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Development of a methodology to analyze the geographical distribution of CCS plants and ramp-up of CO2-flow over time

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Abstract

Development of large scale CO2 transport systems will obviously depend on geographical distribution of CCS installations and CO2 volumes over time and their location relative to appropriate storage sites with sufficient injectivity. However, installation of CCS at any facility is likely to be based on company specific planning and company specific strategies with the risk that there will be a considerable geographical spread of such installations over time leading to several small scale and single source-sink transport systems which will be more costly, affect the surroundings more and potentially also lead to increased local opposition to CCS. Additionally, such a development is also likely to require longer overall lead times since each system will have to be treated individually by for instance permitting authorities. This paper presents a methodology to distribute capture installations and captured volumes geographically over time in order to identify, analyze and visualize potential problems related to large scale build-up of CCS installations within Europe.

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Keywords: Geographical distribution; time; company strategy; lead times

1. Introduction

There is convincing scientific evidence that climate change is happening and also that it is considerable political consensus around commitment to the 2 degrees Celsius target. There should also be little doubt that CCS is considered as one out of several key technologies to achieve GHG emission reductions required to limit the global average temperature increase to 2 degrees Celsius above pre-industrial levels. Both the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) clearly advocates the need of worldwide large-

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scale deployment of CCS to meet the emission reductions required, see for instance [1, 2]. The EU supports the 2 degrees target and is committed to reduce GHG emissions by 20% relative to 1990 by 2020 and has suggested a 40% reduction by 2030 [3] and, in the longer term, 80 to 95% reduction in 2050, in both cases relative to 1990 [4].

However, the development of CCS has been slow up to now and according to [2] the cost of GHG abatement would increase significantly if CCS is abandoned as a mitigation technology while at the same time it would also increase the pressure on the other mitigation technologies. The scale at which CCS needs to be deployed is huge according to [2]. Already in 2020 there should be 120 large-scale integrated CCS projects in operation worldwide to be "on track" to reach the 2 degrees target while only 4 projects actually were in operation as of end 2011. By 2050 there should be almost 2,000 industrial sites with CCS plus ca 960 GW power generation capacity installed with CCS worldwide. Between 2015 and 2050 some 123 Gt CO2 is expected to be captured, transported and stored in order to meet the 2 degrees Celsius target [2]. Considering that it may take up to ten years to develop a CCS project from the beginning to start of operation this implies that there will need to be a significant scale-up over the next 35 years not only for CCS plants but also for transportation networks and storage infrastructure.

At the same time installation of CCS will require significant investments on plant level [5] and it is therefore likely that installation of CCS will be based on company specific planning and company specific strategies with the risk that there will be a considerable geographical spread of such installations over time leading to several small scale and single source-sink transport systems which will be more costly, affect the surroundings more and potentially also lead to increased local opposition to CCS. Additionally, such a development is also likely to require longer overall lead times since each system will have to be treated individually by for instance permitting authorities. This paper therefore develops a methodology to distribute capture installations and captured volumes geographically over time in order to identify, analyze and visualize potential problems related to large scale build-up of CCS installations. The methodology is applied on power plants in EU-27.

The report is organized as follows: The methodology applied in this work is described in Section 2 while results are given in Section 3. Section 4 discusses the results and Section 5 gives the main conclusions from the work.

2. Methodology

The work presented in this paper utilizes Chalmers power plant database together with Chalmers Electricity Investment Model (ELIN) to determine the CO2 flow over time as a result of the development of CCS technologies as obtained from the ELIN output. Chalmers power plant database comprises all power plants in Europe with thermal plants and hydro plants listed down to block level. The database contains some 10,500 operational units in EU-28 plus Norway and Switzerland with a combined capacity of 944 GW. Additionally, the database contains some 1,300 units under development with a combined capacity of 339 GW. Data that is registered on a per unit basis (block level) includes fuel, age, thermal input and output capacity and power generation capacity, boiler and turbine data, emission (CO2) and generation data, precise location of the power plant sites etc (for more information on Chalmers database, see [6]). ELIN is a techno-economic model utilizing Chalmers power plant database yielding the economic optimum of electricity generation technologies in the countries investigated (excluding taxes and subsidies) over the time period studied and under assumed boundary conditions. Boundary conditions are exogenously set and include conditions such as demand projections, policy decisions with regard to CO2 emission reduction requirements, officially announced renewable and energy efficiency targets and nuclear power phase outs. Although each country is modelled separately, it is assumed that total electricity demand within the entire region studied (EU-27 plus Norway and Switzerland) should be met on a common electricity market and emissions may be traded among the MS in a similar manner as in the EU ETS. The model includes current limitations in transmission capacities between the countries and allows for investments in new transmission capacity. The model yields annually installed CCS capacity by fuel and by country as well as corresponding amount of CO2 being captured.

The paper presents a methodology for analyzing the ramp up of the CO2 transport system applying the technology mix obtained by the ELIN modelling results with the CO2 flow obtained from the CCS technologies (coal, lignite and gas). It is assumed that the CCS plants will be located on existing sites being distributed geographically in such a way that for each country and for each year the CCS capacity yielded by ELIN replaces the oldest operating units with the same fuel (lignite, coal or natural gas). Annual CO2 volumes captured at each individual plant is simply derived as total captured volume by fuel in each country divided by number of operating plants with the same fuel and in the same country in any specific year, i.e. the geographical distribution of CO2-volumes over time.

The effect of ramp-up on cost was also calculated using a modified version of a pipeline cost equation given by [7] and an optimization model which, given network topology and mass flows of CO2 in each pipeline segment, yields the pipeline diameters and booster station locations that minimize system cost without violating physical constraints such as minimum or maximum allowed pressure and fluid velocity in the pipes. In order to discuss the economic consequences of different development paths of a pipeline system for CO2 transport, transport costs were calculated for a bulk system in Germany in three cases;

- Case 1 where the pipeline system is expanded as needed along the way as new sources come into operation with a first pipeline system being built in 2025 and a second system in 2030. This approach may be associated with a relatively low risk since expansion of the transport network can be reconsidered if sources do not come online as expected
- Case 2 where the pipeline system is already built in 2025 to accommodate all sources expected to come online by 2035. This approach can potentially be more cost effective than the case above, but could also be more risky if the anticipated flows are not reached, e.g., due to sources not being commissioned according to plan.
- Case 3 illustrating the economic risks involved in the second case. The pipeline system is built with the same specifications as in case two, i.e., to handle the flows from all sources anticipated between 2025 and 2035. However, the sources expected to connect to the system between 2030 and 2035 are assumed to fail to come into operation, which illustrates the risk involved with constructing a system designed to accommodate sources connecting over a long period of time.

3. Results

Figure 1 shows the annual CO2-flow by country between 2025 and 2050 as yielded by ELIN in one modelling exercise assuming 99% CO2 emission reduction in 2050 relative to 1990. In order to reach such a high emission reduction target, a substantial amount of coal and lignite plants are co-fuelled with biomass. In total 8.0 Gt is captured between 2025 and 2050 in the scenario shown. In the modelling exercise, CCS is available as a mitigation option from 2020 but the model does not include CCS until 2025.

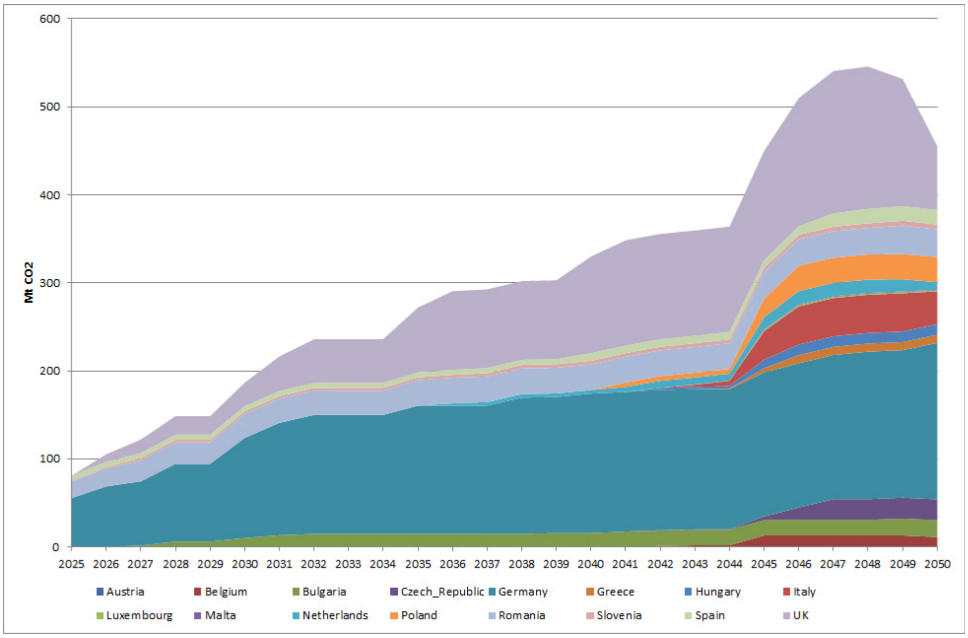

Figure 1: Modell results for captured CO2 by country 2025-2050

As can be seen from Figure 1, captured CO2 within EU-27 increases relatively modestly, from 81 Mt in 2025 to 364 Mt in 2044 followed by a rapid rise to a peak of 546 Mt in 2048 before it falls back reaching 455 Mt in 2050. Most CO2 is captured from lignite plants in Germany and coal plants in the UK, 3.5 and 2.1 Gt respectively on aggregate over the period.

Figures 2a to 2d shows the distribution of CCS plants in 2025, 2035, 2045 and 2050 respectively applying the model results showed in Figure 1 and the methodology discussed above with regard to geographical distribution of CCS plants over time. Lignite CCS plants are shown as brown circles, coal CCS plants as black circles while gas CCS plants are shown as red circles. The figures shown in each map refers to capture plants; installed capacity, number of sites and captured CO2.

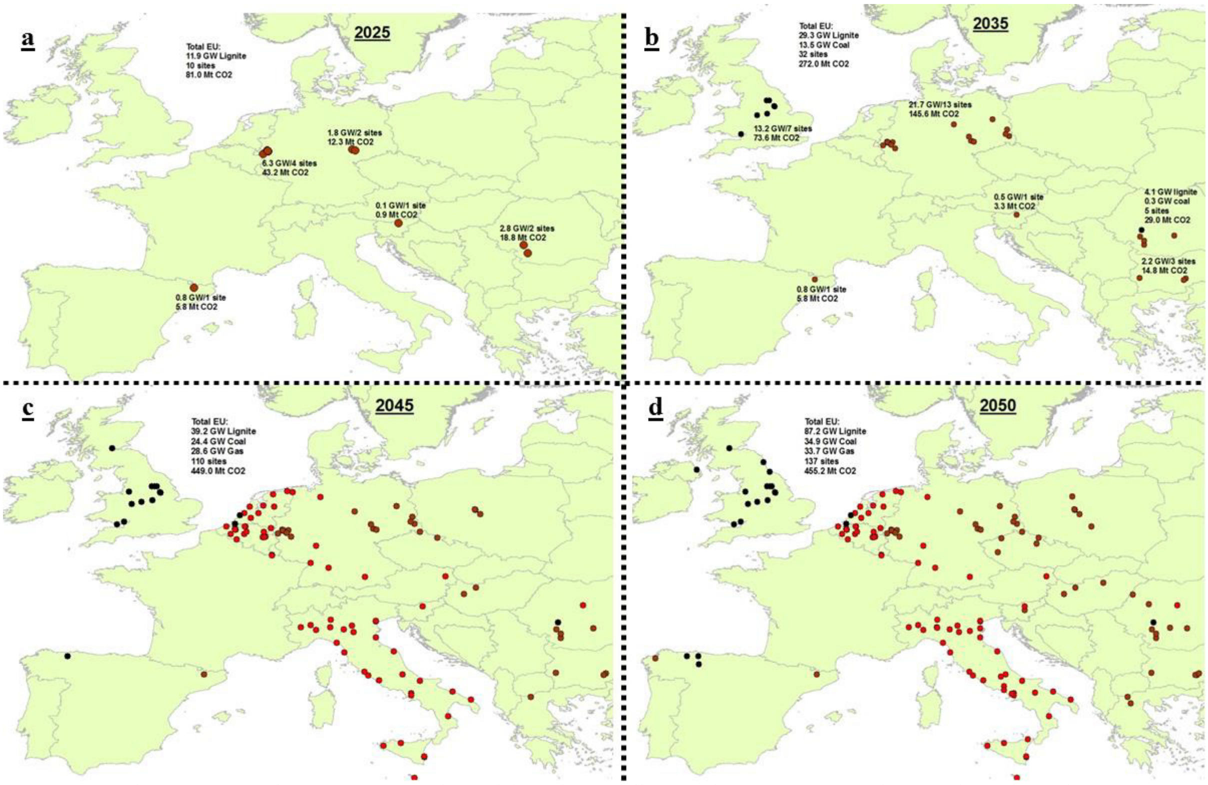

Figure 2: Distribution of CCS plants in EU-27 as obtained from the modelling results assuming CCS plants are being located on existing sites according to age in a) 2025, in b) 2035, in c) 2045 and in d) 2050. Brown circles refer to lignite plants, black to coal plants and red to gas plants.

According to the model results the number of sites and countries with CCS increases from 10 sites and 4 countries in 2025 to 137 sites and 13 countries in 2050 while the volume of captured CO2 increases from 81 Mt to a peak of 546 Mt in 2048.

Owner concentration is an advantage with regard to future planning of CCS infrastructure. In Germany in 2025 (Figure 2a) four CCS plants have been located in the Ruhr-area in the west and two in Saxony-Anhalt in the east. The four CCS plants in the Ruhr-area are owned by RWE while the two CCS plants in Saxony-Anhalt are owned by Mibrag. By 2035 however, another six CCS plants with three different owners (of which Mibrag is one) are installed in the east. Since these companies hardly will know each other plans in advance, the risk is that several CO2 pipelines will be built in East Germany. Moreover, assuming that CO2 captured in Germany for various reasons will utilize storage sites located in the Southern gas basin in the UK (see Figure 3) the risk is that multiple pipelines will be constructed across Germany instead of one single bulk pipeline from the east to the west taking German CO2 to the gas fields in the UK.

Already in 2035 where captured volumes have reached 272 Mt, there is considerable geographical spread of capture plants stretching over 2,400 km from UK in the west to Bulgaria in the east. A large number of gas plants with CCS are added in Belgium, Italy and the Netherlands after 2035 and looking at Figures 2b and 2c it can be observed that there is a significant geographical expansion between 2035 and 2045. However, in 2035 this is of course an unknown implying that new pipelines will have to be built in this period unless some entity is willing to accept the economic risk of having to operate an underutilized bulk pipeline for an unknown number of years and, in the worst case, forever.

As shown in Figures 2c and 2d a significant number of capture plants are added in Italy and Eastern Europe after 2035. This is however based on the assumption that most CO2 can be stored domestically which yields CCS competitive relative to other mitigation options. If storage and injection capacity in these countries is significantly lower than anticipated in this report, these plants may have to transport the CO2 all the way to the North Sea which will raise cost significantly possibly making CCS economically infeasible.

Figures 2a to 2d clearly demonstrates how difficult it will be to build up large-scale CCS infrastructure since 1) installation of CCS will be a decision taken in each individual company and 2) no-one will know in advance which plants that will install capture and when they choose to do so, i.e. CO2-volumes as well as when and where will all be unknown factors. Additionally, CCS will only be developed at a site provided the developer has first verified and secured access to sufficient storage and injection capacity corresponding to his/her requirements. This also means that the developer is unlikely to explore the reservoir's storage and injection capacity *beyond* his own requirements, in particular if the reservoir is offshore where cost for exploration and verification may be significant. In other words, distribution of storage capacity and injectivity is also likely to be an unknown to other potential developers of CCS plants. All these uncertainties are further emphasized given the large political uncertainties both with regard to CCS and the future emission regime within EU.

Figure 3 shows the early capture plants being installed in Germany up to 2035 (see Figure 2b) along with storage sites where green refers to aquifers, red to gas fields and blue to oil fields. Also shown are two bulk pipelines collecting the CO2 being captured in eastern and western Germany in the 2025-2035 period and bringing it to an onshore collection site at Dornum from where it is sent to storage in offshore reservoirs. In total, almost 22 GW lignite based CCS capacity distributed over 15 sites is installed in Germany up to 2035 and captured CO2 volume increases from 55 Mtpa in 2025 to 146 Mtpa in 2035. Cumulatively over the period almost 1.2 Gt CO2 is being captured up to 2035. After 2035 model results show that captured CO2 in Germany continues to increase up to 2050 reaching 178 Mt and 3.6 Gt on aggregate between 2025 and 2050.

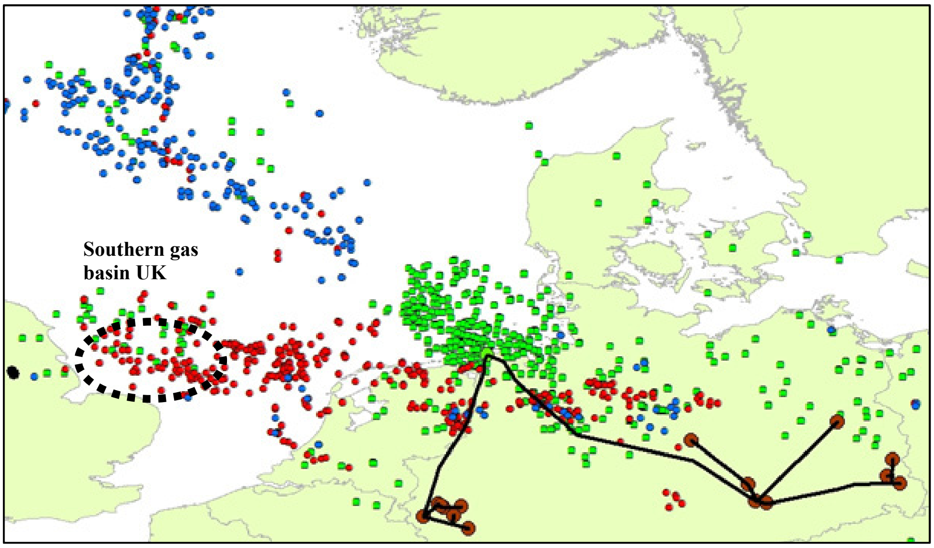

Figure 3: Lignite CCS plants (brown circles) installed in Germany between 2025-2035 along with storage sites where red refer to gas fields, blue to oil fields and green to aquifers. Also shown are two bulk pipelines collecting the CO2 from CCS sites in eastern and western Germany and transporting it to a processing site at Dornum. The dashed black circle shows a rough areal distribution of the Southern gas basin in the UK.

At a first glance there appears to be plenty of storage sites but taking into consideration that onshore storage so far has had a very hard time gaining local acceptance in Germany (as well as in other countries in Europe) and that storage capacity in German offshore aquifers appears to be both uncertain and limited with only a few individual aquifers with an estimated storage capacity above 50 Mt [8, 9], the importance of being early in the development of CCS seems obvious since transport to Danish, British or Norwegian storage sites may add up to several hundred kilometers of offshore transport distance. Total offshore storage capacity in the aquifers in the German part of the North Sea has been estimated to between 1.9 and 3.9 Gt but limiting storage to aquifers with at least 50 Mt storage capacity would reduce this to between 0.9 and 2.2 Gt distributed over 8 to 15 sites [8, 9].

Injectivity, i.e. the rate at which you may inject CO2, may be another limiting factor governing the transport network. Although injectivity is a highly reservoir specific parameter assuming for instance that at least 45 years would be required to fill any specific aquifer you may, at the very best, be able to inject 87 Mt annually in German offshore aquifers which is way below what will be required according to the modelling results (146 Mt in 2035 and 178 Mt in 2050). Thus, modelling results together with mapping of sources and sinks indicate that in the case of constrained storage capacity and/or injection capacity, early movers may have an advantage being able to secure the best storage sites.

As mentioned in Section 2, cost has been calculated for the two pipeline systems shown in Figure 3 in three different ways in order to assess the impact of ramp-up on cost. Table 1 shows

Table 1: Cost of pipeline systems cases 1-3 in Germany

System	Pipeline length km	CO2 transported Mt	CAPEX MEUR	OPEX MEUR/yr	Spec Cost EUR/ton
Case 1	1860	1,167	5,120	178	2.91
Case 2	930	1,167	5,126	164	2.81
Case 3	930	374	5,126	164	3.45

As can be seen from Table 1, case 2 yields the most cost efficient solution, i.e. to build one large bulk pipeline already in 2025 to accommodate CO2 from all capture plants being installed up to 2035. However, the impact on specific cost is marginal as can be seen when case 2 is compared to case 1 which instead refers to two smaller pipelines being built in 2025 and 2030 respectively; specific cost increases by 3.5%, from € 2.81/ton to € 2.91/ton. At the same time, case 3 illustrates the risk of building one large pipeline already in 2025 for the case when the expected additional flow from 2030 onwards does not materialize; specific cost increases by almost 23%, from € 2.81 to € 3.45 per ton. It is important to underline that the results shown in Table 1 refers to the specific case selected in this report and that individual cases of course will be strongly affected by the evolvement of the CO2-flow over time.

4. Discussions

The distribution of CCS plants is based on the assumption that CCS plants will be located on existing sites replacing blocks according to age. Permission to construct a power plant on a greenfield site is usually difficult to achieve and an existing site is already prepared for a power plant with regard to cooling, fuel handling and the electricity grid. Besides, location of the individual plants does not really matter as the main point of this report is to illustrate and analyze the consequences of a casual distribution of CCS plants over time.

The distribution of capture sites shown in Figures 2a to 2d is based on the current knowledge of distribution of storage capacity and injection capacity, i.e. the model includes estimated cost of CCS (capture + transport + storage) for each country individually based on, among other things, distribution of storage capacity and injection capacity. Thus, since estimates of storage capacity and injection capacity is highly uncertain, the distribution of capture sites may be altered significantly as data on storage sites are being constantly refined and thus maybe also the cost of CCS.

The large uncertainties with regard to CCS risk to seriously hamper the development of CCS. One way to alleviate these uncertainties is to reduce the risks related to underutilization of large scale CCS transport infrastructure and the process of exploring and verifying storage and injection capacity. It therefore seems obvious that governments will have to take a more active role to ascertain a cost efficient build-up of a CCS infrastructure with a minimal impact on the environment either through public-private partnerships or through companies owned in full by the state.

5. Conclusions

The main conclusion drawn from the work presented in this report is that a CO2 transport network will be determined by the distribution of installed capture plants over time in combination with location of verified storage capacity and injectivity. However, since installation of individual capture plants is likely to be based on company specific strategies, the risk is that there will be a considerable geographical spread of CCS plants over time.

The large uncertainties related to distribution of CCS plants over time as well as distribution of verified storage and injection capacity risk to seriously hamper the development of CCS. The risk is also that CCS infrastructure will evolve in a way that is not optimal with respect to cost and impact on the surroundings. Such a development may also lead to longer overall lead times since each individual system will have to be treated individually by for instance permitting authorities.

In order to certify an efficient development of CCS infrastructure, i.e. of transport and storage systems, it seems obvious that the state will have to participate in the exploration and verification process of storage sites as well as in the construction of bulk pipelines, either through public-private partnerships or through entities entirely owned by the state.

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