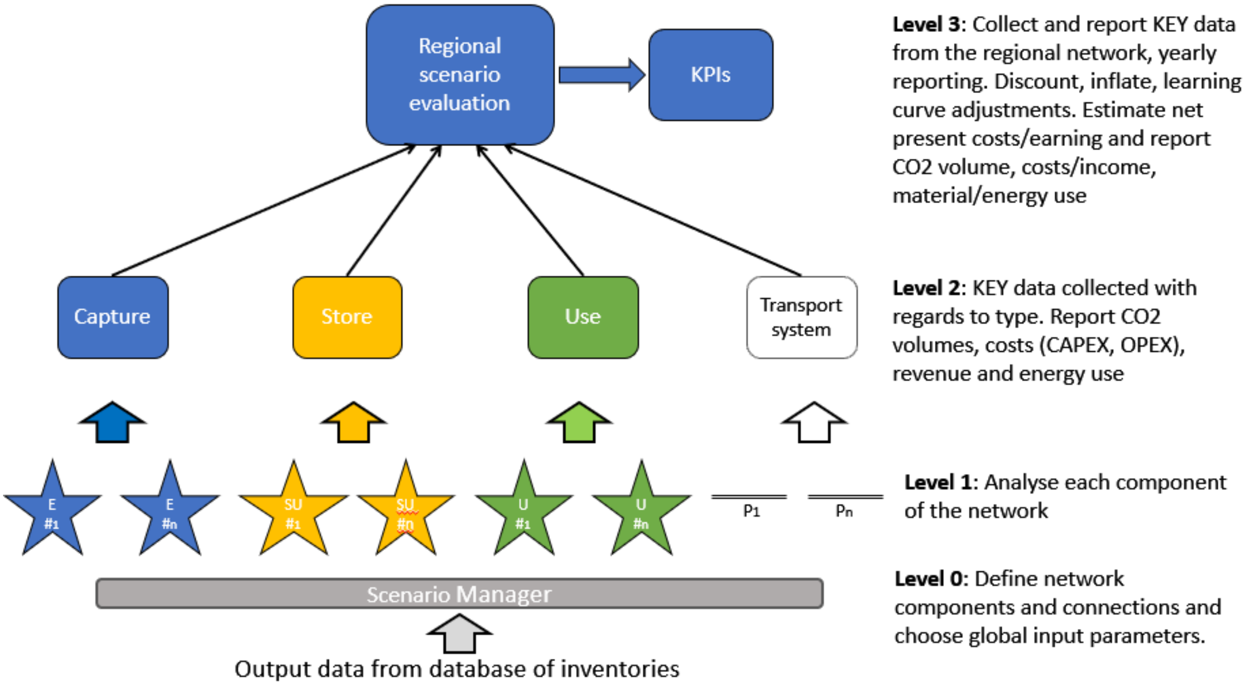
2. Description of the tool

The tool is developed in a set of Excel files, where data from the other work packages are used as inputs to the ‘scenario manager’ module. In this file, the user designs the CCUS network, and specifies the external parameters (global inputs) such as European emission trading systems (EU ETS) of CO_2 price and electricity price, inflation, learning curve, etc. I.e., important factors that are beyond the designer control yet can affect the output of the network analysis.

While designing the CCUS network, the user defines the timeline for the regional scenario by explicitly defining when specific capture and storage sites, potential CO_2 use cases are coming online and how they are connected by various transport and storage solutions. The user starts at the bottom of Figure 1, and once a scenario is adequately defined, each component of the network needs to be analyzed separately to make sure the estimates for all emitters, storage units, utilization factories, and transport-segments are correct. This is referred to as Level 1 analysis. For each storage unit and transport segment, a separate excel file is generated, while a single excel-file is used to evaluate the capture sites, and another single file for utilization.

Once all elements in the network are quality checked, selected data is transferred to Level 2, where all capture plants, storage locations, use cases and transport network segments are accumulated. Key data is then transferred to Level 3, where a regional scenario analysis is performed. Level 2 and Level 3 of the analysis is done in a separate Excel file.

Level 3 calculates and reports selected KPIs for yearly CO_2-amounts captured (from fossil or biological net-negative origin), utilized (the CO_2 released when the product is used, e.g. in e-fuel, green houses etc, or arrested in products in mineralization), leaked, transported, stored, as well as associated indirect CO_2 emissions for each module of the tool. All factors are consistently accounted to determine the actual emission reduction compared to "do-nothing" scenario (i.e. extrapolation of today's situation). Level 2 and 3 enable the user to evaluate internal consistency. The whole scenario tool is designed to ensure adequate comparison between regions and how modifications in each region may optimize the CCUS network. Any change in the global input parameters, or changes to how the scenario is defined, will result in changes in KPIs.



Level 3: Collect and report KEY data from the regional network, yearly reporting. Discount, inflate, learning curve adjustments. Estimate net present costs/earning and report CO2 volume, costs/income, material/energy use

Level 2: KEY data collected with regards to type. Report CO2 volumes, costs (CAPEX, OPEX), revenue and energy use

Level 1: Analyse each component of the network

Level 0: Define network components and connections and choose global input parameters.

Figure 1. Structure of the tool. In the scenario manager the user defines the network and connections (where CO_2 should flow and choose global input parameters in the scenario. Input data in each region are acquired from a data base of inventories. In Leve 1 each component is analysed before key data is collected and displayed for each network type in the network. In Level 3 regional data is collected, adjusted, and displayed before key performance indicators are reported for each scenario.

2.1. Defining a scenario by using the scenario manager

The time sequence at which emitters, utilization facilities, and storages will be connected to the CCUS network is explicitly defined by the user in the scenario manager, and the transportation network connecting the point sources and sinks is set. Information on emission points and storage facilities were retrieved from an inventory database of industries and geological structures developed in another work package in the Strategy CCUS project. Network hubs, where pipelines merge, are defined here. As one of the results, the module provides a network graph of the CO_2 transport system linking emission and storage sites in geographical coordinates (Figure 2). The optimal position of the pipeline in the terrain and boat and train routes is handled explicitly in the transport module. As defined by the user, yearly amounts of captured CO_2 not planned to be utilized at the emission site, will be transported to utilization factories at other places, whereas the rest of CO_2 will be stored. The maximal planned yearly capacities were used to assess adequate transport infrastructure investments (pipeline, train, truck, or CO_2 vessels on sea/rivers), and to estimate OPEX and energy use.

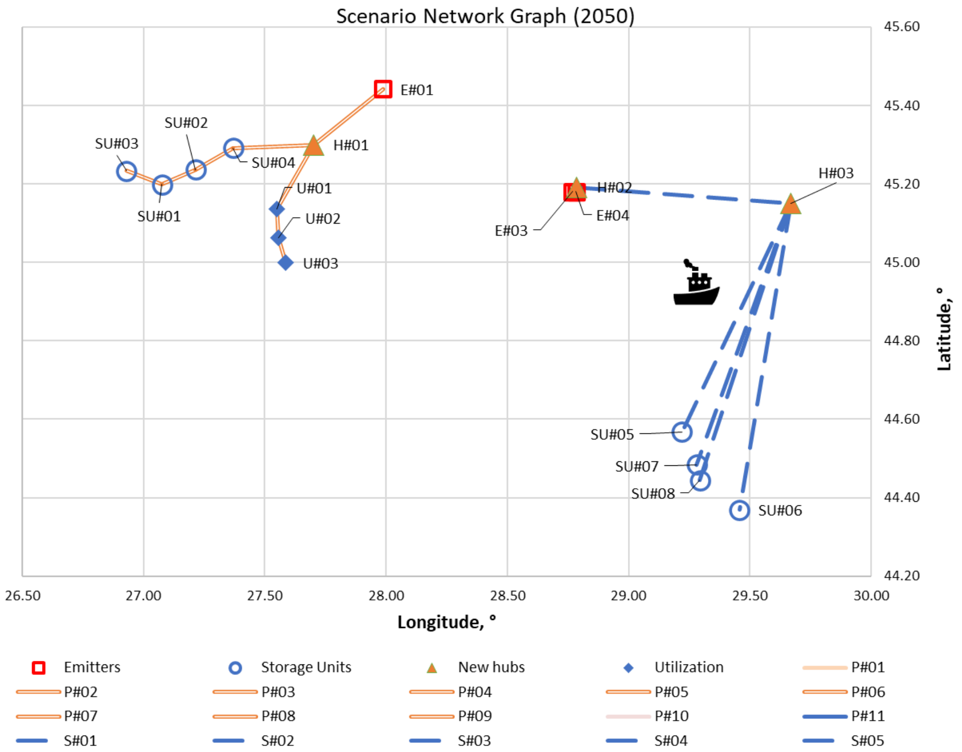


Figure 2. Example of a network graph of a scenario that was evaluated displaying the location of emitters (red squares), hubs (orange triangles), storage locations (blue circles), utilization factories (blue diamonds), and transport segments (dashed and solid lines).

The scenario manager also checks that the scenario is correctly defined, and the material balance is observed for inbound and outbound CO2-flows of the nodes.

Finally, the scenario manager also handles and distributes global input parameters which are beyond the user control. These parameters govern the techno-economic environment for CCUS and may serve as important constrictions for each scenario, such as future projections for: 1) EU ETS costs, 2) regional electricity prices, 3) CO_2 intensity of the electricity production, and 4) potential national emission taxes. For each of these four cases, three alternatives could be defined (example in Figure 2), so that the user could shift between the three and study how the techno-economic calculations and net emission trends would change.

For example, the CO_2 footprint of the electric energy (gCO2/kWh) may vary significantly in different parts of Europe. Further, the evolution in this factor until 2050 depends upon the rate at which fossil sources are phased out of the electricity production. The tool allows the user to provide projections in each region, and thereby, emissions from energy use in the CCUS network will vary. Along the same logic, the energy price in a region is dictated by the imbalance between production and demand, if not fixed priced contracts are given, and it is up to the user to decide on this until 2050. We have experienced high volatility and spatially varying energy prices, and the rate of electrification and rate of buildup of green sources will determine future price outlook. It is up to the user to define which scenario he / she puts faith into. With regards CO_2 taxation and the future cost of EU emission allowances (EU ETC credits) is determined by the number of available quotas and the need to emit. For each of these four input factors, the user can make three alternative future outlooks that can be switched between in the tool. An example of outlook can be seen in Figure 3. In the upper right pane, the historical costs EU ETS in the trading system are displayed from from 2008 until October 2021. Numbers varied from 2-3 to 35 €/t, while in 16th of August 2022 a cost of 90.7 €/ton were seen [4]. The price varies in response to the continental emission trends and yearly reduction of EU quotas (emission cap reduction).

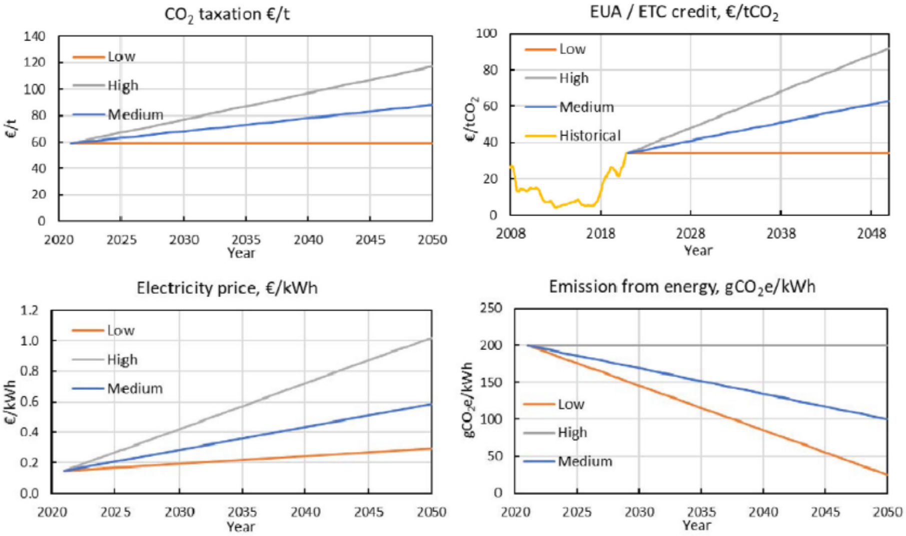


Figure 3. Global (external) inputs used for the techno-economic analysis of the defined scenario. National CO2 tax of emissions, EUA-ETC credits, electricity price and purity of the electricity used is important. High, medium and low projections (controlled by a switch) allow for further simpler analyses after the scenario is properly designed and each component of the network is checked and corrected.

The inflation, discount rate and the reference year, at which discounted cash flows/costs are evaluated, is defined in the scenario manager. Further, any potentially cost reduction effects, due to learning from experience, scale-up and technology maturation is defined here. In the model we decided to include learning on the CAPEX of capture units as they become stream-lined and tailor made, modular, and potentially to be produced on assembly lines at adequate scales to the user. The tool is flexible for the user to decide which future cost elements that should be affected by learning curve adjustments. The tool ensures that these input factors are treated equally in all modules, i.e. separate Excel files, of the tool.

2.2. Capture module

Once a scenario has been developed, and capture sites are selected with key information from the database (or hand-typed into the tool), then each capture site must be analyzed individually. The tool allows for up to 15 units in a single Excel (can be extended). The objective of this analysis is to provide estimates of yearly volumes, energy use and OPEX/CAPEX costs in each industrial facility. The module was focused on the industries with high CO_2 emissions, that are steel mills, incinerators, cement plants, gas/coal power plants, pulp and paper mills, refineries, glass, and other chemistry, while allowing for both post/syn and pre- capture facility. Further, different cost-functions are used if the capture is included in the design and construction of the factory, or if capture units are retrofitted to existing infrastructure. The input of the tool includes name, type, location, and past reported emissions – automatically copied from the data base. The user defines the time at which construction and operation should start, thereby distributing CAPEX in the years in advance. The module provides its estimates based on scaling-relations acquired from a large data base of capture sites of studied technologies. Depending upon the actual size, factory type and what fuel is used, the module provides its estimates for each case. The module allows for mixes of fuel types including Low/high sulphur coal, Lignite, natural gas, petchoke, and different biomass such as straw, wood, and biogass.

Based on the input data, combined with the scaling factors from a range studied capture technologies, the tool provides yearly fossil and bio emissions from running the operation. As an example, in a power plant more coal is required to capture the emissions, since CO_2-capture is an energy consuming process. These numbers are then compared to the yearly emission captured, and relying of the input fuel type, potential negative emissions are calculated (i.e. if the carbon in the fuels are of a non-fossil origin). Total CAPEX costs spread out in the construction period, and fixed and variable OPEX are then estimated as function of time as well as additional energy use of the operation. These data are plotted in time in the ‘OutputFactory’ sheet for each unit in the network.

The display of data allows the user to quality check and assess the reality of the output; and if necessary, go back and adjust inputs or adjust the ‘facultative inputs’ representing the core of the scaling relation (as a way to force-feed results if he/she is confident in the actual technology). The output data of each factory is grouped together so that results of all capture facilities in a region are displayed as function of time until 2050. For each year the additional energy use, CAPEX and OPEX cash flows are taken further into the regional analysis.

The facultative input, i.e. the scaling relations are obtained from a literature survey. As there are many capture technologies existing, with different maturity and technological readiness level. Today the amine-based post combustion techniques have the highest TRL-level although it is a higher energy consuming technology than other technologies are underway of being tested and piloted. Only a handful of full-size capture plants exist today, and it is expected that the construction and operation of new capture sites will become less expensive in the future. Future cost-reductions due to learning are not considered at this level (Level 1) in our analysis, but they are included in Level 2.

Input data used for our analysis were:

- For coal and gas power were originating from three reports [5 -7].
- For cement industries the following key references were used [8-10].
- For iron and steel plants we considered different cases with air-blown blast furnace (ABF), top gas recycling blast furnace (TGR-BF), smelting reduction vessel (SRV), calcium looping lime kiln (CaL-LK); and the CO2 capture technologies: amine scrubbing (AS), pressure swing adsorption (PSA), membrane separation (MS), calcium looping (CaL), and hydrate crystallization (HC) [6, 11].
- For paper industry the following references apply [12-14].
- For refineries, two types of installations have been included in the capture module (fluid catalytic cracking FCC) and hydrocracker (with H2 plan). The input data was acquired from [6 Platform Z.E. (2015)]
- For the glass industry, less reliable information can be found in the literature. The industry, as many of the afore mentioned, is diverse. Glass industry includes filament fiberglass, domestic and special glasses, mineral and high temperature insulation wools and a range of other products. According to Friedmanns (2019) report

[15], the energy density of furnaces is comparable to steel industry furnaces and the carbon intensity is comparable to the Clinker kiln of the cement industry. Two reports were used as basis of our scaling relations [15-16].

For each of the capture nodes the input data was scaled to the data acquired from the references above to provide estimates of CAPEX, fixed and variable OPEX, energy consumption, and additional emissions from the deployment of the capture. Once the CO_2 is captured it is either used at the capture facility or transported away for utilization and storage.

2.3. Transport module

In the scenario manager the start and end location, operation years, and yearly CO_2 volume of each transport segment in the network are defined as well as the transport type. Transport by pipeline, train (editable to trucks), and ship were considered. The tool generates a single excel file for each transport unit based on a template workbook. Once all transport files are generated, each segment of the network must be analyzed for adequate dimension, energy use and reliable cost estimates. Based on the different transport types, a series of considerations are needed for more reliable estimates of each segment.

If the specific transport segment is a pipeline, the route between the start and end locations is determined in a GIS-routine developed in the project. The routine uses weighted terrain factors related with land use, land cover and elevation to determine the more suitable areas for pipeline crossing (since the crossing of different terrains comes at different economic, environmental and safety costs), and least cost path analysis (LCPA) to define the most cost-effective pipeline route, given the weight factors fed into the tool. The outputs of this step are pipeline length, percentages of terrain types crossed, number of other infrastructure (pipelines, roads, railways) that are crossed, and the elevation profile. When the route is obtained, the pipeline must be designed to comply with the CCUS network.

When analyzing each pipeline segment, the user can input a range of parameters for adequate design and cost estimates, with many of the parameters being specific to the different regions in Europe. The main editable parameters are construction duration, upstream pressure and temperature, minimum and maximum transport pressure allowed, CO_2 annual flow rate, steel strength and cost, terrain related costs. These parameters dictate pipeline diameter and wall thickness, initial pressure, and if a booster station is needed if the calculated CO2 pressure along the pipeline [Vandeginste2008] falls below a pre-defined value.

Train and ship transport are analyzed based on distance, ship/train capacity, gasification/liquefaction facilities, buffer storage, and loading and unloading times. These factors determine the number of trains/ships that are each year.

If the transport segment is a pipeline, the user work with the following worksheets:

- ‘Pipeline transport’ – main worksheet containing main inputs and outputs, yearly CO_2 volumes and costs.
- ‘Pipeline design’ – pipeline dimensioning and compression calculations.
- ‘Pipeline costs’ – calculates pipeline construction costs relying on parameters such as materials, labor, and additional costs
- ‘Terrain factors’ – contains lengths of a pipeline and the relative weighted costs for each terrain type (land use, land cover, three different off-shore environments, and slope) and the number and costs of road/railway/pipeline crossings. The user can edit the relative costs directly and get calculations in the tool, if preferred other pipeline routes can be inserted manually.
- ‘Pressure profile’ – the spread sheet calculates the pipeline pressure from viscous dissipation [17] and elevation profile at regular intervals and identify zones where the pressure goes below the minimum pressure. This information feeds back to the pipeline design, with this information the user can decide on different pressure control measures changing the pipeline diameter or the need for booster-stations

If the segment is a shipping route of CO_2 transport, then the following worksheets apply:

- 'Ship transport' – Feed in main inputs (distance to travel and ship capacity) and estimate yearly transport costs, energy use outputs.
- 'Shipping parameters' – Specify ship transport cost parameters (ship construction and operation, liquefaction/gasification, buffer storage, harbor fees, loading/unloading).

If the CO_2 is transported on railways then the user must input parameters into:

- 'Train transport' – Feed in main parameters (distance to travel, wagon capacity, maximum number of wagons per train,) and provide outputs broken down to yearly costs and energy use.
- 'Train parameters' - Train transport cost parameters fed into the tool (train and wagon costs, liquefaction/gasification, buffer storage, loading/unloading)

Once all transport segments in the network have been analyzed individually for each transport segment, the key data is transmitted to Level 2 for an aggregated review of all transport data in the scenario. On this level, the overall CAPEX flow during construction time of all segments planned at different times, and operative costs related to maintenance, and energy use is accounted for displayed – on a regional scale.

2.4. Utilization module

The potential to use CO_2 as an input factor for value creation is underway of becoming reality as a variety of innovative industrial processes are underway of being developed.

The tool developed here includes a utilization module for estimating value created by using the CO_2 molecule in product generation. There are, in this context, two ways in which we treat the outcome of the CO_2-utilization further in the analysis: a) as a delayed emission of the captured carbon, for example green houses or synthetic fuels, where the carbon is re-emitted when the product is consumed, or b) when the captured CO_2 is arrested in the product for example when CO_2 is used for mineralization and building material. The first case does not allow for ETS-credit and CO_2-tax subtraction for the emitting industry, while in b) we assume the C-atom is not released to the atmosphere within foreseeable time, thereby allowing for subtraction of ETS credit and CO_2 tax.

There are mutual benefits of the CCS and utilization sector, even though the economic incentives differ. The CCS sector is focused on carbon emission reduction, the utilization sector uses CO_2 as a commodity for value creation. Another difference is the annual usages, where utilization deals with kilo-tons (kt) per year, while, the regional based CCS address numbers in the million ton (Mt) scale per year. In the presented tool, the utilized CO_2 is bought from the CCS-network at an agreed price, up to the user to define. We recommend, at this point, to have a selling price a fixed amount above the EU ETS credit price, although any CO_2 or product sales price be fed into the tool each year. Thus, having a buyer on-stream may bringing down the CCS network cost, and the utilization factory will reduce operative risks by having access to commonly shared CCS network with several suppliers allowing – for stable production. Although, dependent upon how the CO_2 is used will decide if EU ETS expenses or CO_2-taxes could be subtracted.

The utilization module was included to understand how industries built up around CO_2 usage would affect the CCS business case, and what to understand what CO_2 procurement prices could be reasonable in the different cases (depending on the value created). If the region has access to captured CO_2 as a biological non-fossil origin (i.e. negative emission technologies), not obliged to EUAs or taxes, then this amount is sold directly to the utilizing factories. Or, if the CO_2 only comes from fossil sources, then the tax and EU-ETC subtraction could only be performed if CO_2 is arrested in the product, and not released to the atmosphere.

There was, at the time where the analysis was performed, political uncertainty on how the origin of CO_2 could integrate economically with the utilization (especially when CO_2 is re-released to the atmosphere). It was chosen to utilize the whole volume of CO_2, and not only the bio-CO_2 that would enable negative emissions in stead of avoided when arrested in permanent products. This can be determined by each project design. The different products for CO_2 use were:

- **Pure CO2** with >99% purity for beverages, food, chemical and pharmaceutical industries [18].
- **Methanol** production where CO_2 is combined with green/blue hydrogen for methanol synthesis. Methanol could be used as feedstock for other chemical products and e-fuels. Key reference [19].
- **E-fuels**: 3 types of e-fuels were considered from methanol, dimethyl-eter, and e-fuels from algae that has a range of TRLs. Key references: [20-22]
- **Greenhouses** where the supplement of CO2 boost plant growth. Incremental growths and economic benefits are included in the analysis. Key reference [23].
- **Carbonated minerals** where CO_2 reacts with alkaline waste minerals and other minerals to create aggregates that can be used in road foundations, construction bricks, concrete fillers.
- **Increased oil production** as the injection of CO_2 into oil reservoirs enhance the oil production rate the utilization may buy CO_2 from the network, produce oil, and then gradually turn its reservoir into a storage site when oil production declines. At this stage the operator goes from buying Co2 to getting paid to safely store it away. The shift from being a 'buyer' to 'getting paid', will occur in consequence of a carbon budget, i.e. number of C- atoms entering into the reservoir as to what is coming out in the form of back-produced CO2 and hydrocarbons. Key reference [18].

The utilization module was built from the utilization industry's viewpoint, where CO_2 as raw material is used for value creation by products sold in a market. The module is flexible and adaptable, in the sense that the user is obliged to feed in data to convert CO_2 input volumes to product volumes (and price per unit).

In the module, the available flow is read into the tool from the scenario manager, and the yearly rates are specified. The investment CAPEX and OPEX to set up the specific industry requires other sources and must be hand-typed into the tool. The Price paid for CO_2 is chosen by the user, and we recommend relating it to the EU emission trading system EU ETS. The energy prices are supplied by the scenario manager, where this is defined. The tool includes calculations based on the type of fuel used to convert CO_2 into the useful product (selected from a list). For the different products, the module estimates the conversion rate from the amount of CO_2 used to the amounts of products used. The price of each product produced is included in an inventory market price list (based on January 2021) provided in the tool. Any other desired price can be included, if otherwise in the specific region.

Based on the input prices of CO_2, the relation between of CO_2 procured and the amount of valuable products generated, and the price for that, the tool estimates yearly revenues when combined with capital and operative expenses are included. This enables the tool to provide yearly cash flows that is laying the foundation for internal rate of return estimates, and thus what value the down-stream industry provides in the region.

The contribution of this module to the CCUS regional evaluation is based on the permanent utilized CO_2 volume, which is integrated as avoided volume, and its corresponding monetary value (as CO_2 volume times CO_2 price) included as revenues in the final evaluation.

2.5. Storage module

The CO_2 that is not used at utilization plants, or leaked during transport, will be injected in underground reservoirs. The tool allows for up to ten storage units to be included simultaneously. The scenario manager allocates the yearly amounts of CO_2 into each reservoir, and the purpose of this module is to identify if the planned injection rates can be accommodated in the field as limited by how the average reservoir pressure evolve with time. Depending upon the reservoir and well characteristics, required number of wells is estimated, so that one may estimate CAPEX and OPEX costs from site development, well drilling and maintenance, plug and abandonment, as well as energy required to compress CO_2 for injection. The model estimates the pressure evolution using the Fetkovich aquifer model for open, semi-open or closed reservoirs (chosen by the user), and the fluid and reservoir characteristics. Figure 4 display two synthetic cases where CO_2 is injected into a semi-open and closed storage location. Key reservoir data, retrieved from a database compiled by another work package of the project, such as reservoir depth, temperature, fluid content, reservoir thickness and areal extent, connectivity to reservoirs, are used to estimate the ultimate storage potential. When the injected CO_2 leads to a reservoir pressure build-up exceeding a certain threshold, the model gives a warning to the planner to either stop the injection (if the reservoir limits are closed) or to reduce the injection rate to balance out the water flow to the nearby aquifer.

The storage module is based on a single-cell reservoir pressure model connected to an aquifer described by the Fetkovich aquifer model [24]. It consists of a pressure build-up term, input and output fluxes and elastic behavior of the rock formation, fluid saturations evolution and fluid compressibility for four immiscible phases of gas (methane), oil, water and CO_2. Such a simplified approach allows for rough, yet physically consistent and flexible description of multiple storage sites with a few, most essential reservoir parameters. As the reservoir model is zero-dimensional, only average reservoir parameters are required, even though we acknowledge that spatial differences may be important. The fluid properties are acquired from the NIST thermodynamic database [25] and formatted as look-up tables for representative ranges of pressures and temperatures. The reservoir model was verified by a one-to-one comparison with a commercial reservoir simulator.

To estimate costs and energy use, the user should provide sets of parameters describing capital (CAPEX) and operational (OPEX) expenses. The CAPEX elements are related to well drilling, upgrade/installation of surface equipment (such as compressors) and abandonment. The required number wells may vary with time as the yearly injection rate may change according to the input from CCUS network. Depending on injection and reservoir pressure, permeability and reservoir formation thickness the tool calculates the number of wells needed. The OPEX elements include the well maintenance costs per well, administration costs to run the storage site and compression costs.

OPEX related to CO_2 compression are estimated though amount of energy required to compress CO_2 to an injection pressure. The compression work is estimated via specific CO_2 entropies and enthalpies retrieved from the NIST tables for the isothermal compressor. Then associated costs and greenhouse emissions can be evaluated for various energy sources. In this project, we assumed the injection to be powered by electricity. This assumption allows to link injections costs and emissions to electricity price and associated CO_2 footprint per kWh for the considered region (external input parameters for each region). CO_2 leakages while running the operation are estimated (from joints, wells and compressors) as a given percentage of the handled CO_2. These emissions are reported further into the Level 2 and 3.

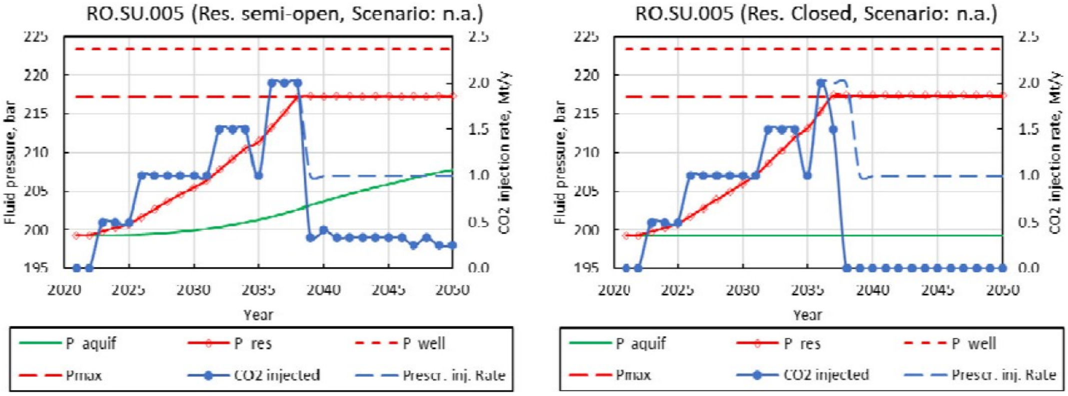


Figure 4. Reservoir pressure, CO2 injection rate and aquifer pressure as function of time in a semi-open reservoir (left) and closed reservoir (right). When the maximal pressure (15% above hydrostatic) is reached the injection rate is reduced to around 0.4 Mt/y, that balances the reservoir-aquifer flow, while in the closed case the injection rate is zero. The year at which Pmax is reached is 2028 and 2036 for the two cases respectively. The bottom hole pressure and reservoir pressure each year is used to determine the number of wells needed for the planned injection rate.

The outputs of the reservoir module are yearly CAPEX and OPEX, CO_2 stored and emitted from the operation, and energy used to power each storage site. These key data are displayed as function of time, and transmitted further to Level 2 analysis where all storage units are displayed together.

2.6. Level 2 analysis

When all units of the network have been analyzed, their data are collected with regards to type, that is, the CAPEX, fixed and variable OPEX, energy use, CO_2 captured from fossil and biological sources, CO_2 emitted, of all capture facilities, utilization plants, storage units and all transport segments are displayed together of each type. Data is displayed as function of time. On this level, the economic adjustments with regards to discounting and inflation, and potentially the inclusion of learning facture for cost reduction are performed.

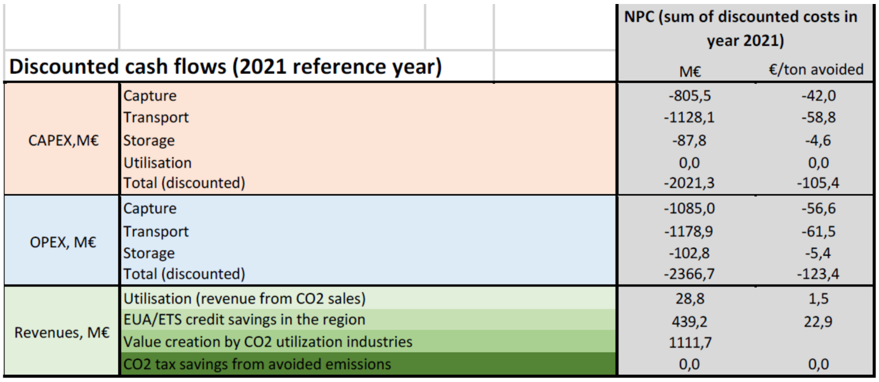
The aggregated numbers of each type are then included in level 3 of the analysis. Level 2 and level 3 of our analysis were performed in the same Excel file.

2.7. Level 3 evaluation module – total regional KPIs

On Level 3 in our analysis, all numbers relevant for the regional case are displayed together. Here, we display yearly amounts of CO_2 captured, CO_2 used and re-emitted and CO_2 used in mineralization (stored in product), the yearly stored amounts, the emissions from operation (both direct and indirect via the electricity use) so that the total avoided emissions can be calculated. In addition, the net negative emissions (from biological sources) are displayed, so that a realistic comparison between the industrial region with business as usual with the region with CCUS can be obtained. The total energy calculations are converted to GWh per year and the electrical energy cost is displayed. These are important ingredients when planning such infrastructure developments.

The discounted and undiscounted CAPEX and OPEX for capture, transport, storage and utilization (if any) are displayed. Revenues are calculated from the sales of CO_2 to downstream industry, the total costs of CCUs are compared to the total costs of the EU-ETS without CCUS investments, national CO_2 tax savings (if any).

Table 1. Example of discounted cash flows for CAPEX (red shade) and OPEX (blue) of capture, transport, storage and utilization for the whole region x. Revenues are displayed in green.

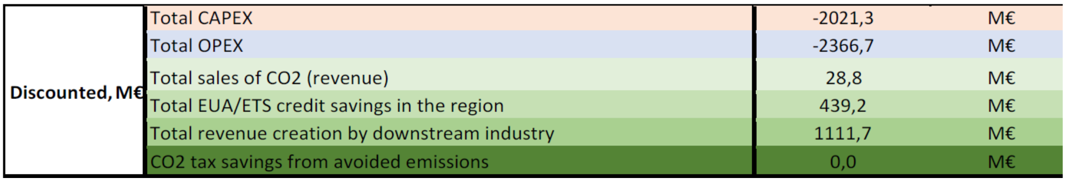


Discounted cash flows (2021 reference year)		NPC (sum of discounted costs in year 2021) M€	€/ton avoided
CAPEX,M€	Capture	-805,5	-42,0
	Transport	-1128,1	-58,8
	Storage	-87,8	-4,6
	Utilisation	0,0	0,0
	Total (discounted)	-2021,3	-105,4
OPEX, M€	Capture	-1085,0	-56,6
	Transport	-1178,9	-61,5
	Storage	-102,8	-5,4
	Total (discounted)	-2366,7	-123,4
Revenues, M€	Utilisation (revenue from CO2 sales)	28,8	1,5
	EUA/ETS credit savings in the region	439,2	22,9
	Value creation by CO2 utilization industries	1111,7	
	CO2 tax savings from avoided emissions	0,0	0,0

These calculations enable direct calculations of yearly total costs for the CCS network, and total costs minus CO_2 sales and savings from not having to buy EU-ETS quotas, including permanent utilized CO_2. Both discounted and undiscounted cash flows each year are reported, and cumulative values of both enabling the total calculation in the whole-time span till 2050.

This collection allows for a selection of Key Performance Indicators in the proposed scenario, where discounted costs broken down to euro per ton CO_2 avoided are displayed. The relative importance of capture, transport and storage are displayed, while the overall income by CO_2 sales and EU ETS savings are displayed.

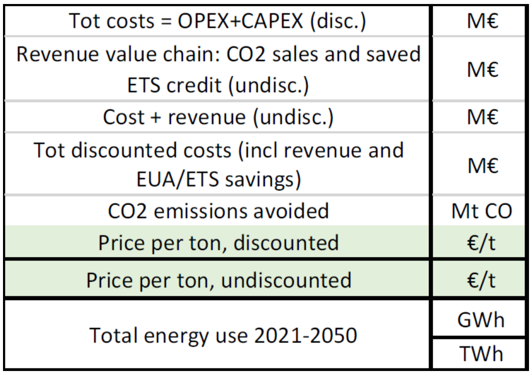
Table 2. Discounted total capex opex cash flows during the time til 2050 of a sythetic example. The sales of CO2 and EU-ETS credit savings are displayed. The revenue created by down stream industries in the region are also displayed, as well as tax savings (if applicable in the region).



Discounted, M€	Total CAPEX	-2021,3	M€
	Total OPEX	-2366,7	M€
	Total sales of CO2 (revenue)	28,8	M€
	Total EUA/ETS credit savings in the region	439,2	M€
	Total revenue creation by downstream industry	1111,7	M€
	CO2 tax savings from avoided emissions	0,0	M€

Selected KPIs of the whole regional scenario are displayed in the sheet where overall costs, energy use, and CO_2 streams are quantified. The tool breaks down the discounted costs to the reference year. Further, the CAPEX and OPEX costs are displayed with regards to €/ton CO_2 avoided. Then, the income from CO_2 sales and EU ETS credit savings in the region is displayed. The volumes of CO_2 are broken down to the various categories, such as: captured, utilized (both released upon use and captured in products), stored, emitted during CCUS, as well as the avoided and potential negative emissions. The share of the national reduction objective is provided for comparison. With regards to the price of allowances, and the regional expense to be expected without CCUS are displayed together with the energy needed to run the operation. All this data is displayed with yearly amounts. See Figure 5.

Table 3. Overall table of KPIs of each industrial region. The reported data may be subject to change for any change in the scenario or the global input parameters. Once a scenario is developed, it is simpler to perform incremental adjustments and study how these changes lead to regional improvements.



Tot costs = OPEX+CAPEX (disc.)	M€
Revenue value chain: CO2 sales and saved ETS credit (undisc.)	M€
Cost + revenue (undisc.)	M€
Tot discounted costs (incl revenue and EUA/ETS savings)	M€
CO2 emissions avoided	Mt CO
Price per ton, discounted	€/t
Price per ton, undiscounted	€/t
Total energy use 2021-2050	GWh TWh

3. Summary and Conclusions

CCUS paves a way to de-carbonization of European industrial regions. Commonly shared infrastructure allows for significant cost reduction; however, it required careful and holistic planning before large investments are made.

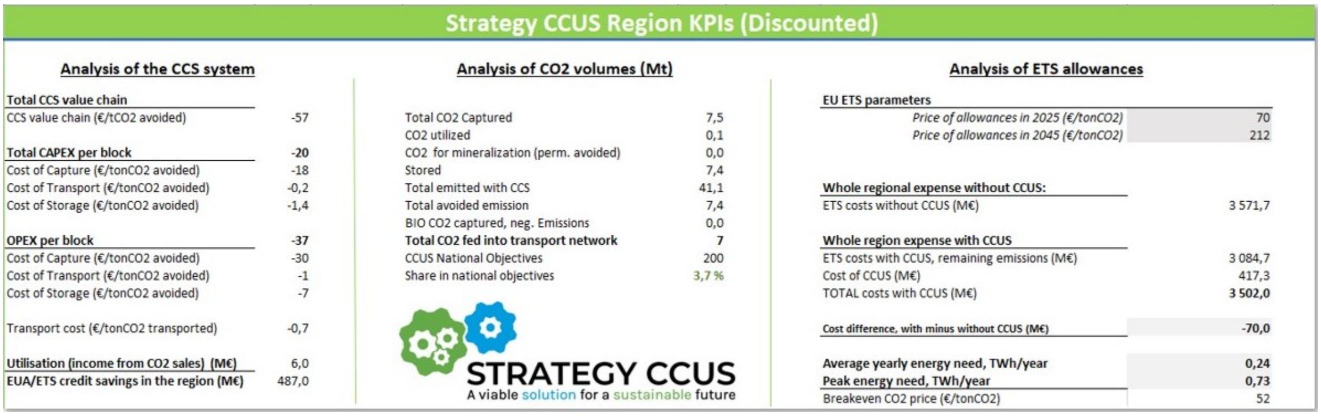
We believe that the presented tool can significantly facilitate and support regional planning of CCUS. The tool uses set of rather basic input parameters and allows for simplified yet consistent evaluation of regional CO_2 abatement strategies. It enables comparison of different scenarios, ensuring both their internal consistency and comparability, and helps to understand, improve, and select the best option available for CCUS technologies implementation in a regional approach.

The main lesson learned from the tool development is to make sure that end-users are involved as early as possible. Their constructive and critical feedback has been paramount to finalize the tool. The users' questions and comments spotted numerous errors, and required additional flexibility not considered initially. This improved the quality of the end-product, and boosted the rate at which the tool was developed.

In the future we would like to develop the tool further into a stand-alone program that would facilitate its usage and streamline data flow between all the modules.

The authors welcome initiatives that may employ the tool in forth-coming projects related to regional planning of CCUS infrastructure.

Figure 5.Key performance indicators from a regional assessments given the CCUS network design and input parameters.



Strategy CCUS Region KPIs (Discounted)

Analysis of the CCS system

Total CCS value chain	
CCS value chain (€/tCO2 avoided)	-57
Total CAPEX per block	**-20**
Cost of Capture (€/tonCO2 avoided)	-18
Cost of Transport (€/tonCO2 avoided)	-0,2
Cost of Storage (€/tonCO2 avoided)	-1,4
OPEX per block	**-37**
Cost of Capture (€/tonCO2 avoided)	-30
Cost of Transport (€/tonCO2 avoided)	-1
Cost of Storage (€/tonCO2 avoided)	-7
Transport cost (€/tonCO2 transported)	-0,7
Utilisation (income from CO2 sales) (M€)	6,0
EUA/ETS credit savings in the region (M€)	487,0

Analysis of CO2 volumes (Mt)

Total CO2 Captured	7,5
CO2 utilized	0,1
CO2 for mineralization (perm. avoided)	0,0
Stored	7,4
Total emitted with CCS	41,1
Total avoided emission	7,4
BIO CO2 captured, neg. Emissions	0,0
Total CO2 fed into transport network	**7**
CCUS National Objectives	200
Share in national objectives	3,7 %

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Analysis of ETS allowances

EU ETS parameters	
Price of allowances in 2025 (€/tonCO2)	70
Price of allowances in 2045 (€/tonCO2)	212
Whole regional expense without CCUS:	
ETS costs without CCUS (M€)	3 571,7
Whole region expense with CCUS	
ETS costs with CCUS, remaining emissions (M€)	3 084,7
Cost of CCUS (M€)	417,3
TOTAL costs with CCUS (M€)	**3 502,0**
Cost difference, with minus without CCUS (M€)	**-70,0**
Average yearly energy need, TWh/year	**0,24**
Peak energy need, TWh/year	**0,73**
Breakeven CO2 price (€/tonCO2)	52

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