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Large-scale CCS transport and storage networks in North-west and Central Europe

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Abstract

Carbon Capture and Storage (CCS) is one of the measures that can be used to reduce CO_2 emissions to the atmosphere in Europe. Of the total CCS chain the transport infrastructure may be the most planning and guidance-intensive part during the development of large-scale CCS. The EU FP7 CO_2Europipe project aims to pave the road towards large-scale, Europe-wide infrastructure for the transport and injection of CO_2 from large point sources. The study presented here is part of that project and presents an assessment of the North-west and Central European sources and sinks of CO_2; matching of the sources and sinks is performed in order to identify likely future transport routes and the volumes that can be expected to be transported. The results are presented in maps with major transport corridors. The matching shows that, theoretically, sufficient storage capacity is available up to 2050, with the main part located in the North Sea. Aquifers are to play an important part in the storage and thus require early exploration activities. Infrastructure networks will be extensive and pipeline construction will need to be performed at a fast pace between 2020 and 2050 to make sure that transport can occur between the source clusters and the storage fields in time. To achieve this, international co-operation is required since cross-border transport will be inevitable if the EU is to achieve its GHG emission reduction target. Also, necessary legal frameworks for CCS need to be in place in each affected country to allow this process to go ahead.

Keywords: CCS, transport, large-scale infrastructure, Europe

1. Introduction

Carbon Capture and Storage (CCS) is regarded by European and national governments as part of a portfolio of measures to reduce CO_2 emissions. CO_2 transport is probably the least cost intensive element of the full CCS chain, but may be the most planning and guidance-intensive part during the development of large scale CCS.

The EU FP7 CO_2Europipe project, running from April 2009 through October 2011 aims to present a roadmap towards a Europe-wide infrastructure network for the transport and storage of CO_2. The central idea of

CO2Europipe is that future, large-scale CCS transport and storage networks will evolve up to 2050 through coalescence of the infrastructure constructed by early, small-scale CCS projects. The aim of the first part of the project, which is presented here, is to identify likely transport corridors by performing source – sink matching, to estimate the order of magnitude of transported volumes. According to recent publications regarding transport infrastructure required for CCS [1-3] its development is feasible in principle, but significant hurdles exist at the regulatory level, rather than the technical level. The results of this project show the relevance of cross-border transport of CO_2 and they provide the required input for the technical and regulatory transport solution investigated in the remainder of the project.

2. Source and sink clusters

Large-scale CCS is likely to result in the linking of source clusters with sink clusters by trunk lines (backbone), in combination with satellite pipelines to link the individual sources and sinks within the cluster to the trunk line. This way the CO_2 demand and supply can be matched in a flexible way, similar to the existing European pipeline network for natural gas. For this reason clustering of sources and sinks is performed. Clustering sources and sinks also reduces the uncertainties associated with both the development of capture and the availability of storage capacity.

CO_2 emission and storage data were taken from the Geocapacity database [4]. This database was the result of the European Geocapacity project and contains data on European point sources (power plants and industrial sources) and sinks (oil and gas fields and saline aquifers). The Geocapacity data represents data from the year 2005. Data for Sweden and Finland was derived from the EPER database which represents data from the year 2007.

2.1. Source clustering

For an estimate of the sources that could be used for CCS, only point sources with an output of at least 250 kt CO_2/yr were considered. Point sources were clustered on a national scale, with each cluster contributing a significant fraction to the total national CO_2 emission. Excluding point sources with small amounts of CO_2 emissions and remotely located sources, the total point source emissions as represented in the regional clusters are on average about 90% of the total amount of national emissions related the main industrial sectors.

2.2. Sink clustering

Based on cluster sizes (geographically) of previous studies regarding source-sink matching (e.g. [5]), hydrocarbon field and deep saline aquifer clusters were established using the Geocapacity database. Clustering was performed per sink type, and on a national basis, except for sinks in the North Sea (since fields from different countries sometimes lie adjacent) meaning that clusters in the North Sea can contain sinks from several countries. In contrast to the sources the clustering was not limited to sinks which contribute a significant fraction to the total capacity.

3. Emission and capture scenario

For each country involved in the assessment, captured amounts were derived for the timeline 2020, 2030 and 2050:

- 2020. Small scale pilot projects which are close to realization are taken into account. A pilot project is said to be close to realization if subsidy is granted, commitment is made on budget and personnel or information is detailed and widely available.
- 2030. The PRIMES economic growth model developed by the University of Athens has been used, which models national economic projections, energy demand and corresponding CO_2 production up to 2030. The emission scenario developed is ‘CO2Europipe Policy Scenario’ (CPS), which is based on EU policy developments since 2007. The fuel mix is taken into account and it is assumed that approximately 1/3 of the emission reduction targets (up to 80% in 2050) will be realized by means of CCS. The results are updated by recent Member State developments for Germany, Belgium, the Netherlands and Norway.

- 2050. Projections for 2050 were obtained by extrapolation of the PRIMES results between 2020 and 2030, taking into account the same assumptions.

The results on national amounts of CO_2 to be captured are shown in Table 1. The national amounts were divided over the source clusters. Clusters with currently high emissions and those with pilot projects planned will cover the largest part of CO_2 to be captured since they are assumed to attract (new) capture projects.

Table 1 National amounts of CO_2 to be captured in order to achieve the recommended CCS contribution of 1/3 to the emission reduction goals.

Country	**Total captured CO_2 [Mt/year]**		
	2020	**2030**	**2050**
Norway	6	8	9
UK	21	36	112
Denmark	2	6	22
The Netherlands	8	22	49
Germany	5	73	379
Poland	2	89	133
Czech Republic	0	32	80
Slovakia	0	5	17
Estonia	0	6	10
Lithuania	0	1	3
Hungary	0	9	25
Romania	0	36	72
Bulgaria	0	13	39
France	2	6	94
Belgium	0	10	66
Sweden	0	2	41
Finland	0	7	70
Total (Mt/yr)	46	358	1222

4. Storage capacity

The sink capacity values as recorded in the Geocapacity database and regional geological studies (if available) were used to define cluster capacities. For the practical availability some assumptions had to be made. For oil and gas fields availability was assumed 50 years after the discovery of the field. For saline aquifers availability of the total cluster capacity was assumed to evolve linearly between 2025 and 2050, to take into account the time needed to fully characterize all saline aquifer storage locations in a cluster.

It has to be noted that the sink capacities recorded are theoretical values. Especially for saline aquifers the capacity can be overestimated, since often only the geometry of the structure is known and properties of the reservoir are extrapolated (estimated) from nearby or similar structures. Due to elaborate oil and gas exploration and production, the capacities recorded for oil and gas fields are more certain. However, geological and engineering constraints (cut offs) and techno-economic, legal and regulatory barriers will decrease the capacity of fields or even exclude fields [e.g., 6]. The capacities in the database are therefore considered as a maximum.

Since storage capacity of a sink in terms of injection rate is often not available, either confidential (hydrocarbon fields) or unknown (saline formations), it was assumed, based on reservoir simulations on a number of depleted gas fields, that small reservoirs can be filled within 10 years, while large reservoirs take up to 40 years to reach their limit.

Table 2 shows the total injection rates that are assumed to be available in the different types of storage reservoir. These (theoretically feasible) rates for the different sink types are large, especially for saline aquifers, of which there are many throughout the area considered. The rates increase in the period 2020 – 2050, as reservoirs become available: hydrocarbon fields become depleted. Aquifers are assumed to be mapped and tested in this period, resulting in an increasing storage rate as more and more aquifer structures become proven.

The main part of the storage capacity is located in the North Sea.

Table 2 Total theoretical injection rates for the different storage types from 2020 to 2050. Gas field injection rates increase because of increasing numbers of gas fields reaching their end of field life; aquifer injection rate capacity increases as aquifer structures are mapped and proven.

	Total (theoretical) injection rate [Mt/a]		
	2020	**2030**	**2050**
Gas fields	260	580	800
Oil fields	20	170	250
Aquifers	1260	2840	7660
Total	**1540**	**3590**	**8710**

5. Source – sink matching

After the assessment of the sources and sinks for the countries involved, a matching was performed in terms of storage capacity and injection rate.

5.1. Assumptions and scenarios

Several assumptions and starting points comprise the basis of the matching procedure:

- The matching of sources and sinks was performed at cluster level rather than at the level of individual sources and sinks. This removes part of the uncertainty associated with the development of capture on specific sources, as well as of the uncertainty associated with the feasibility of CO_2 storage in specific sinks.
- The matching of sources and sinks was performed at injection rate, as well as storage capacity levels. The fill fraction of a cluster determines the remaining injection rate; storage is moved to a different (nearby) cluster when the cluster reaches its limit.
- Infrastructure required for the initial pilot projects in 2020 are the basis for further development of infrastructure.
- National storage options have priority over storage options abroad.
- Viable legal CCS frameworks are assumed to be in place soon in all affected countries.
- It is assumed that CCS is economically viable.

Three scenarios were elaborated:

- Reference scenario: based on current national CCS plans for 2020, from which infra-structure has been further developed in 2030 and 2050, based on national assumptions. National assumptions include a preference for onshore or offshore storage and a preference for storage in depleted hydrocarbon fields or saline aquifers.
- Offshore-only scenario: onshore storage options are discarded in order to see the effects of stringent permitting issues.
- EOR scenario: the offshore-only scenario extended with possibilities for EOR.

5.2. Future CO_2 regional transport

Reference scenario

In 2020 the infrastructure is still limited since only few pilot sites will be operational. By 2030 the emission reduction targets are sufficiently severe that CCS needs to be developed on a large scale in all countries and in all source clusters considered. As a result, infrastructure requirements are much more extensive (Figure 1). Most of the countries in North-west Europe are able to store their captured CO_2 nationally. Some cross-border transport is required, from Belgium to the Netherlands and from Poland to Germany. The Baltic States, Sweden, Finland, Romania and Hungary lack (sufficient) domestic storage capacity, which results in transport to neighbouring countries. Volumes to be transported are limited, with the largest volume from the Ruhr area and the Brandenburg area in Germany (both almost 50 Mt/yr). The requirements in 2050 (Figure 2) are similar, except that the volumes to be transported are higher, with the largest volume again from the Ruhr area (almost 250 Mt/yr). Furthermore, in contrast to 2030, Poland and the Baltic states now have sufficient national storage capacity due to vast amounts of aquifer capacity becoming available. This is the result of characterizing large parts of their domestic saline aquifer storage reservoirs before that time.

Offshore-only and EOR scenarios

The infrastructure of the two alternative scenarios is similar since the offshore oil fields are located close to the offshore gas fields and saline aquifers. Both are, however, different from the reference scenario since onshore transport corridors form a large network transporting CO_2 towards the North Sea. Due to accumulation of CO_2 in the pipelines all the way from Bulgaria to the coast in Germany, large amounts of CO_2 leave Germany, heading for the North Sea. Volumes to be transported are up to ~750 Mt/yr in 2050. While such volumes are not realistic, these results illustrate the effect of stringent regulations for onshore CO_2 storage.

6. Implications for large scale CCS

6.1. Pipeline construction

The results of the source – sink matching show that a large effort in the construction of infrastructure is required between 2020 and 2030 since many additional transport corridors emerge. After 2030 the effort is large due to the construction of parallel pipelines along existing corridors. (The maximum amount to be transported per pipeline (48") is ~70 Mt/yr (150 barg) onshore and ~100Mt/yr (200 barg) offshore. Volumes to be transported well exceed such limits.)

Assuming that all transport will occur by pipeline, in 2050 a total amount of ~22.000 km and ~33.000 km of pipeline needs to be in place for the reference and the two alternative scenarios respectively (Table 3). A rough calculation shows that on average ~50-100 km of pipeline per month needs to be constructed, during the period 2020 – 2050. Current pipeline projects have a similar construction pace, so these rates are not uncommon. The Northstream and Nabucco projects, involving pipeline construction for natural gas from Russia to Germany through the Baltic Sea (1200 km) and from Turkey to Austria through Bulgaria, Romania and Hungary (3300 km) are examples of such projects. For these projects, the ime required between start of the planning and end of construction is in the order of 10 to 15 years.

6.2. Cross-border transport

Cross-border transport of CO_2 is foreseen to take place on a significant scale as early as 2030. In the reference scenario this is already 25% of the total amount of CO_2 captured, while about 70% is to be transported across borders in the offshore-only and EOR scenarios (Table 3). This implies that viable legal frameworks for cross-border transport need to be in place soon on EU and national levels. Apart from the legal level, compatibility must be present at the technical level, to ensure cost-effective linking of national systems.

Cross-border transport in the reference scenario is caused by insufficient national storage capacity. The additional cross-border transport in the two alternative scenarios is caused by the lack of offshore storage options in most countries.

6.3. Storage capacity

The storage capacity is sufficient at all points in time to store the CO_2 captured. For each scenario, the main part of the CO_2 is stored in aquifers (60-80%) and the remaining part in gas fields. Only in the EOR scenario, oil fields have been included, covering 27% of the total amount (Table 4).

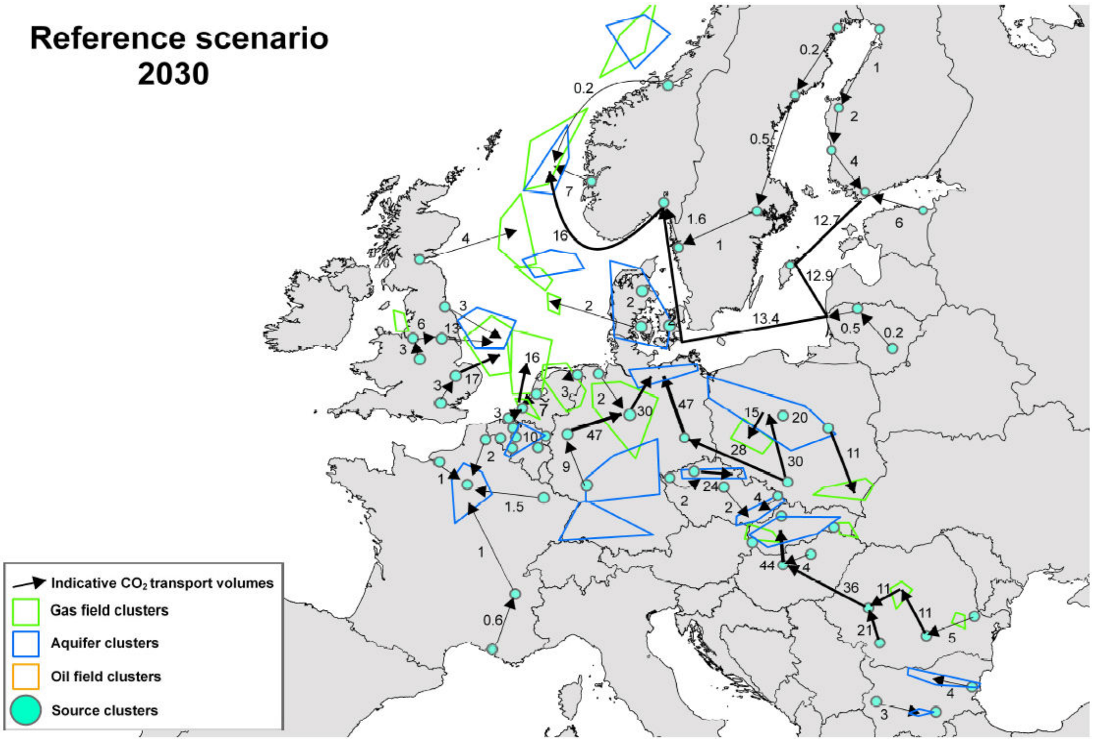

Figure 1 Transport corridors and corresponding volumes (Mt/yr), reference scenario 2030.

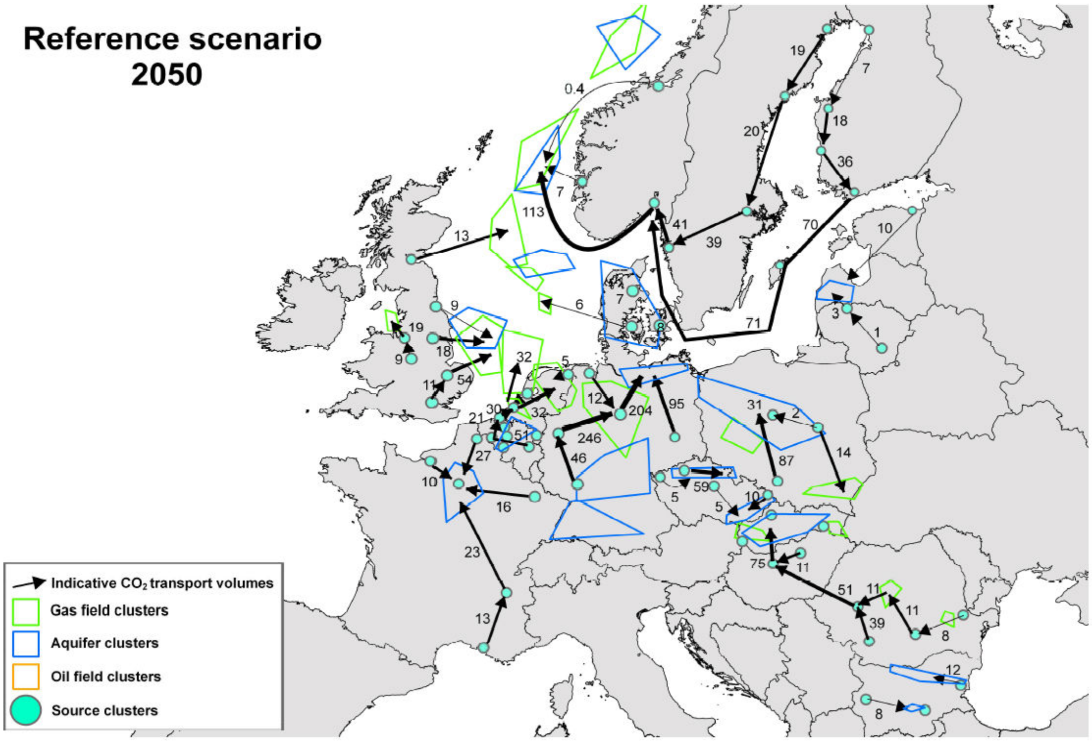

Figure 2 Transport corridors and corresponding volumes (Mt/yr), reference scenario 2050.

Table 3 Length of backbone pipeline required and amount of cross border transport predicted in time, given for the three scenarios Reference, Offshore and EOR.

	Backbone requirements (km)			Cross border transport (% of total)		
Year	**Reference**	**Offshore**	**EOR**	**Reference**	**Offshore**	**EOR**
2020	2.300	4.200	5.300	-	7	19
2030	14.300	20.900	20.900	25	70	71
2050	21.800	32.000	33.200	18	70	70

Table 4 Percentage of the different storage types filled and corresponding partitioning in 2050. * Oil fields have only been taken into account in the EOR scenario.

	Partitioning (% of total CO_2)			Capacity filled (% of total capacity)		
Storage type	**Reference**	**Offshore**	**EOR**	**Reference**	**Offshore**	**EOR**
Gas fields	27	19	14	29	18	13
Oil fields*	0	0	27	0	0	85
Aquifers	73	81	59	5	5	4

Only a small part of the fields have been filled by the end of 2050. On average 20% of the gas field capacity has been used and 5% of the aquifer capacity (Table 4), implying that a broad margin exists in case the total capacity would turn out to be much lower after extensive exploration. Otherwise a large part of the capacity remains in case CCS continues to play an important part in the emission reduction strategy after 2050.

7. Conclusions

A matching of sources and sinks in Northwest and Central Europe is performed in order to show the requirements in infrastructure and effort for CCS to play an important role in the CO_2 emission reduction strategy in Europe.

The results show that sufficient (theoretical) storage capacity is available to store the CO_2 captured in North-west and Central Europe, up to at least 2050. Aquifer capacity must play an important role in large-scale CCS. This implies that mapping and testing of specific fields and structures should start as soon as possible.

Cross-border transport will be significant, requiring international co-operation. This cooperation should start as soon as the first small-scale projects are developed, to ensure that by the time that national pilot projects grow into large-scale, Europe-wide CCS projects (between 2020 and 2030) there is technical compatibility.

The length of trunklines that can be derived from the maps suggests that an extensive pipeline network needs to be constructed within a relatively short time. While CCS projects are relatively sparse in 2020, significant construction efforts are required between 2020 and 2030, as by 2030 CCS is assumed to happen in most countries considered. Although between 2030 and 2050 the geographical extension of the European CCS transport network is similar to that already in place by 2030, increasing captured volumes require increasing the transport capacity along existing corridors. This results in continuing pipeline construction efforts between 2030 and 2050. These efforts are significant (of the order of 50 – 100 km/month, in the period 2020 – 2050), but feasible.

Since large-scale pipeline construction projects require a long planning and construction period, it is necessary that planning start as soon as possible. The recent EU financial involvements within EEPR and NER300 represent two starting points of the economic framework needed to foster CCS deployment.

Finally, the results demonstrate the implications of stringent regulations for onshore storage, which would render onshore storage effectively impossible. Without onshore storage, it will be impossible for many countries in Europe, who have insufficient domestic storage capacity.

8. References

- [1] Haszeldine RS. Carbon Capture and Storage: How Green Can Black Be? Science 2009;325:1647-1652.
- [2] ICF International. Developing a pipeline infrastructure for CO2 capture and storage: issues and challenges; 2009.

- [3] BERR. Development of a CO2 transport and storage network in the North Sea; report to the North Sea Basin Task Force; 2007.
- [4] Vangkilde-Pedersen T, Kirk K, Smith N, Maurand N, Wojcicky A, Neele F, Hendriks C, Le Nindre YM and Anthonsen KL. Assessing European capacity for geological storage of carbon dioxide. GeoCapacity Deliverable 42, final report; 2009.
- [5] Wildenborg AFB, van der Kuip MDC, Koenen M, Kramers L, Pluymaekers MPD, Smith NA, Kirk KL and Dalhoff F. CO2 capture and storage scenarios in the European Union (CCS-SCEN). TNO report 2008-U-R0215/B; 2008.
- [6] Van der Velde R, Mieog J., Breunese J. and Remmelts G. Potential for CO2 storage in depleted gas fields on the Dutch Continental shelf Phase 1: Technical assessment. By order of NOGEPA and the Dutch Ministry of Economic Affairs;2008.