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CO_2 Highways for Europe

Modelling a Carbon Capture, Transport and Storage Infrastructure for Europe

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Abstract

We present a mixed integer, multi-period, cost-minimising model for a carbon capture, transport and storage (CCTS) network in Europe. The model incorporates endogenous decisions about carbon capture, pipeline and storage investments. The capture, flow and injection quantities are based on given costs, certificate prices, storage capacities and point source emissions. The results indicate that CCTS can theoretically contribute to the decarbonisation of Europe's energy and industrial sectors. This requires a CO_2 certificate price rising to €55 per tCO_2 in 2050, and sufficient CO_2 storage capacity available for both on- and offshore sites. Yet CCTS deployment is highest in CO_2-intensive industries where emissions cannot be avoided by fuel switching or alternative production processes. In all scenarios, the importance of the industrial sector as a first-mover to induce the deployment of CCTS is highlighted. By contrast, a decrease in available storage capacity or a more moderate increase in CO_2 prices will significantly reduce the role of CCTS as a CO_2 mitigation technology, especially in the energy sector. Furthermore, continued public resistance to onshore CO_2 storage can only be overcome by constructing expensive offshore storage. Under this restriction, reaching the same levels of CCTS penetration would require a doubling of CO_2 certificate prices.

Keywords: carbon capture and storage, pipeline, infrastructure, optimisation

JEL Codes: C61, H54, O33

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Security of Energy Considering its Uncertainty, Risks and Economic implications

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MODELLING A CARBON CAPTURE, TRANSPORT AND STORAGE INFRASTRUCTURE FOR EUROPE

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Introduction

The International Energy Agency (IEA) (2009b) estimates that reducing CO_2 emissions by 50% in 2050 compared with the 1990 level absent the use of carbon capture, transport and storage (CCTS) technology would produce global additional mitigation costs of US$1.28 trillion annually. This is equivalent to a cost increase of 71%. According to the IEA's "Technology Roadmap" (IEA, 2009c), it is likely that an integrated CO_2 transport network will be an integral part of a least-cost mitigation strategy from the perspective of 2050. By contrast, the Roadmap also acknowledges the real danger that the ambitious development plans for CCTS demonstration in Europe in the next decade will remain unfulfilled, partly owing to institutional questions about the regulation of transport infrastructure and concerns about storage. A CO_2 pipeline network has high sunk costs and large economies of scale. It has become more obvious that the real bottlenecks to CCTS deployment are transport and storage infrastructure. Against this background, only a few simplified CCTS models actually address the pipeline transport of large volumes of CO_2.

The Global Energy Technology Strategy Program modelled the adoption of a CCTS system within three fossil fuel-intensive, electricity generation regions of the US. The results show that CCTS implementation depends more on allowable CO_2 injection rates and total reservoir capacity than on the number of potential consumers who would use the CO_2 for enhanced oil recovery (EOR) (Dooley et al., 2006). McPherson et al. (2006) and Kobos et al. (2007) introduced the "String of Pearls" concept to evaluate and demonstrate the means for achieving an 18% reduction in carbon intensity by 2012 using CCTS. Their dynamic simulation model connects each CO_2 source to the nearest sink and automatically routes pipelines to the next neighbouring sink, thus creating a trunk line connection for all of the sinks. While the model can determine an optimal, straight-line pipeline network, it is not possible to group flows from several sources to one sink.

Fritze (2009) has developed a least-cost path model, which connects each source with the nearest existing CO_2 sink. He examines a hypothetical case of main trunk lines constructed by

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This paper is an outcome of the research programme on "Resource Markets", carried out jointly by TU Berlin (WIP), DIW Berlin and TU Dresden (EE2). Earlier versions of the paper were presented at the "5th Enerday" (April 2010, Dresden) and the "11th European Conference of the IAEE" (August 2010, Vilnius). The authors would like to thank participants at these conferences, as well as Jan Abrell, Christian von Hirschhausen and Andreas Tanner for their valuable comments on model design and interpretation of the results.

the US federal government and their influence on the total costs. Yet no economies of scale are implemented in the model for construction, and thus the costs of building the public trunk lines are greater than the avoided costs of private enterprises. Nevertheless, public trunk lines allow greater network flexibility and redundancy, which can lead to cost savings in times of emergency and when storage capacity needs to be balanced.

Middleton et al. (2007) and (2009a) designed the first version of the scalable infrastructure model SimCCS, which is based on mixed integer, linear programming. With its coupled, geospatial engineering-economic optimisation modelling approach, SimCCS minimises the costs of a CCTS network capturing a given amount of CO_2. An updated version by Middleton et al. (2009b) comprising 37 CO_2 sources and 14 storage reservoirs in California simultaneously optimises the model according to the amount of CO_2 to be captured from each source, siting and building pipelines by size, and the amount of CO_2 to be stored in each sink. The decisions are endogenous, but the total amount of CO_2 stored is exogenous. Economies of scale are implemented through possible pipeline diameters in four-inch steps, each with its own cost function. Kuby et al. (2009) extend a smaller version of the model that employs 12 sources and 5 sinks in California with a market price of CO_2 as well as a benefit when used in EOR. This model minimises the costs of CCTS, but only examines one period. The findings of a CO_2 price sensitivity analysis indicate that infrastructure deployment is not always sensitive to the price of $CO_{2.}$

In January 2006 the EU-based GeoCapacity project was launched to continue the studies of the earlier GESTCO and CASTOR EU research projects designed to examine the development of CCTS technologies in Europe. Carried out by 25 European partners and 1 Chinese partner, the GeoCapacity project maps the large point sources (emitting facilities), infrastructure and geological storage possibilities in most European countries (GeoCapacity, 2009a). Being involved in the GeoCapacity project, Kazmierczak et al. (2009) and Neele et al. (2009) have developed an algorithm to create a low-cost network and a decision support system to evaluate the economic and technical feasibility of storage. A realistic estimate of the economic feasibility of a potential CCTS project is possible, but detailed planning at a project level is not determined by the algorithm. Compared with GESTCO, GeoCapacity can handle more realistic scenarios with multiple sources and reservoir locations based on exogenous decisions about the amount of CO_2 to be stored.

In summary, only a few models include economies of scale in the form of possible trunk lines, but they operate at a static level or are based on an exogenously set amount to be stored. Therefore the models exclude the option of buying CO_2 certificates instead of investing in the CCTS infrastructure.

In this paper, we extend the existing literature by introducing a scalable mixed integer, multi-period, welfare-optimising CCTS network model, hereafter termed ‘CCTSMOD’. The model incorporates endogenous decisions on carbon capture, pipeline and storage investments. The capture, flow and injection quantities are based on given costs, a certificate price path, capacities and a set of emissions point sources from the European power sector and industry. Sources and sinks are aggregated to nodes according to their geographical position and pipelines are constructed between neighbouring nodes. The distance between two neighbouring nodes can be chosen arbitrarily, making CCTSMOD scalable to Europe-wide levels. Economies of scale are implemented by discrete pipeline diameters with respective capacities and costs.

We apply the model to the potential development of a CCTS infrastructure network in Europe. In particular, we are interested in the nature of the CO_2 transport infrastructure that is likely to emerge in north-west Europe, i.e. in Germany and south and east of it, ranging to France and up to the North Sea and its neighbouring states. We run several scenarios that differ by the geological storage potential assumed, the expected CO_2 certificate price in 2050, and public acceptance or rejection of onshore storage – with the alternative being exclusively (expensive) offshore storage under the North Sea. We find that under certain assumptions, such as a relatively high CO_2 price (above €55 per tCO_2 in 2050) and very optimistic CO_2 storage availability, a large-scale CCTS rollout might indeed be expected. In a more likely scenario, however, including lower storage availability and public resistance to onshore storage, a large-scale rollout is much less likely. In all scenarios, CCTS deployment is highest in CO_2-intensive non-energy industries, where emissions cannot be avoided by fuel switching or alternative production processes.

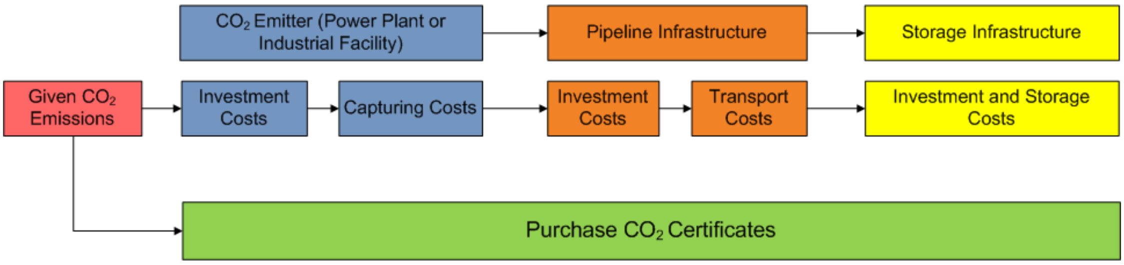
The next section describes the model approach and the mathematical formulation. We then discuss the data on CO_2 emission sources, transportation and storage in section 2, before turning to the scenarios in section 3, which also contains an in-depth discussion of the results. Summing up, section 4 presents our conclusions on the role of CCTS technology in Europe.

1. Model description

1.1 CCTS decision tree

Figure 1 illustrates the decision path of CCTSMOD based on the CO_2 disposal chain. Each producer of CO_2 must decide whether to release it into the atmosphere or store it through CCTS. The decision is based on the price for CO_2 certificates and the investment required for the capture unit, the pipeline and the storage facilities, and the variable costs of using the CCTS infrastructure. Our model runs in five-year periods beginning in 2005 and ending in 2050.[1] Capacity extensions can be used in the period after construction, for all kinds of investments in the model.

Figure 1. Decision tree in the CO_2 disposal chain of the CCTSMOD



Source: Own illustration.

We apply a stylised institutional setting, with a potentially vertically-integrated CCTS company. A single omniscient and rational decision-maker makes all investment and operational decisions. Under these simplifying assumptions the model is run using a single cost minimisation.[2]

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[1] The model runs until 2060 but the last two periods are implemented only to give an incentive to start new investments up to 2050. These two periods are not considered in the interpretation of the result.

[2] It is evident that a more complex institutional structure would require a more complex model set-up, including game-theoretic approaches in the case of a multi-actor value-added chain.

1.2 Mathematical formulation

We define the objective function to be minimised:[3]

$$\min_{\substack{x_{Pa},\, inv\_x_{Pa},\, z_{Pa},\, f_{ija},\\ inv\_f_{ijda},\, plan_{ija},\, y_{Sa},\, inv\_y_{Sa}}} \quad h = \sum_a \left[\left(\frac{1}{1+r} \right)^{(year_a - start)} \cdot \right.$$

$$\left(\sum_P \left[5 \cdot c\_ccs_{Pa} \cdot x_{Pa} + c\_inv\_x_P \cdot inv\_x_{Pa} + 5 \cdot cert_a \cdot z_{Pa} \right] \right.$$

$$+ \sum_i \sum_j \left[E_{ij} \cdot \left(5 \cdot c\_f \cdot f_{ija} + \sum_d \left(c\_inv\_f_d \cdot inv\_f_{ijd} \right) + c\_plan \cdot plan_{ija} \right) \right]$$

$$\left. \left. + \sum_S \left[c\_inv\_y_{Sa} \cdot inv\_y_{Sa} \right] \right) \right] \qquad (1)$$

subject to

$$x_{P_a} + z_{P_a} = CO2_{P_a} \qquad (2)$$

$$x_{Pa} \le \sum_{b<a} \left(inv\_x_{Pb} \right) \qquad (3)$$

$$f_{ija} \le \sum_{b<a} \sum_d \left(cap\_d_d \cdot inv\_f_{ijdb} \right) + \sum_{b<a} \sum_d \left(cap\_d_d \cdot inv\_f_{jidb} \right) \qquad (4)$$

$$\sum_d \left(inv\_f_{ijda} \right) \le max\_pipe \cdot \sum_{b \le a} \left(plan_{ijb} \right) \qquad (5)$$

$$\sum_a \left(5 \cdot y_{Sa} \right) \le cap\_stor_S \qquad (6)$$

$$y_{Sa} \le \sum_{b<a} inv\_y_{Sb} \qquad (7)$$

$$\sum_i f_{ija} - \sum_i f_{jia} + \sum_P \left(match\_P_{Pj} \cdot x_{Pa} \right) - \sum_S \left(match\_S_{Sj} \cdot y_{Sa} \right) = 0 \qquad (8)$$

$$x_{Pa},\ inv\_x_{Pa},\ z_{Pa},\ f_{ija},\ y_{Sa},\ inv\_y_{Sa} \ \ge 0 \qquad (9)$$

$$plan_{ija} \in \{0,1\} \qquad (10)$$

$$inv\_f_{ijda} \in N_0 \qquad (11)$$

The objective function (1) is multiplied by a discount factor, where r is the interest rate, $year_a$ is the starting year of period a and $start$ is the starting year of the model. From here on the objective (1) can be split into three separate parts representing the three steps of the CCTS

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[3] Please note that the definitions of indices, parameters and variables are given in the appendix.

chain. The decision variables are the quantity x_{Pa} injected into a pipeline by the producer P, the carbon capturing investment inv_x_{Pa} and the emitted CO_2 z_{Pa}. An individual variable is declared for every emitter P in period a.

The second part represents the transportation step. The following decision variables are used: f_{ija} declares the CO_2 flow from node i to j in period a; inv_f_{ijda} denotes the number of pipelines to be built between nodes i and j with the diameter d in period a; $plan_{ija}$ is a binary variable and has the value one if a pipeline route between nodes i and j is planned and licensed in period a, and zero if not. As the routing of pipelines is a central aspect of our study, we implement a detailed process of pipeline building by introducing the planning variable and thus separating the planning and development costs from the rest of the capital costs. Additional pipelines on already licensed routes do not face licensing or planning costs. The desired effect is that new pipelines are rather routed along old pipelines, as is observed in reality.

The third part represents storage. The following decision variables are used: y_{Sa} is the quantity stored in storage facility S in period a and inv_y_{Sa} denotes the investments in additional annual injection capacity. As declared in (9), (10) and (11), all introduced variables must be non-negative.

In the objective function (1) each decision variable is multiplied by its respective cost factor. E_{ij} is a distance matrix indicating whether two nodes i and j can or cannot be connected directly. If they are, the values of the matrix give the distances in kilometres between i and j. Scaling is easily done by varying the distance between nodes and their number. The spatial focus can be adjusted to a region, e.g. the Rhine area, or to a wider perspective, e.g. the whole of Europe. As the assignment of geographical position is based on the relative position of the respective entity to a previously chosen reference point, the focus of the model can be easily shifted and adjusted.[4]

Equation (2) states that every producer P has a certain amount of CO_{2Pa} to emit, inject or divide between the two options. The capturing capacity of each producer P in period a is given in (3). Note that all terms in this inequality are decision variables, meaning that injection in period a can only happen if the capacity was expanded prior to period a. The capacity restriction of the pipeline (4) works similarly to (3). cap_d_d is the flow capacity of a pipeline with diameter d. The term $\sum_{b<a}\sum_{d}\left(cap\_d_d \cdot inv\_f_{jidb}\right)$ is included twice, except that in the indices of inv_f_{jidb} i and j are interchanged. This enables CO_2 to be sent in both directions of a constructed pipeline.[5]

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[4] Scaling the model is automated in the General Algebraic Modelling System programme of CCTSMOD. Adjusting the distance in degree of longitude and latitude between the nodes, entering the number of nodes and setting a reference point fully determine the model's grid and it does not need further adjustment.

[5] Booster capacity is neglected owing to complex implementation and comparatively low costs. The advantages of this approach are that there are fewer restrictions to consider for the model solver (shorter computing time) and that pipelines can be optimally used in both directions at different periods without

Planning and licensing for constructed pipelines is ensured through (5). max_pipe is the maximum number of pipelines that can be built on a licensed route.

As all flow quantities and all operating costs are included on a per year basis, the respective cost terms need to be multiplied by five to comply with the five-year model periods in (1). Injection quantities also have to be multiplied by five so that the amount of CO_2 injected is correctly computed (see inequality (6)). Inequality (7) states that the annual injection rate of a storage facility S is limited to the sum of investments in injection capacity inv_y_{Sb} from previous periods b. We distinguish between the constant total capacity of sink S (cap_stor_S) and the yearly expandable injection capacity $\sum_{b<a} inv\_y_{Sb}$ for sink S in period a.

Equation (8) specifies the physical balance condition, which states that all flows feeding into a node j must be discharged from the same node. $match\_P_{Pj}$ declares whether or not producer P is located at node j:

$$match\_P_{Pj} = \begin{cases} 1 & \text{if producer } P \text{ is located at node } j \\ 0 & \text{otherwise} \end{cases}$$

$match\_S_{Sj}$ assigns sinks to nodes in the same way:

$$match\_S_{Sj} = \begin{cases} 1 & \text{if sink } S \text{ is located at node } j \\ 0 & \text{otherwise} \end{cases}$$

The model is solved in the General Algebraic Modelling System using the CPLEX solver.

2. Data

2.1 CO_2 Emission sources

Comprehensive data are collected for each step of the CCTS chain. For existing point sources from the industrial and energy sectors, data on yearly emissions, capacity and location are taken from the “European Pollutant Release and Transfer Register” (EEA, 2007). Investment costs are defined as the additional technology costs for the capturing facility. Unfortunately, data are available only for the electricity sector, providing different costs in € per kW depending on the technology installed (Tzimas, 2009). Our calculated investments in capture facilities for a CO_2 emitter range between €12 and €478 per tonne of CO_2 capture capacity depending on the region (different national emission factors are implemented) and type of emitter (different factors for industry and power generation). Technological learning is implemented according to the meta-analysis on CO_2 capturing costs in the RECCS study (Wuppertal Institute, 2008). Detailed data for capturing investments, efficiency losses and technology learning and costs are shown in Table 1.

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building new pipelines. Although theoretically bidirectional flows in the same period are possible in this model formulation, in an optimal solution they will never occur due to cost minimisation.

Table 1. Additional capital costs for CO_2 capture, efficiencies and applied technological learning

	Reference plant	CCTS demonstration	Penalty for CO_2 capture	Future expected penalty for CO_2 capture			
	2010	2010	2010	2020	2030	2040	2050
Coal/ lignite (€/kW)	1,478	2,500	1,022	1,022	949	876	876
Efficiency (in %)	46	35	11	11	11	11	11
Gas/oil (€/kW)	742	1,300	558	558	474	391	391
Efficiency (in %)	58	46	12	12	10.6	9.3	9.3

Sources: Tzimas (2009) and Wuppertal Institute (2008).

Variable costs are calculated as the product of loss in rated power multiplied by the average energy production costs. For the efficiency loss, data are applied from Tzimas (2009) and Wuppertal Institute (2008). Our calculated variable costs range from €9.3 per tonne CO_2 for the cheapest facilities to €40.7 per tonne for the most expensive plants.

For industrial sources, only data on total costs of CO_2 capture are available to calculate capital and variable capture costs. As for coal power plants, both aggregated and disaggregated costs are available (IEA, 2009b); their typical capital and operating costs are taken as a reference value. We assume that the reference coal plant is equipped with post-combustion technology, as is the case in those industrial plants where carbon capture is already practised. Applying data from IEA (2009b), we derived a factor representing the ratio of cost that a facility from a certain industry typically faces when CCTS is implemented compared with the capture costs of a post-combustion coal power plant (see Table 2).

Table 2. Cost intensity of CO_2 capture investment and operating costs for an industrial plant compared with a post-combustion coal power plant

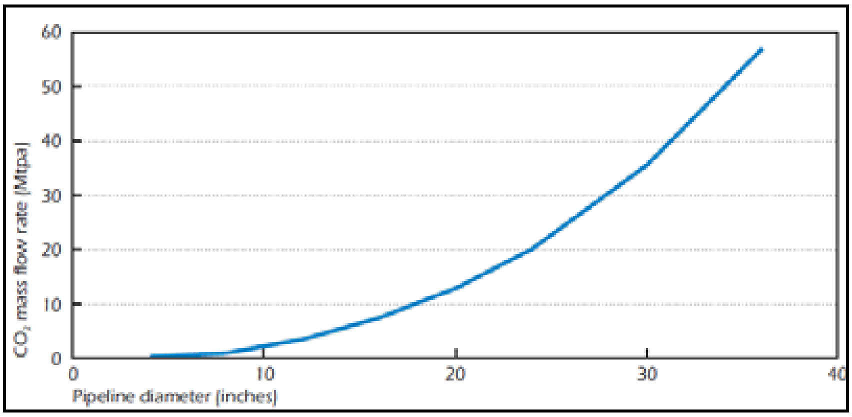
Industrial sector	Cost intensity
Cement industry	0.58
Steel industry	0.60
Ammonia industry	0.06
Oil refineries	0.72
Hydrogen industry	0.06
Petrochemical industry	0.70
Paper industry	0.58

Source: Own calculations based on IEA (2009b).

2.2 CO_2 Transport

We select pipeline transport as the most practical option for Europe (Rubin, 2005). Pipeline capacity is derived from the IEA study on CO_2 capture and storage (IEA, 2009b), providing a relation between the pipeline diameter and the possible flow per year (see Figure 2).

Figure 2. Pipeline diameter and respective CO_2 flow capacity

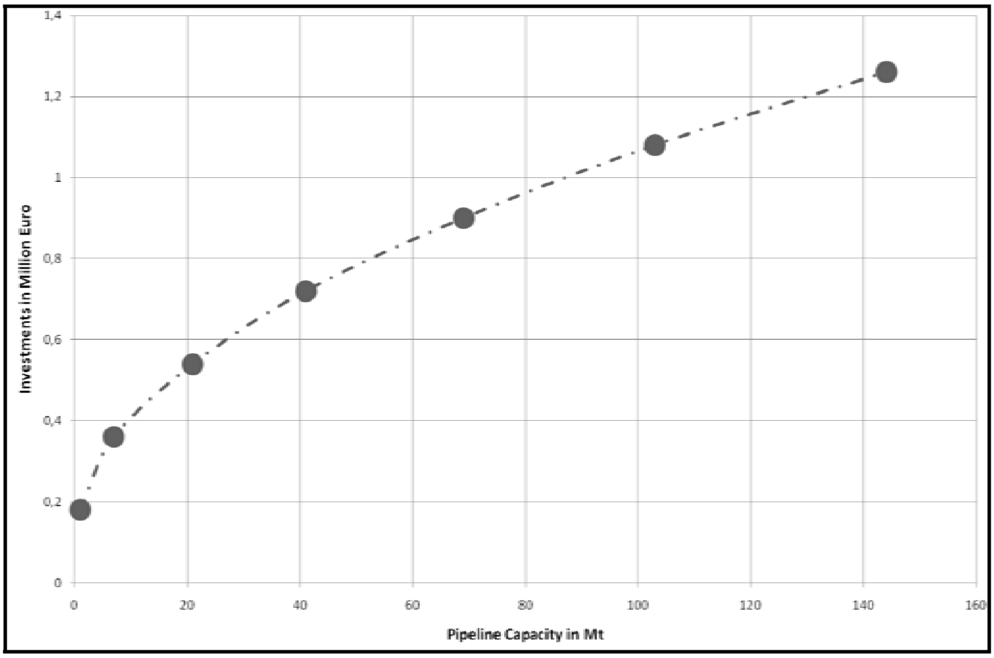


Source: IEA (2009b).

Transportation costs are divided into three categories:

- **Planning and development (P&D) costs** include right of way (ROW) costs, land purchase and routing costs, and they lead to the construction of pipelines along corridors. Cost data for gas pipelines are used to approximate CO_2 pipeline costs. According to Heddle et al. (2003), ROW costs account for 4 to 9% of total gas pipeline construction costs depending on the diameter of the pipe. Adding the other cost terms we assume P&D costs of 5% for the most commonly used diameter of 0.8 m, resulting in €36,000 per km.
- **Operating and maintenance (O&M)** costs are considerably lower in comparison with the expenditures needed for pipeline construction. Including the flow-dependent cost component is important to ensure that CO_2 is routed the shortest way possible. Wildenborg et al. (2004) concluded that operation costs vary between €0.01 and €0.025 million per km and year depending on pipeline diameter and total pipeline length and including costs for booster stations; we thus use €0.01 million per km and megatonne of CO_2 transported.
- **Capital costs** are assumed to be linear in relation to diameter (IPCC, 2005). We correct these costs by subtracting the P&D costs that occur only for the first pipeline built on a certain route. Capital costs rise with pipeline capacity but marginal costs decrease with the capacity. This is the way economies of scale are implemented in CCTSMOD. We choose discrete pipeline capacities as shown in Figure 3.

Figure 3. Selected possible pipeline capacities and their respective costs

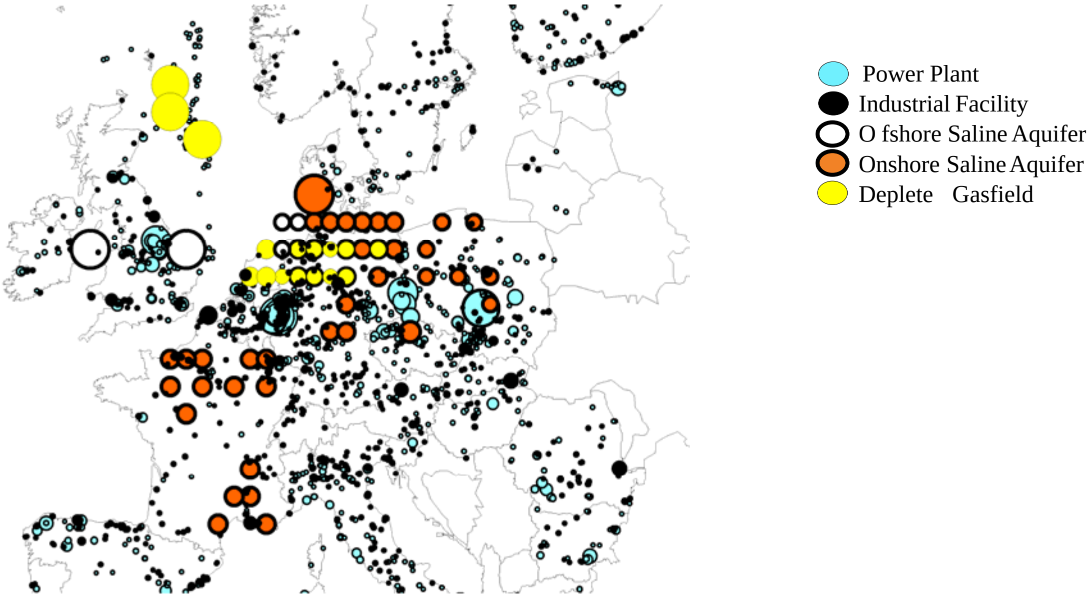


Source: Own source according to data used for the CCTSMOD.

2.3 Storage

The model includes three kinds of storage sites that represent the most promising options for long-term CO_2 sequestration with respect to their static range and availability in Europe: onshore and offshore saline aquifers, and depleted gas fields. The locations chosen are based on GeoCapacity (2009a) project data, with data on storage volumes also taken from the same source (see Figure 4).

Figure 4. Visualisation of input data for CO_2 point sources and potential storage sites



Sources: Own illustration based on input data from EEA (2007) and GeoCapacity (2009a, b).

According to Heddle et al. (2003) costs for CO_2 storage are determined by various factors, including type of storage facility, storage depth, permeability, number of injection points and injection pressure. Total storage costs therefore vary significantly in different studies (Wuppertal Institute, 2010). A characteristic value for a storage project is the sum of costs per injection well, including site development, drilling, surface facilities and monitoring investments for a given annual CO_2 injection rate. Storage investments exhibit a strong sunk-cost character and according to IEA (2005), variable costs sum up to only 7 to 8% of total costs. Thus storage costs are implemented on a total cost basis (see Table 3).

Table 3. Site development, drilling, surface facilities and monitoring investments as well as operating costs per CO_2 storage well for a given Mt CO_2 per year injection rate

Type of storage site	**Gas**		**Aquifer**	
	Onshore	**Offshore**	**Onshore**	**Offshore**
Drilling depth (vertical + horizontal) (m)	3,000	4,000	3,000	4,000
Well injection rate according to IEA (2005) (Mt CO_2/a)	1.25	1.25	1	1
Well injection rate according to Gerling (2010) (Mt CO_2/a)	0.42	0.42	0.33	0.33
Site development costs (€ mn)	1.6	1.8	1.6	1.8
Drilling costs (€/m)	1,750	2,500	1,750	2,500
Investment in surface facilities (€ mn)	0.4	25	0.4	25
Monitoring investments (€ mn)	0.2	0.2	0.2	0.2
Wells per location	6	6	6	6
Total drilling costs (€ mn)	5.25	10	5.25	10
Total capital costs per well (€ mn)	5.62	14.50	5.62	14.50
Operation, maintenance and monitoring costs (%)	7	8	7	8

Notes: Data presented by IEA (2005) assume an optimistic injection rate of 1.25 Mt per year for gas fields and 1 Mt per year for saline aquifers. According to Gerling's (Federal Institute for Geosciences and Natural Resources (BGR)) presentation at the "Berlin Seminar on Energy and Climate", such injection rates only occur at very few sites with perfect conditions (Gerling, 2010). The average annual injection rate for onshore saline aquifers is more likely to be around 0.33 Mt per year. In accordance with Gerling's presentation, we assume that one-third of the injection rates presented in the IEA dataset are a more realistic assumption for Europe.

Sources: Own calculations based on data from IEA (2005); Gerling (2010).

3. Scenarios

3.1 Three key variables

The future shape and scope of Europe's CCTS infrastructure are determined by the price of CO_2, its storage potential and its usability given political and public acceptance. These three drivers produce the scenarios shown in Table 4.

- First, the future development of the CO_2 certificate price in Europe is a political variable that strongly influences the deployment of CCTS. Starting at €15 per tonne CO_2, we implement alternative linear price paths to examine the development of the CCTS infrastructure with respect to CO_2 certificate price variation: prices in 2050 range from €31 to €120.

- Second, total subsurface storage potential for CO_2 exhibits a high degree of uncertainty because of a lack of high-resolution data (GeoCapacity, 2009a) and different calculation methods (Wuppertal Institute, 2010). We use storage potential for Europe from the GeoCapacity project (GeoCapacity, 2009a) and define the following European scenarios:
    - 'GeoCapacity', which is the estimation presented by the GeoCapacity project of 100 Gt CO_2 as the first approximations of the real storage potential;
    - 'GeoCapacity conservative', which is a conservative estimation of the storage potential of 50 Gt; and
    - 'very low storage potential', whereby in accordance with the prolonged decrease of storage potential estimations in recent studies (Wuppertal Institute, 2010), we assume an additional decrease of 50% to 25 Gt.
- Third, a rapid and broad deployment of CCTS technology is dependent on public opinion and political will. For example, in Germany the strong public rejection of onshore storage led to prolonged delays of RWE's proposed CO_2 storage project in Husum.[6] Although offshore storage is possibly a solution to the NIMBY (not in my backyard) problem, the technical complexity and increased costs may prove insurmountable. Such uncertainty is revealed by the ban on onshore storage in some of the scenarios.

Table 4 illustrates the input parameters for the above-defined uncertainties in the different scenarios.

Table 4. Scenario overviews

Scenario	Geological storage potential	CO_2 certificate price in 2050 (€/tCO_2)	Public acceptance
BAU (business as usual)	GeoCapacity (100 Gt for Europe)	43	Onshore + offshore
On + Off 31	GeoCapacity (100 Gt for Europe)	31	Onshore + offshore
On + Off 55	GeoCapacity (100 Gt for Europe)	55	Onshore + offshore
Off 55	GeoCapacity (100 Gt for Europe)	55	Offshore storage only
Off 120	GeoCapacity (100 Gt for Europe)	120	Offshore storage only
Off 100	GeoCapacity (100 Gt for Europe)	100	Offshore storage only
Conservative storage potential	GeoCapacity Conservative (50 Gt for Europe)	43	Onshore + offshore
Low storage potential	50% of GeoCapacity conservative(25 Gt for Europe)	43	Onshore + offshore

Note: Unless otherwise indicated, all scenario data are similar to business-as-usual input data described in detail in section 3.2.

Source: Own calculations.

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[6] See "Klimagas: Kein CO_2-Speicher in Nordfriesland", *taz.de*, 13 November 2009 (http://www.taz.de/1/nord/artikel/1/kein-co2-speicher-in-nordfriesland).

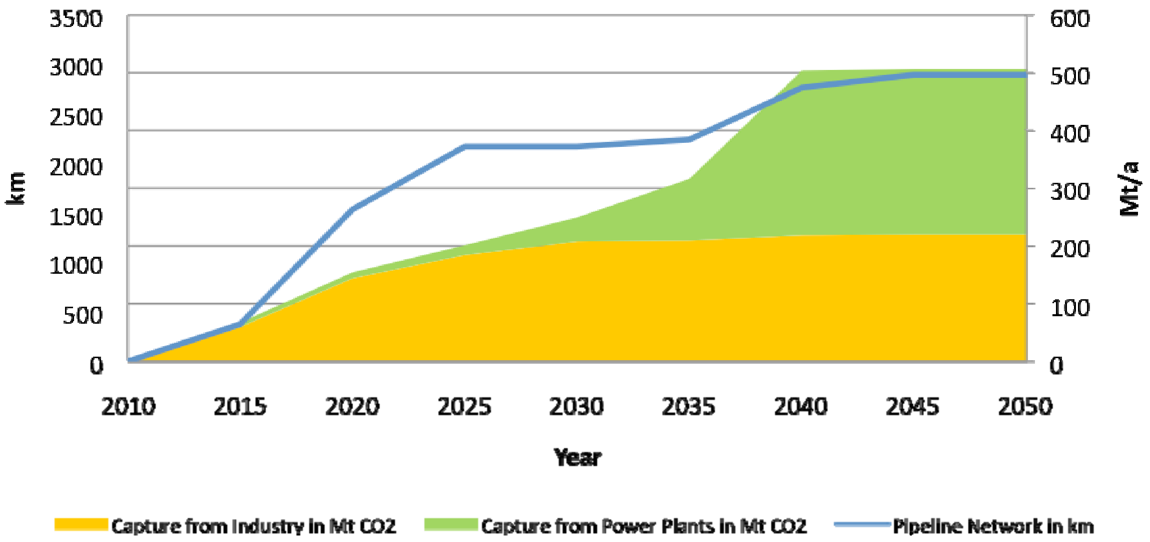
3.2 Business-as-usual scenario

The business-as-usual (BAU) scenario simulates the cost-optimal deployment of a European CCTS infrastructure for the period 2010–50 given a CO_2 certificate price starting at €15 in 2010 and rising to €43 in 2050. Storage capacity is assumed to match the standard estimations of the GeoCapacity project and is divided into 9 offshore and 66 onshore storage sites with locations and capacities according to GeoCapacity data (GeoCapacity, 2009b). In this scenario, both onshore and offshore storage are available. Point source emissions, storage sites and potential pipelines are mapped on a spherical grid covering Europe. The distance between two neighbouring grid nodes is one degree (on average about 100 km).

3.3 BAU results

In the BAU scenario, 19% (498 Mt) of the total CO_2 emissions are captured, transported and stored through CCTS annually in 2050. CCTS implementation starts in 2010 with the first infrastructure investments in the industrial sector (see Figure 5). CCTS infrastructure gradually ramps up from 2020 to 2040.[7] At first, the industrial facilities with low capturing costs situated close to potential storage sites are the predominant users of CCTS. While industrial CCTS penetration reaches saturation with a capturing rate of 207 Mt CO_2 per year in 2030, CCTS becomes a more attractive abatement option for the power sector due to the higher CO_2 prices. The share of stored CO_2 from power generation in the total annual storage increases from 8% in 2025 to 56% in 2050.

Figure 5. Annual capturing rates for the industrial and the power generation sectors and length of pipeline infrastructure in the BAU scenario



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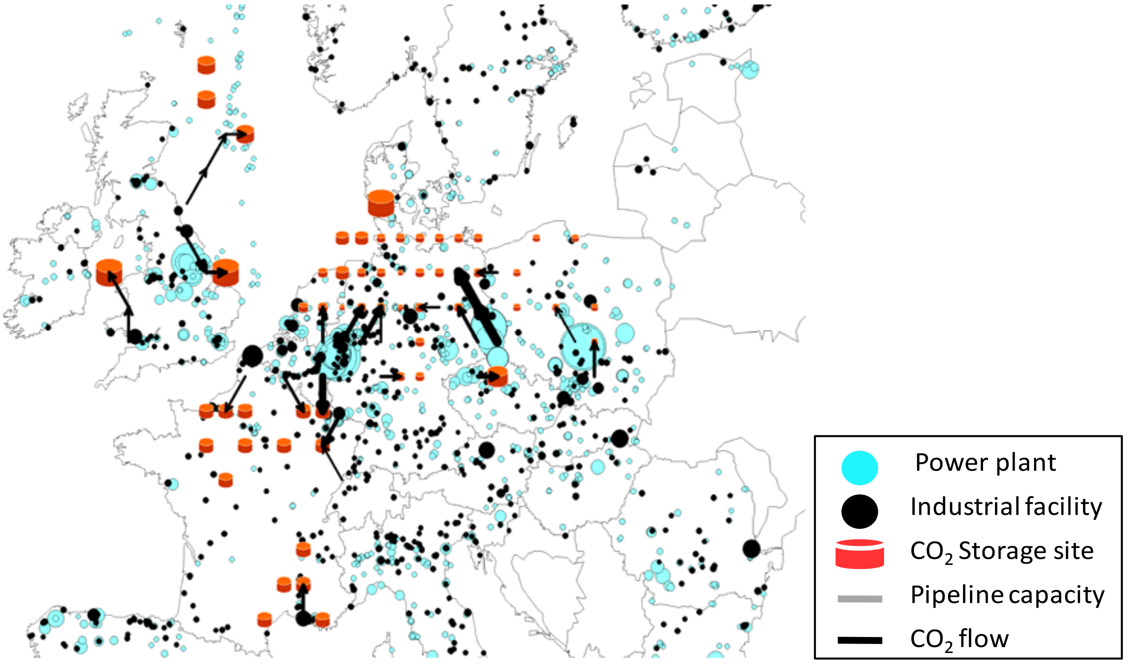
[7] We define the ramp-up phase as the period when the majority of the costs accrue for investments in CCTS, through the building of the CCTS infrastructure. Furthermore Furthermore, we define the commercialisation phase as the time after the ramp-up phase, when the main share of CCTS expenditures arise from the operational costs of the infrastructure.

Investments in the capture facility and the operation costs of capturing comprise the largest share of total CCTS costs in both the ramp-up and the saturation phases. Until commercialisation is reached in 2040, capturing investments account for, on average, 81% of total investment costs while transport and storage investments account for 8 and 11%, respectively. Afterwards, operation costs for capturing account for 96% of total operating costs.

We note that under the applied CO_2 price path, CCTS is an option solely for countries with a regional proximity between CO_2-intensive regions and storage sites. Only Poland, Germany, the Netherlands, Belgium, France and the UK can implement the technology. Moreover, we find no interconnected, transnational transportation network (see Figure 6). Industry facilities facing comparatively low capturing investment costs will be the first-movers, but they do not capture enough CO_2 to benefit from economies of scale in CO_2 transport. Therefore, the majority of the pipeline infrastructure is constructed only when the power sector applies the CCTS technology.

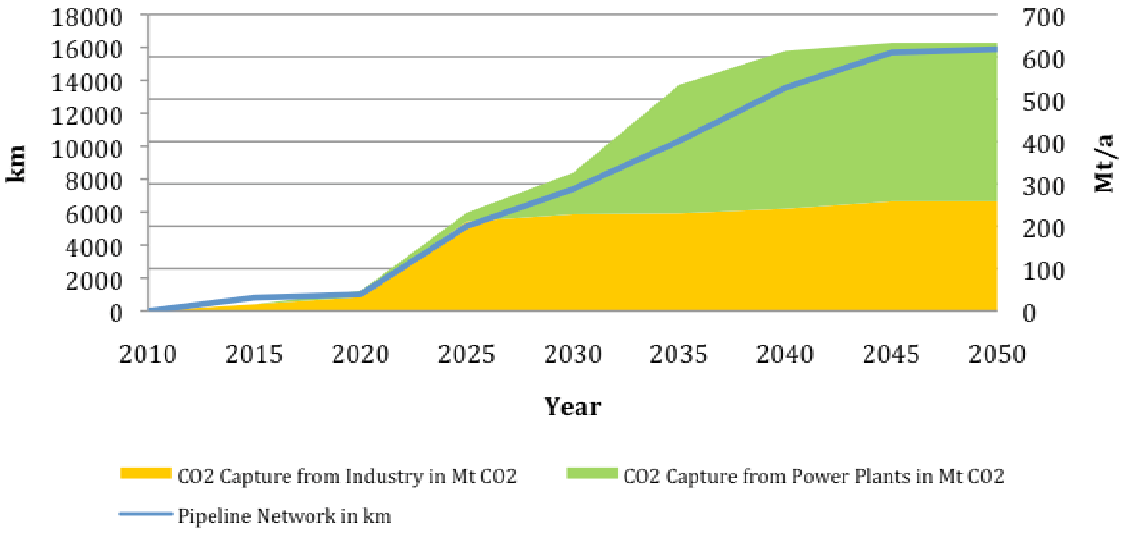
Figure 6. BAU: CCTS infrastructure in 2050



3.4 Offshore 120 results

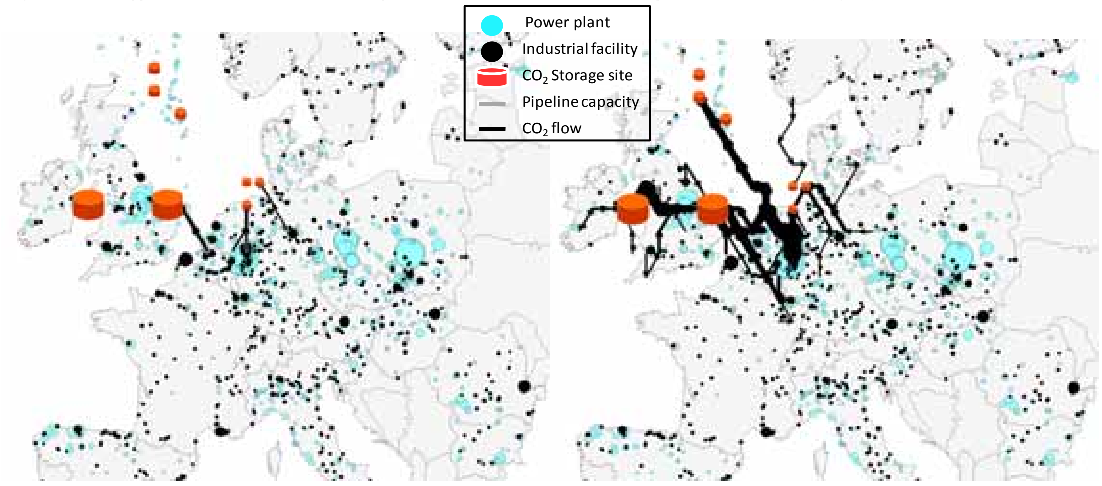
In the Offshore 120 scenario, 25% of the CO_2 emissions from the emissions database are stored annually in 2050. Similar to the BAU scenario, capturing activity starts in the industrial sector and then spreads to the power generation sector. But in this scenario, capture from power generation catches up with CO_2 from industry by 2035 and it accounts for 60% of total CO_2 stored in 2050. As in the BAU scenario, the ramp-up phase also starts in 2020 but proceeds more progressively and reaches BAU 2050 storage levels in 2035. To cope with the long distances between the CO_2 sources and the storage sites, a massive pipeline infrastructure is constructed, adding up to a network of up to 15,900 km in 2050 (see Figure 7 and Figure 8).

Figure 7. Annual capturing rates for the industrial and the power generation sectors and length of pipeline infrastructure in the Offshore 120 scenario



During the ramp-up phase, capturing investments account for 74% of total investments while storage accounts for 21% and transport for 5%. This is based on the much steeper price path for certificates, which leads to more CO_2 storage in the early years. Since the annual injection rate per well is limited for technical reasons, a greater storage investment is needed to cope with the higher CO_2 flow. When CCTS commercialisation is reached in 2045, operation costs for capture represent 75% of the total costs, and transport costs account for 25%.[8]

Figure 8. Offshore 120: CCTS infrastructure in 2020 (left) and 2050 (right)



Assuming extended public resistance to onshore storage and the CO_2 certificate price regime presented above, an interconnected European CCTS network becomes the cost-optimal mitigation strategy. Starting at locations where industrial facilities first apply CCTS, the network rapidly expands to cover the industrial regions of Germany (Rhine area), northern

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[8] Note that storage costs are calculated on a total cost basis with the operating costs included in the investment costs; thus, no individual running costs are calculated for the use of the storage facility.

France, the Netherlands, Belgium and the UK by 2050. Industrial regions in Central and Eastern Europe are not connected to the network due to the long distances to storage sites and adverse capturing costs. While industry continues to be a first-mover, in this scenario it plays an increasingly minor role for two reasons: 1) the much steeper CO_2 price path allows for capture from the more expensive power sector, and 2) the significant infrastructure investments can only be beneficial with the great transportation volumes induced by CO_2 capture from power generation.

3.5 Overview of results

Table 5 shows that the BAU scenario and Offshore 120 scenario exhibit similar annual storage rates for 2050, but deviate significantly in the underlying infrastructure. In the BAU scenario, less than 3,000 km of pipeline network are sufficient to connect CO_2 sources and storage sites. In the Offshore 120 scenario, pipeline infrastructure is more than five times longer. At the same time, industry accounts for 54% of total CO_2 storage by 2050 in the BAU scenario but only 47% in the Offshore 120 scenario.

Table 5. Overview of scenario results

Scenario	CO_2 price in 2050 (€/tCO_2)	CO_2 stored via CCTS in 2050 (%)	Annual storage rate exceeds 100 Mt CO_2/a (a)	Pipeline infrastructure longer than 1,200km (a)	Infrastructure length in 2050 (km)	Share of CO_2 from industry (%)
BAU	43	19.4	2020	2020	2,897	54.0
On+Off 31	31	3.9	2045	-	-	89.4
On+Off 55	55	48.6	2020	2020	13,359	40.7
Off 55	55	8.2	2025	2025	1,490	68.1
Off 100	100	14.0	2020	2025	3,419	55.5
Off 120	120	24.7	2020	2025	15,889	47.2
Conservative storage potential	43	13.5	2025	2025	1,333	60.6
Low storage potential	43	5.6	2035	-	-	66.8

Source: Own calculations.

The BAU scenario is characterised by short regional networks and the Offshore 120 scenario by an integrated pipeline network spanning most of Western Europe. Comparing the pipeline routing in both scenarios indicates that an early and integrated infrastructure planning process can capture economies of scale, e.g. in northern France and the Rhine area. Note that in the BAU scenario the CO_2 splits into a southern and a northern stream, leading to nearby storage sites in France and northern Germany and that in the Offshore 120 scenario the two streams combine into a broad stream leading to offshore storage sites in the North Sea.

4. Conclusions

In this paper we apply a model for carbon capture, transportation and storage to assess the nature and dynamics of a potential rollout of CCTS technology. Our results indicate that CCTS may theoretically contribute significantly to the decarbonisation of Europe's electricity and industry sector. Yet it is only at a CO_2 certificate price rising to €55 in 2050 and given sufficient CO_2 storage capacity available both on- and offshore that CCTS may have a role to play in future energy concepts. Nevertheless, it can be a bridging technology to a low emissions energy sector and serve as a beneficial alternative for CO_2-intensive industries that cannot avoid emissions. This confirms the conclusions of earlier studies using other methodologies, such as Praetorius et al. (2009a) and Praetorius and Schumacher (2009b).

The scenario results indicate that with a moderate development of the CO_2 certificate price, the deployment of CCTS technology will remain regional in character, without an integrated European network infrastructure. At the same time, European cooperation could still be of benefit in areas where industrial and power generation centres are divided by country borders.

Given the level of public opposition to onshore storage and concomitant lack of political will, CO_2 abatement by means of CCTS can only be pushed by much higher prices for CO_2 certificates. Otherwise, we suggest that policy-makers consider CCTS solely for coastal areas and small industrial sites where CO_2 transport does not require additional infrastructure investment.

Our results also reveal that the development of the CCTS infrastructure is highly sensitive to the availability of storage sites. Therefore, early integration of Europe's industrial and electricity sectors in the CO_2 infrastructure planning seems to be a good 'issue' for further consideration.

In all scenarios, industry plays an important role as a first-mover to induce deployment of CCTS. A decrease in available storage capacity or a more moderate increase in future CO_2 certificate prices could significantly reduce the role of CCTS as a CO_2 mitigation technology, and especially its role in the decarbonisation of the electricity sector.

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Appendix. Definition of indices, parameters and variables

The CCTSMOD is a *mixed integer, linear problem* minimising total system costs subject to capacity, integer, non-negativity and further constraints. We define the following abbreviations with their units in square brackets, if available:

Indices

$a_{,}\ b$	–	Model period
P	–	Individual CO_2 producer
S	–	Individual CO_2 storage site
$i_{,}\ j$	–	Node
d	–	Pipeline diameter [m]

Parameters

r	Rate of interest [%]
$year_a$	Starting year of a model period a
$start$	Starting year of the model
end	Ending year of the model
c_ccs_{Pa}	Variable costs of CO_2 capture for producer P in period a [€/t CO_2]
$c\_inv\_x_P$	Investment costs of CO_2 capture for producer P [€/kw]
$CO2_{P_a}$	Total quantity of CO_2 produced by producer P in period a [t CO_2]
$cert_a$	CO_2 certificate price in period a [€/ t CO_2]
c_f	CO_2 flow costs [t CO_2]
$c\_inv\_f_d$	Pipeline investment costs [€/km · m (diameter)]
c_plan	Pipeline planning and development costs [€/km]
cap_d_d	Capacity of a pipeline with diameter d [t CO_2/a]
max_pipe	Maximum number of pipelines built along planned route [1]
$c\_inv\_y_{Sa}$ –	Investment costs for storage in sink S in period a [€/t CO_2]
cap_stor_S	Storage capacity of sink S [t CO_2]
$match\_P_{Pj}$	Mapping of producer P to node j

$match\_S_{Sj}$	Mapping of Sink S to node j
E_{ij}	Distance matrix of possible connections between nodes i and j

Variables

h	Net present value of total CO_2 abatement costs over the whole model time frame [€]
x_{Pa}	Quantity of CO_2 captured by producer P in period a [t CO_2/a]
inv_x_{Pa}	Investment in additional CO_2 capture capacity for producer P in period a [t CO_2/a]
z_{Pa}	Quantity of CO_2 emitted into atmosphere by producer P in period a [t CO_2/a]
f_{ija}	CO_2 flow from node i to j in period a [t CO_2/a]
inv_f_{ijda}	Investment in additional pipeline capacity with diameter d connecting nodes i and j in period a [1]
$plan_{ija}$	Pipeline planning and development between nodes i and j in period a [1]
y_{Sa}	Quantity of CO_2 stored per year in sink S in period a [t CO_2/a]
inv_y_{Sa}	Investment in additional injection capacity of sink S in period a [t CO_2/a]

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