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Modeling a Carbon Capture, Transport and Storage Infrastructure for Europe

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CO_2 Highways for Europe

Modeling a Carbon Capture, Transport and Storage Infrastructure for Europe

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Abstract

We present a mixed integer, multi-period, cost-minimizing carbon capture, transport and storage (CCTS) network model for Europe. The model incorporates endogenous decisions about carbon capture, pipeline and storage investments; capture, flow and injection quantities based on given costs, certificate prices, storage capacities and point source emissions. The results indicate that CCTS can theoretically contribute to the decarbonization of Europe's energy and industry sectors. This requires a CO_2 certificate price rising to 55 € in 2050, and sufficient CO_2 storage capacity available for both on- and offshore sites. However, 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 of 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. Continued public resistance to onshore CO_2 storage can only be overcome by constructing expensive offshore storage. Under this restriction, to reach the same levels of CCTS penetration will require doubling of CO_2 certificate prices.

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

JEL Codes: C61, H54, O33

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1. Introduction

The International Energy Agency (IEA, 2009b) estimates that reducing CO_2 emissions by 50 percent in 2050 compared to the 1990 level absent the use of Carbon Capture, Transport and Storage technology (CCTS) would produce global additional mitigation costs of 1.28 trillion USD annually. This is equivalent to a cost increase of 71 percent. According to the IEA 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, due in part 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 (GTSP) modeled the adoption of a CCTS system within three fossil-fuel-intensive electricity generation regions of the U.S. 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 percent 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 neighboring 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) 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 the U.S. federal government and their influence on the total costs. However, no economies of scale are implemented for construction, 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 (MILP). With its coupled geospatial engineering-economic optimization modeling approach, SimCCS minimizes 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 optimizes the model according to: amount of CO_2 to be captured from each source; siting and building pipelines by size; and 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 via possible pipeline diameters in four-inch steps, each with its own cost function. Kuby et al. (2009) extend a smaller version of the model which 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 minimizes 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 one Chinese partner, the GeoCapacity project maps the large point sources (emitting facilities), infrastructure and potential geological storage possibilities in most European countries (GeoCapacity, 2009a). Beeing involved into the GeoCapacity project Kazmierczak et al. (2009) and Neele et al. (2009) developed an algorithm to create a low-cost network and a decision support system to evaluate the economical and technical feasibility of storage. A realistic estimate of the economic feasibility of a potential CCTS project is possible, but no detailed planning on project level is determined by the algorithm. Compared to 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 on 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-optimizing CCTS network model, hereafter termed CCTSMOD. The model incorporates endogenous decisions on carbon capture, pipeline and storage investments; capture, flow and injection quantities 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 neighboring nodes. The distance between two neighboring 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 the North West of Europe, i.e. in Germany and South and East of it, ranging to France and up to the North Sea and its neighboring 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, 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 t CO_2 in 2050), and very optimistic CO_2 storage availability, a large-scale CCTS roll-out might indeed be expected. However, in a more likely scenario, including lower storage availability and public resistance against onshore storage, a large-scale roll-out 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 switch or alternative production processes.

The next section describes the model approach and the mathematical formulation. We then discuss the data on CO_2 emissions sources, transportation, and storage, before turning to the scenarios in Section 4, which also contains an in-depth discussion of the results. Summing up Section 5 presents our conclusions on the role of the CCTS technology in Europe.

2. Model description

2.1. 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 via 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.[2] Capacity extensions can be used in the period after construction, for all types of investments in the model.

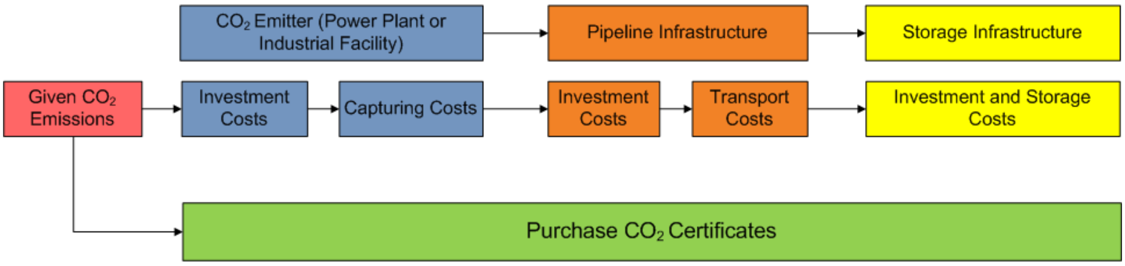

Figure 1: Decision tree in the CO_2 disposal chain of the CCTSMOD

Source: own illustration

We apply a stylized institutional setting, with a potentially vertically integrated CCTS company. The single omniscient and rational decision-maker makes all investment and operational decisions. Under these simplifying assumptions the model is run using a single cost minimization.[3]

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

[3] 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.

2.2. Mathematical formulation

We define the objective function to be minimized:

$$\begin{aligned}
&\min_{\substack{x_{Pa},\, inv\_x_{Pa},\, z_{Pa},\, f_{ija},\\ inv\_f_{ijda},\, plan_{ija},\, y_{Sa},\, inv\_y_{Sa}}} \quad h = \sum_a \Bigg[\left(\frac{1}{1+r}\right)^{(year_a - start)} \cdot \\
&\Bigg(\quad \sum_P \left[5 \cdot c\_ccs_{Pa} \cdot x_{Pa} + c\_inv\_x_P \cdot inv\_x_{Pa} + 5 \cdot cert_a \cdot z_{Pa} \right] \\
&\quad + \sum_i \sum_j \Big[E_{ij} \cdot \Big(5 \cdot c\_f \cdot f_{ija} + \sum_d \left(c\_inv\_f_d \cdot inv\_f_{ijd} \right) + c\_plan \cdot plan_{ija} \Big) \Big] \\
&\quad + \sum_S \left[c\_inv\_y_{Sa} \cdot inv\_y_{Sa} \right] \quad \Bigg) \Bigg]
\end{aligned} \tag{1}$$

subject to

$$x_{P_a} + z_{P_a} = CO2_{P_a} \tag{2}$$

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

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

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

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

$$y_{Sa} \leq \sum_{b<a} inv\_y_{Sb} \tag{7}$$

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

$$x_{Pa},\ inv\_x_{Pa},\ z_{Pa},\ f_{ija},\ y_{Sa},\ inv\_y_{Sa} \geq 0 \tag{9}$$

$$plan_{ija} \in \{0,1\} \tag{10}$$

$$inv\_f_{ijda} \in N_0 \tag{11}$$

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 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 CO2 z_{Pa}. An individual variable is declared for every emitter P in period a.

The second part represents the transportation step. The decision variables are: f_{ija} declares the CO2 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 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 nor planning costs. The desired effect is that new pipelines are rather routed along old pipelines, as it is observed in reality.

The third part represents storage. The decision variables are: 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 gives the distances in kilometers 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 a wider perspective, e.g., whole 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 CO_{2Pa} to either 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,

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[4] Scaling the model is automated in the GAMS program 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 determines the model's grid and does not need further adjustment.

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 indies of inv_f_{jidb} i and j are interchanged. This enables to send CO_2 in both directions of a constructed pipeline.[5]

Planning and licensing for constructed pipelines is ensured via (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 General Algebraic Modeling System (GAMS) using the CPLEX solver.

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[5] Booster capacity is neglected due to a 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 time periods without building new pipelines. Although theoretically bidirectional flows in the same time period are possible in this model formulation, in an optimal solution they will never occur due to cost minimization.

3. Data

3.1. CO_2 emission sources

Comprehensive data are collected for each step of the CCTS chain. For existing point sources from the industry and energy sector, 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 installed depending on the technology installed (Tzimas, 2009). Our calculated investments in capture facilities for a CO_2 emitter range between 12 and 478 Euro per ton of CO_2 capture capacity depending on region (different national emission factors 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 is shown in Table 1.

	Reference plant	**CCTS demonstration**	**Penalty for CO_2 capture**	**Future expected penalty for CO_2 capture**			
Year	2010	2010	2010	2020	2030	2040	2050
Coal / lignite (€/kW)	1478	2500	1022	1022	949	876	876
Efficiency (in %)	46	35	11	11	11	11	11
Gas / oil (€/kW)	742	1300	558	558	474	391	391
Efficiency (in %)	58	46	12	12	10.6	9.3	9.3

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

Source: Tzimas (2009), 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 ton CO_2 for the cheapest facilities to 40.7 € per ton for the most expensive plants.

For industrial sources, only data on total costs of CO_2 capture is 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 it is the case in those industrial plants where carbon capture is already practiced. 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 to capture costs of a post-combustion coal power plant (see Table 2).

Industrial sector	**Cost intensity**
Cement industry	0.58
Steel industry	0.6
Ammonia industry	0.06
Oil refineries	0.72
Hydrogen industry	0.06
Petrochemical industry	0.7
Paper industry	0.58

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

Source: own calculation based IEA (2009b)

3.2. 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).

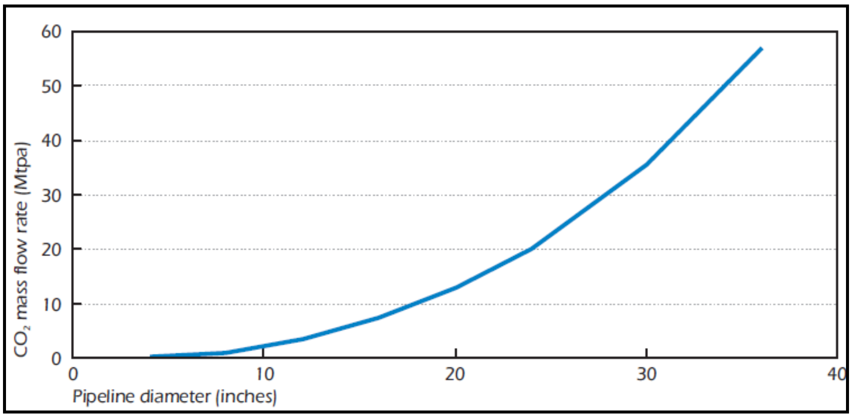

Figure 2: Pipeline diameter and respective CO_2 flow capacity

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 leads to the construction of pipelines along corridors. Cost data for gas pipelines are used to approximate CO_2 pipeline costs. According to

Heddle (2003) ROW costs account for 4 to 9 percent of total gas pipeline construction costs depending on the diameter of the pipe. Adding the other cost terms we assumed P&D costs of 5 percent of the most commonly used diameter of 0.8 m resulting in 36,000 € per km.

Operating and maintenance (O&M) costs are considerably low in comparison to 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. TNO (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 a number of 0.01 million € per year and km.

Capital costs are assumed to be linear in diameter (IPCC, 2005). We correct these costs by subtracting the P&D costs which occur only for the first pipeline built on a certain route. Capital costs are rising with pipeline capacity but marginal costs are decreasing with the capacity. This is the way economies of scale are implemented into CCTSMOD. We choose discrete pipeline capacities shown in Figure 3.

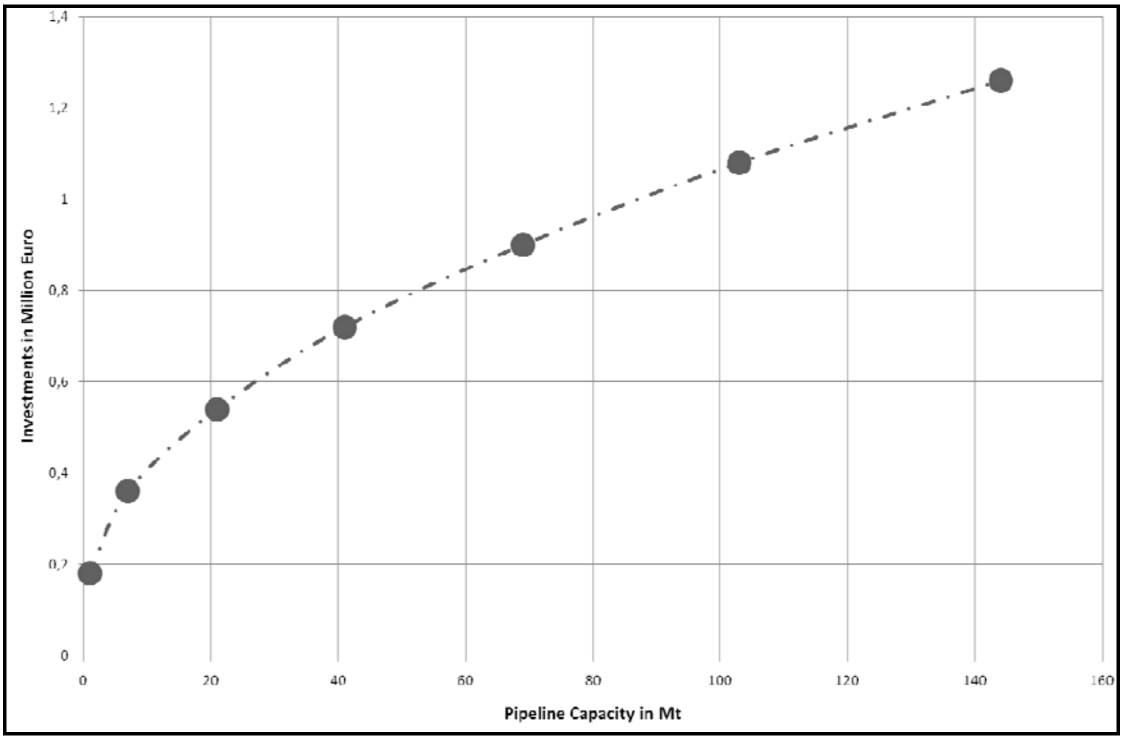

Figure 3: Selected possible pipeline capacities and their respective costs

Source: own source according to data used for the CCTSMOD

3.3. Storage

The model includes three types of storage sites which 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 project data (GeoCapacity, 2009a); data on storage volumes is also taken from GeoCapacity (2009a).(see Figure 4)

According to Heddle (2003) costs for CO_2 storage are determined by different factors including: type of storage facility, storage depth, permeability, number of injection points, injection pressure, etc. 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 seven to eight percent of total costs. Thus storage costs are implemented on a total costs basis (see Table 3).

Type of storage site	**Gas**		**Aquifer**	
	Onshore	Offshore	Onshore	Offshore
Drilling depth (vertical + horizontal) [m]	3000	4000	3000	4000
Well injection rate according to IEA (2005) [(Mt CO_2/a)]	1.25	1.25	1	1
Well injection rate according to Gerling (2010)[6] [Mt CO_2/a]	0.42	0.42	0.33	0.33
Site development costs [M€]	1.6	1.8	1.6	1.8
Drilling costs [€/m]	1750	2500	1750	2500
Investment in surface facilities [M€]	0.4	25	0.4	25
Monitoring investments [M€]	0.2	0.2	0.2	0.2
Wells per location	6	6	6	6
Total drilling costs [M€]	5.25	10	5.25	10
Total capital costs per well [M€]	5.62	14.50	5.62	14.50
Operation, maintenance and monitoring costs [%]	7	8	7	8

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

Source: Own calculation based on data from IEA (2005)

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

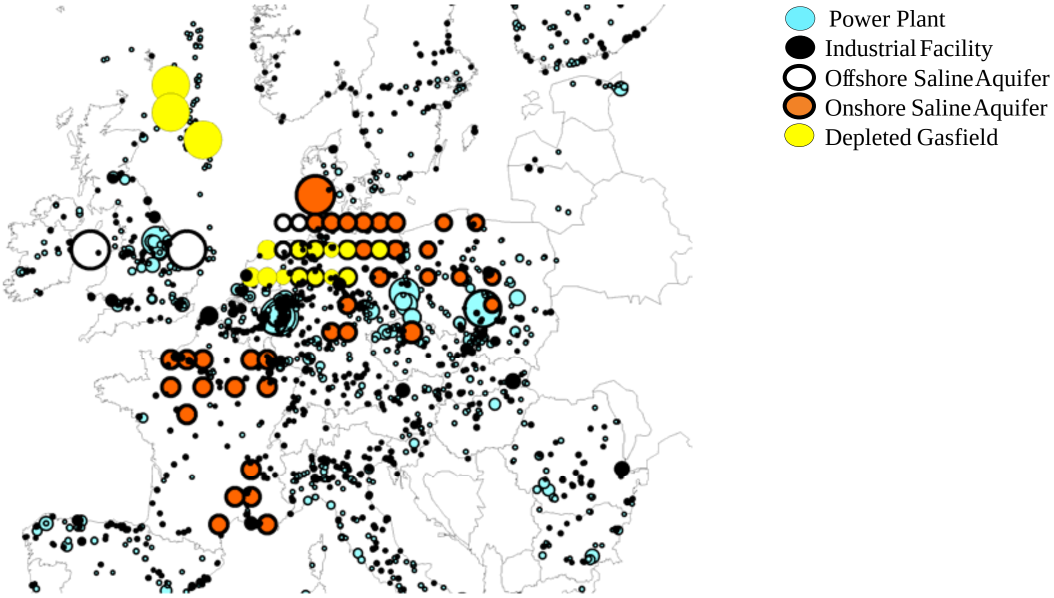

Figure 4: Visualization of input data for CO_2 point sources and potential storage sites

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

4. Scenarios

4.1. 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 due to 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 ton CO_2, we implement different 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 Euro.
- Second, total subsurface storage potential for CO_2 exhibits high uncertainty due to a lack of high resolution data (GeoCapacity, 2009a) and different calculation methods (Wuppertal Institute, 2010). We use storage potentials for Europe from the GeoCapacity Project (GeoCapacity, 2009a) and define the following European scenarios:
    - GeoCapacity: estimation presented by the GeoCapacity Project of 100 Gt CO_2 as first approximations to the real storage potentials
    - GeoCapacity Conservative: conservative estimation of the storage potential of 50 Gt

  - Very Low Storage Potential: 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 the CCTS technology is dependent on public opinion and political will. For example, in Germany the high public rejection of onshore storage led to prolonged delays of RWE's proposed CO_2 storage project in Husum.[7] Although offshore storage is potentially a solution to the NIMBY problem, technical complexity and increased costs may prove insurmountable. Such uncertainty is revealed by the ban on onshore storage in some of the scenarios.

Table 5 illustrates the input parameters for the above defined uncertainties in the different scenarios.

Scenario	Geological storage potential	CO_2 certificate price in 2050	Public acceptance
BAU	GeoCapacity (100 Gt for Europe)	43 Euro	Onshore + offshore
On + Off 31	GeoCapacity (100 Gt for Europe)	31 Euro	Onshore + offshore
On + Off 55	GeoCapacity (100 Gt for Europe)	55 Euro	Onshore + offshore
Off 55	GeoCapacity (100 Gt for Europe)	55 Euro	Offshore storage only
Off 120	GeoCapacity (100 Gt for Europe)	120 Euro	Offshore storage only
Off 100	GeoCapacity (100 Gt for Europe)	100 Euro	Offshore storage only
Conservative storage potential	GeoCapacity Conservative (50 Gt for Europe)	43 Euro	Onshore + offshore
Low storage potential	50 percent of GeoCapacity Conservative (25 Gt for Europe)	43 Euro	Onshore + offshore

Table 4: Scenario overviews, if not otherwise indicated, all scenario data are similar to BAU input data described in detail in Section 4.2.

4.2. Business as usual scenario (BAU)

The BAU scenario simulates the cost-optimal deployment of a European CCTS infrastructure for the period 2010-2050 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 nine offshore and 66 onshore

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[7] See *Klimagas: Kein CO_2-Speicher in Nordfriesland, in taz.de.* (taz) Retrieved 07 14, 2010, from http://www.taz.de/1/nord/artikel/1/kein-co2-speicher-in-nordfriesland

storage sites with locations and capacities according to GeoCapacity data (GeoCapacity, 2009b).In this scenario both onshore and offshore storage are available. Point sources emissions, storage sites and potential pipelines are mapped on a spherical grid covering Europe. The distance between two neighboring grid nodes is one degree (on average about 100 km).

4.3. BAU results

In the BAU scenario, 19 percent (498 Mt) of the total CO_2 emissions are captured, transported and stored via CCTS annually in 2050. CCTS implementation starts in 2010 with the first infrastructure investments in the industrial sector. CCTS infrastructure gradually ramps up from 2020 to 2040.[8] At first, the industrial facilities with low capturing costs situated close to potential storage sites are the dominant users of CCTS. While industry 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 eight percent in 2025 to 56 percent in 2050.

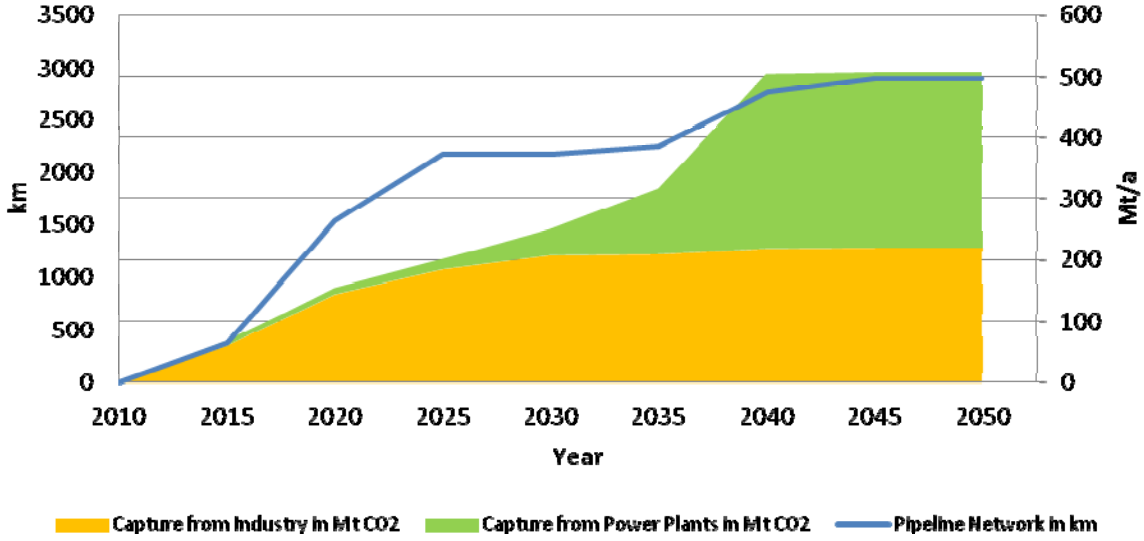

Figure 5: Annual capturing rates for the industry and the power generation sector and length of pipeline infrastructure in the BAU scenario

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 commercialization is reached in 2040, capturing investments account for, on average,

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[8] We define the ramp-up phase as the time period when the main part of costs is caused by the investments in CCTS. This is the time when infrastructure is build. Furthermore, we define the commercialization phase as the time after the ramp-up phase, when the main part of CCTS expenditure is caused by the operational costs of the infrastructure.

81 percent of total investment costs while transport and storage investments account for eight and eleven percent, respectively. Afterwards, operation costs for capturing account for 96 percent of total operating costs.

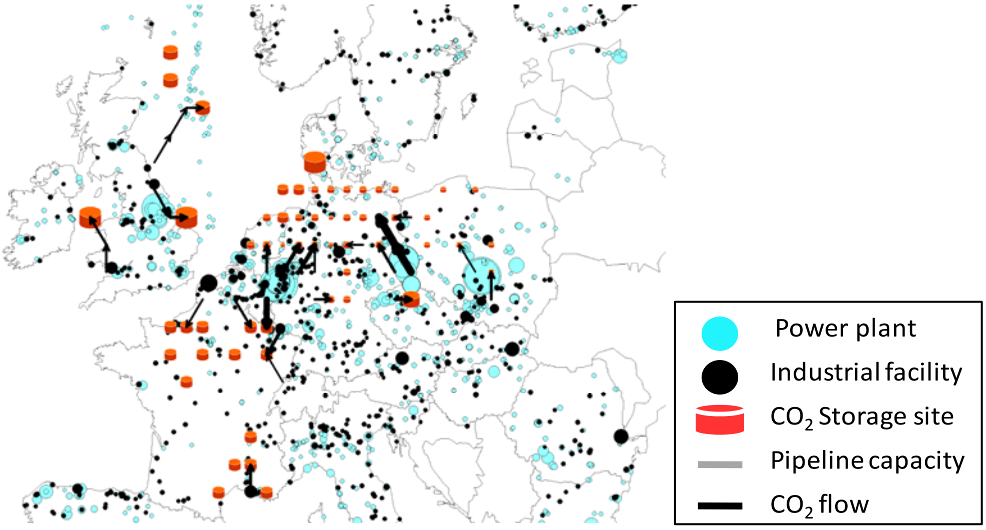

Figure 6: BAU: CCTS infrastructure in 2050

We note that under the applied CO_2 price path, CCTS is only an option for countries with a regional proximity between CO_2-intensive regions and storage sites. Only Poland, Germany, The Netherlands, Belgium, France and UK can implement the technology. However, we find no interconnected transnational transportation network. 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 only constructed when the power sector applies the CCTS technology.

4.4. Offshore 120 results

In the Offshore 120 Scenario, 25 percent of the CO_2 emissions from the emission data base are stored annually in 2050. Similar to the BAU scenario, capturing activity starts in the industry 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 percent 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 15900 km in 2050 (see Figure 7).

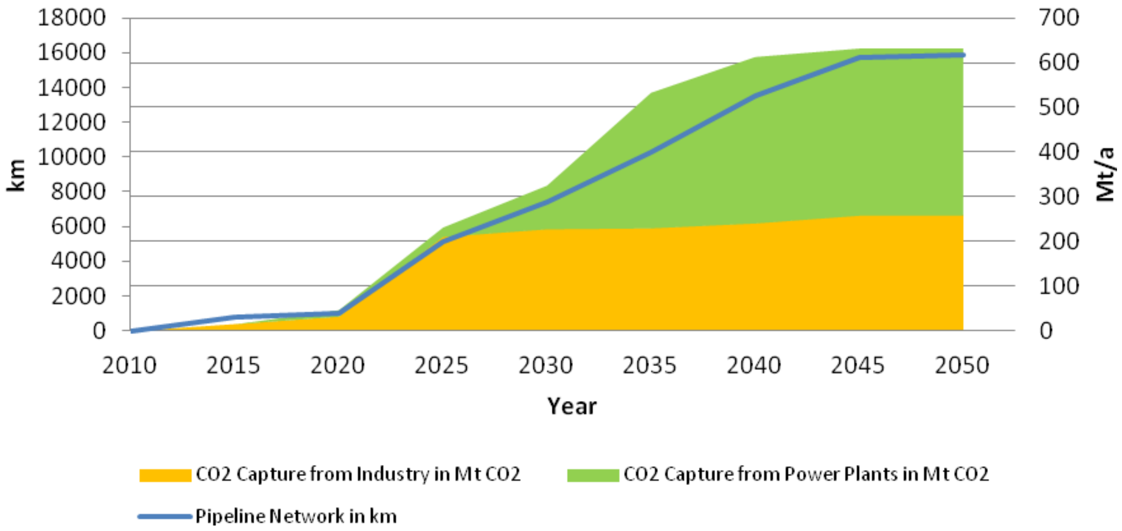

Figure 7: Annual capturing rates for the industry and the power generation sector and length of pipeline infrastructure in the Offshore 120 scenario

During the ramp-up phase capturing investments account for 74 percent of total investments while storage accounts for 21 percent and transport for 5 percent. 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 commercialization is reached in 2045, operation costs for capture represent 75 percent of the total costs, and transport costs account for 25 percent.[9]

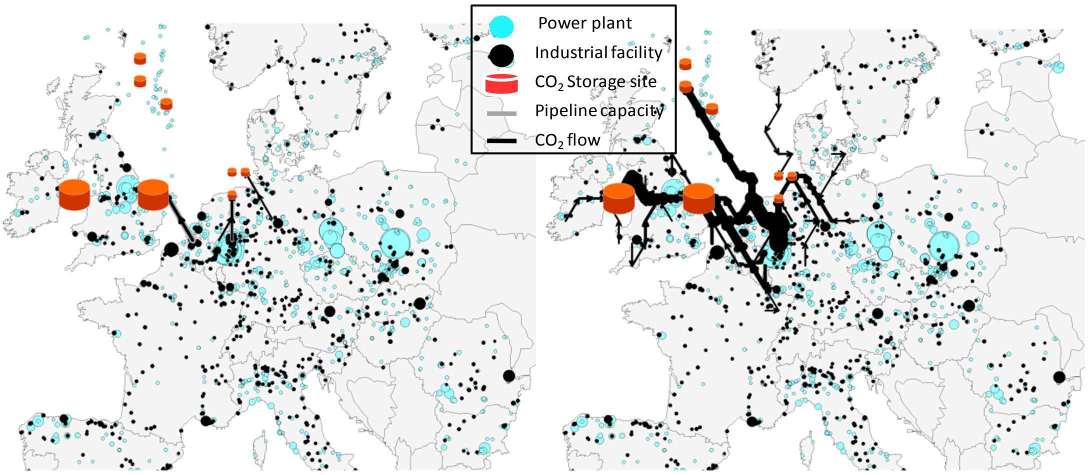

Figure 8: Offshore 120: CCTS infrastructure in 2020 (left) and 2050 (right)

Assuming extended public resistance to onshore storage and the presented CO_2 certificate price regime, an interconnected European CCTS network becomes the cost-optimal mitigation strategy. Starting at locations where industrial facilities first apply

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[9] 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.

CCTS, the network rapidly expands to cover the industrial regions of Germany (Rhine-Area), Northern France, The Netherlands, Belgium and UK by 2050. Industrial regions in Central and Eastern Europe are not connected to the network due to 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.

4.5. Overview of scenario 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 3000 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 percent of total CO_2 storage by 2050 in the BAU Scenario but only 47 percent in the Offshore 120 Scenario.

Scenario	CO_2 price in 2050 [€]	CO_2 stored via CCTS in 2050 [%]	Annual storage rate exceeds 100 Mt CO_2/a [a]	Pipeline infrastructure longer than 1200km [a]	Infrastructure length in 2050 [km]	Share of CO_2 from industry [%]
BAU	43	19.4	2020	2020	2897	54.0
On+Off 31	31	3.9	2045	-	-	89.4
On+Off 55	55	48.6	2020	2020	13359	40.7
Off 55	55	8.2	2025	2025	1490	68.1
Off 100	100	14.0	2020	2025	3419	55.5
Off 120	120	24.7	2020	2025	15889	47.2
Conservative Storage Potential	43	13.5	2025	2025	1333	60.6
Low Storage Potential	43	5.6	2035	-	-	66.8

Table 5: Overview of scenario results

The BAU Scenario is characterized 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 in a broad stream leading to offshore storage sites in the North Sea.

5. Conclusions

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

Scenario results indicate that given a moderate development of the CO_2 certificate price, the deployment of the CCTS technology will remain regional in character with no integrated European network infrastructure. However, European cooperation could still be of benefit in areas where industrial and power generation centers 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 only 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 industry and electricity sectors in the CO_2 infrastructure planning seems to be a good "issue" for further considerations.

In all scenarios, industry plays an important role as a first mover to induce deployment of CCTS. A decrease of 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 decarbonization of the electricity sector.

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7. Appendix I: Definition of Indices, Parameters and Variables

The CCTSMOD is a *mixed integer linear problem* (MILP) minimizing total system costs subject to capacity, integer, non-negativity and further constraints. We define the following abbreviations with its 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]