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Establishing an integrated CCS transport infrastructure in northern Europe – challenges and possibilities

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Abstract

This paper examines cost, challenges and possibilities for the development of an integrated CCS transport infrastructure for the power, cement, refinery and steel and iron sectors in six EU member states: Belgium, Czech Republic, Germany, Netherlands, Poland and Slovakia. Input for ramp-up of CCS within the power sector has been provided by Chalmers Electricity Investment model (ELIN) while ramp-up of CCS in the three industry sectors is based on general assumptions. For each country, three types of CCS infrastructure systems have been assessed; for the power sector only, integrated for the power sector and the three industry sectors and finally, for the three industry sectors only. Transport cost has been calculated to range between € 1.0 and € 4.1 per ton CO_2 in the power sector and to between € 1.6 and € 15.9 per ton in the industry sector. The low cost systems indicate a favorable distribution of sources and sinks while high cost systems are a result of low volumes and offshore transport requirements. Transport cost in the integrated system ranged from € 1.2 to € 4.5 per ton implying that there seems to be little to gain for the power sector by integrating transport networks with the industry in the countries investigated, simply due to the location of sources and sinks and the fact that captured volumes from the industry sources are usually considerably smaller than captured volumes from power plants. The results reveal that the development of a CCS infrastructure to a large extent will depend on the phase-in of actual capture plants over time. The ownership concentration within the power sector in most of the countries investigated in this report may facilitate the build-up of a large centralized transport infrastructure.

Keywords: Ramp-up; CO2-transport; Integrated networks

1. Introduction

The EU has committed itself to reduce GHG emissions by 20% to 2020 which may be raised to 30% depending on reduction efforts in other regions. EU is also advocating an 80 to 95% reduction in 2050 for the industrialized world, in both cases relative to emissions in 1990 [1]. Since CO_2 accounts for around 83% of all GHG emissions and the transport sector alone accounts for 23% of CO_2-emissions, it is likely that there can hardly be any CO_2-emissions at all from the stationary sector in 2050 if EU´s proposal for long-term emission reductions shall be met [2, 3]. Up to 2020 there are basically only three options available to reduce emissions; renewable energy, raise efficiency on all levels and across all sectors and switch of fuel from coal to gas. After 2020, nuclear electricity and CCS from stationary sources may also play an important role and as we are approaching 2050, CCS will probably have to be applied on facilities burning natural gas and possibly even on biomass based emissions. The latter could for instance help to neutralize emissions from the transport sector along with an electrification of this sector, i.e. centralizing the

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emissions. CCS has the potential to play a crucial role in reducing coal based CO_2 emissions while at the same time enhancing energy security in Europe through fuel diversification. Thus, CCS will act as a bridging technology allowing more time for development and large scale introduction of more sustainable solutions. The EU has realized the importance of CCS and is engaged in a large number of research projects related to most aspects of CCS and is also actively (financially) supporting construction of large scale demo plants through the EERP and NER programs[1]. The aim is to have 12 large scale demo plants up and running in 2015.

Four sectors are responsible for almost 95% of the emissions covered by the European Emission Trading Scheme (EU-ETS); power and heat, refineries, iron and steel and cement plants. EU-ETS covers some 10,000 energy intensive facilities representing some 40% of EU's total CO_2-emissions. Even if including plants emitting above 0.5 Mt CO_2 per year (emission limit chosen arbitrarily), some 800 facilities within these four sectors are collectively responsible for more than 80% of the emissions covered by the ETS and around 30% of EU's total GHG emissions [4]. The pulp and paper industry also has large emissions but these come mainly from combustion of biomass and until there are incentives in place for CCS from biomass combustion, the overall contribution from CCS in the pulp and paper industry is likely to be modest.

In the European power sector, the first small scale pilot capture plants have already been installed and, as mentioned above, by 2015 the target is that some 10 to 15 large-scale demo plants will be up and running and the first commercial units may be installed around 2020. However, the situation appears to be more complicated in the industry sectors mentioned above. Firstly, the capture process is more complex with total CO_2 emissions from one plant coming from several separate emission sources and where the various flue gas streams differ regarding their suitability for capture. Second, capture is not considered as the most interesting near-term mitigation option, rather the industries are looking at process integration, fuel shift and other options to reduce CO_2 emissions. Third, there is an ongoing discussion that industry sectors exposed to global competition may receive parts of their emission allowances for free and as of August 2010 it is still not clear how emission intensive industries will be treated in the EU-ETS.

As mentioned above, there are more than 800 facilities in four sectors emitting more than 0.5 Mt CO_2 per year within the EU. These facilities all have different owners and different strategies for emission reductions both with respect to technology choice and implementation in time. At the same time, these factors are decisive for the development of a cost-efficient CCS infrastructure with minimal impact on the surroundings. Although there are a number of techno-economic studies which indicate the role of CCS as part of an overall CO_2 mitigation portfolio under various scenarios, most of these are based on an overall cost estimate for CCS without looking into how CCS can be deployed over time, considering the ramp-up of a transportation and storage infrastructure following the deployment of capture. Recently, however, there are papers which describes various aspects of the build-up of a CCS infrastructure [5, 6, 7, 8], indicating the importance of illustrating a pathway for implementing CCS. This paper adds to these works investigating several countries, i.e. making a first assessment in each country's specific prerequisites for CCS to develop different CCS systems. This paper is restricted to a domestic analysis for each country but ongoing work also addresses transnational systems. Output from a techno-economic modeling work of the power sector, which gives the role of CCS as part of an overall mitigation portfolio for each member state is used as input (CO_2 flow over time) for this work. In this first study, six European countries are chosen for the analysis: Belgium, the Czech Republic, Germany, the Netherlands, Poland and the Slovak Republic. In total these countries emitted 1,625 Mt CO_2 in 2007. Excluding emissions from the transport sector and other sectors not relevant for CCS[2], CO_2 emissions reached 1,090 Mt in 2007 [3]. The six countries have been chosen since they have substantial coal based power generation, the geographical distribution of sources and sinks will provide different solutions for a domestically based CCS system and, for some of the countries such as the Czech Republic, Poland and the Slovak Republic, it may be difficult to deploy a non-domestic CCS system if onshore storage of CO_2 proves difficult to achieve. The paper also calculates and compares the cost of various CO_2 transport options within each

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[1] The Commission has granted € 1 billion to six large scale CCS demo plants as part of the EERP (European Economic Recovery Plan) while the NER program (New Entrants Reserve) will allocate the income from sale of 300 million emission allowances in the ETS (Emission Trading Scheme) to innovative renewable projects and large scale CCS demo plants. One single CCS plant can get up to 50% of required investments covered by the EU through these two programs.

[2] Not relevant sectors here defined as commercial/institutional, residential, agriculture, forestry, fishery, fugitive emissions, solvent and product use, waste and other not specified sources, see [3].

country to i) illustrate the requirement for a diversified approach within different countries and ii) analyze the cost effectiveness in a centralized system across several sectors.

2. Methodology and assumptions

2.1 Power sector

The investigated region contains more than 440 coal based and 200 lignite based power generation units with a combined capacity of almost 100 GWe and with total CO_2-emissions reaching almost 500 Mt in 2007. Chalmers Electricity Investment model (ELIN) is used to investigate the build-up of CCS within the power generation sector between now and 2050 and where CCS is assumed to be commercially available from 2020. ELIN combines information on the existing power plant stock from the Chalmers Energy Infrastructure Database with a techno-economic optimization of investment in new electricity generation to meet exogenously defined demand for electricity[3]. Thus, the evolution of the power sector over time with respect to fuel and technology mix is provided, given boundary conditions on for instance CO_2 emissions, contribution of renewables and efficiency targets. The model includes differentiated costs on transport and storage of CO_2 as described in [9] as well as major limitations in cross border transmission capacity, but can choose to invest in new lines when profitable. The development of the electricity generation in the six countries in this work is taken from modeling the entire EU-27, applying a scenario which assumes targeted policies on GHG emission reductions, energy efficiency and RES based energy to be successfully implemented [9]. For this scenario, the electricity sector is modeled based on a CO_2 emission reduction target of 40% in 2020 and 85% in 2050 (relative to year 1990). The share of renewables is assumed to reach 30% of total generation in 2020 and 45% in 2050 while the effect of efficiency improvements leads to a modest growth in demand; from 3,070 TWhe in 2003 to 3,860 TWhe in 2050, or by 0.5% per annum on average reflecting EU's ambitions to implement energy efficiency improvements. Nuclear generation is assumed to be phased out in Belgium and Germany[4] and maintained at current level in other member states in line with existing policies while lignite *production* (not generation due to the effect of capture and efficiency improvements) is assumed to stay at current levels throughout the period. ELIN provides marginal cost of electricity and marginal cost of CO_2 abatement, i.e. corresponding to the CO_2 emission price within the EU ETS. The resulting CO_2 price may be used as a benchmark to introduce build-up of CCS in the industry sectors[5]. Finally, ELIN provides installed CCS based capacity and CCS based generation by fuel (gas, coal and lignite) as well as the annual volumes of CO_2 captured and stored by country which together with the age structure of the existing plants is used to locate the CCS plants over time and consequently also to describe the ramp-up of a CCS infrastructure within the power sector in the six selected countries mentioned above[6]. The development of the electricity generation for EU-27 is given in [11].

2.2 Industry

In the region, there are more than 100 industrial units (cement, steel and refineries) with annual emissions of at least 0.5 Mt. In 2007 combined CO_2-emissions from these industry sources reached 162 Mt. CCS in the three industry sectors is assumed to start up in 2030 for all facilities within a country or, if CCS is introduced later than 2030 in the country's power sector as modeled in ELIN, assumed to follow the introduction of CCS in the power sector. This is obviously an arbitrary assumption and in reality, introduction of CCS in industry will depend on, among other things, policy measures but there is not yet much information available regarding introduction of CCS on plant level (see also Footnote 5). Also, as mentioned above, industrial CO_2 emissions may come from several

[3] For a closer description of ELIN see [9]. For a closer description of Chalmers Energy Infrastructure database see [10].

[4] In the model, the last nuclear unit is assumed to be phased out in 2025 in Belgium and in 2048 in Germany.

[5] In this study, the benchmark price for CO_2 emissions provided by ELIN has not been used to introduce CCS in the industry but it will be applied in later studies along with other relevant information.

[6] Production of brown coal from existing mines in Poland will start to decline shortly after 2020. However, the association of brown coal producers in Poland has described how brown coal production can be maintained and even expanded by development of new deposits in Legnica (deposits Legnica West, Legnica East and Legnica-Ścinawa-Głogów) and in Gubin (the Gubin-Mosty-Brody deposit). Additionally, there are 450 Mt that can be exploited by the Belchatow plant (Zloczew deposit) and almost 1.2 Gt that can be exploited by the Adamow, Konin, Patnow and Turow plants [12, 13]. The largest Polish generator, the state-owned PGE and owner of the Belchatow plant, is currently investigating all these sites [13] while Enea (reportedly together with Vattenfall) is looking at the possibilities to construct a 800 MW lignite fired power station in Gubin [14]. This may imply that some of the new CCS plants after 2030 may be relocated to the new deposits in Legnica and Gubin.

different sources within the same facility implying that capture will be concentrated to the source with the largest share of the plant's total emissions. In this paper it has been assumed 90% capture rate on 65% of total emissions in refineries and steel plants and on 80% of total emissions in cement plants [4]. This also implies that further emission reductions will have to come through other solutions like various measures to raise the plant's efficiency and renewable energy.

2.3 Storage

National and site specific storage location and storage capacities have been taken from a large number of sources in addition to Chalmers Energy Infrastructure database [10] and the Gestco and GeoCapacity projects [15, 16]. In Belgium it has been assumed that 200 Mt may be stored in aquifers in the Campine basin in the northeastern parts of the country with remaining CO_2 being transported to the UK gas basin in the southern parts of the North Sea. Although [17] estimated that some 430 Mt could be stored in Belgium coal fields through ECBMR (Enhanced Coal Bed Methane Recovery) this was not mentioned in the final reports from GeoCapacity [16]. In Germany all storage has been assumed to take place in aquifers and gas fields in the North German basin. Most of the large gas fields are located in this basin and aquifers are relatively evenly distributed throughout the basin from west to east [16, 18, 19, 20]. Storage capacity in the gas fields can be calculated applying cumulative production figures as provided by [19] and other site specific parameters provided by [10]. According to [16, 18], potential German storage sites are also found in the German parts of the North Sea and in southern Germany but no site specific data has so far been released in open literature. In the Netherlands, storage is assumed to take place in the Annerveen depleted gas field just south of the Groningen gas field and in gas fields in the L-10 quadrant in the Dutch part of the North Sea [21, 22]. In Poland location of aquifers and site specific storage capacity has been taken from [23] published after the release of the final GeoCapacity reports. Finally, location of storage sites and site specific storage capacity in the Czech Republic and in the Slovak Republic have been taken from [10, 16]. Although preliminary and therefore uncertain, storage capacities in the above mentioned countries have found to be sufficient for the required storage volumes modeled in this work except in Belgium where total storage requirement between 2020 and 2050 ranges from 1,240 to 1,530 Mt.

2.4 Transport

For each country, three domestic CCS transport systems have been investigated; CCS in the power sector only (System 1), fully integrated CCS systems for the power and industry sectors (System 2) and finally, a CCS system for the three industry sectors combined (System 3). For each system, the total number of sites connected to the various systems is given along with total pipeline length and specific cost of CO_2 transport and the results have been analyzed and discussed. Each single pipeline system consists of collecting pipelines from each separate source, bulk pipelines carrying the CO_2 from many sources, dedicated reservoir pipelines (RPL) if the volume in one single bulk pipeline has to be injected into several reservoirs and injection pipelines (IPL) based on anticipated reservoir injection rate. In this paper, the injection rate has been set to 1 Mtpa per well. No RPLs were needed in the Czech Republic, Poland and Slovakia due to the low storage volumes and/or the geographical distribution of sources and sinks. In the Netherlands, RPLs were assumed to carry 10 Mtpa over 5 km while in Belgium the corresponding pipelines were set to carry 10 Mtpa over 10 km, mainly due to the much larger CO_2 volumes in Belgium which probably will require more storage sites. In Germany, the RPLs were also assumed to transport 10 Mtpa but the length was calculated specifically for each RPL based on a provisional distribution of storage sites from west to east in the middle of the North German Basin on a north-south axis as illustrated in Figure 1. All pipeline segments have been sized based on segment plateau capacity using Darcy's general equation for pressure loss and applying a correction factor derived from comparison with the simulation software HYSYS. A terrain factor of 1.2 has been applied on all onshore pipelines while the terrain factor was set to 1.1 for offshore pipelines. Pipeline investment costs have been taken from IEA [24] scaled up by a factor 1.522 based on IHS CERA's Downstream Capital Cost Index (DCCI) from quarter 1, 2010 and relative to year 2004. Investment costs and electricity consumption for pumps have been calculated based on equations from [25] assuming a minimum and maximum pressure for onshore pipelines of 86 and 120 bars, respectively [26, 27] while minimum pressure in offshore pipelines was set to 70 bars [28]. The annual transported CO_2-flow from the power sector follows the CO_2-flow modeled in ELIN while the annual flow from the industry follows the assumptions specified in Section 2.2. However, all pipelines are designed for plateau flow already from the start. Economic lifetime has been taken as 20 years for all investments. All investments have thereafter been annuitized over 20 years with 8% discount rate. The rest value in 2051 for investments acquired after 2031 has not been included in the cost calculations. Cost of electricity has been set to € 0.056/kWh as provided by ELIN. All costs are given in 2010 Euros (€).

3. Results and discussions

The power generation sector in EU captures and stores 15.2 Gt CO_2 between 2020 and 2050. In the six countries investigated in this report, capture starts at 24 Mt in 2020 increasing six-fold to 150 Mt in 2031, to almost 310 Mt in 2040 and 435 Mt in 2050. Cumulative some 7.2 Gt is captured, transported and stored in the power sector in the six countries up to 2051. In the Czech Republic, Poland and the Slovak Republic, capture is only initiated on lignite plants according to the modeling results from ELIN. In addition to the CO_2 captured in the power sector, 1.8 Gt is assumed captured and stored in the three industry sectors. Table 1 gives the cumulative amount of CO_2 stored by country and by system, the number of connected capture sites, the total length of the various pipeline systems and the specific cost for transport of CO_2.

Table 1: No of capture sites, cumulative CO2 stored, pipeline length and specific cost of CO_2 transport for systems 1, 2 and 3

	System 1 (Power Sector only)				System 2 (Integrated Power + Industry)				System 3 (Industry only)			
	No of sites	CO2 Stored Mt	PL Length km	Spec. Cost €/t CO2	No of sites	CO2 Stored Mt	PL Length km	Spec. Cost €/t CO2	No of sites	CO2 Stored Mt	PL Length km	Spec. Cost €/t CO2
Belgium	6	1243	697	2.37	21	1527	944	4.53	15	284	440	15.94
Czech Rep.	4	675	165	1.00	12	788	395	1.18	8	113	231	2.30
Germany	18	3472	2306	2.73	67	4448	4648	3.23	49	849	2717	6.09
Netherland	4	456	425	4.06	9	600	433	3.63	5	144	212	4.68
Poland	5	1281	485	1.48	19	1570	1498	2.00	14	290	1074	4.44
Slovak Rep.	1	70	92	2.52	6	247	234	1.84	5	176	200	1.62

For the power sector (System 1), transport costs range from € 1.0 to € 4.1 per ton in the Czech Republic and in the Netherlands respectively. The low costs in the Czech Republic are mainly due to a favourable distribution of sources and sinks while the high costs in the Netherlands are caused by the fact that a substantial part of the system is offshore. Compared to a previous study by the authors on a similar system for the power sector in Germany [29] costs are similar ranging from around € 2.7 to € 2.8 per ton in the two studies. McKinsey [5] estimated transport costs to between € 4 and € 6 per ton for onshore and offshore transport respectively but these were relatively simple transport schemes based on standard pipeline lengths of 200 km onshore and 300 km offshore transporting CO_2 from three 900 MW coal-fuelled power plants[7].

Transport costs are generally higher for System 2 compared to System 1 as a consequence of the lower CO_2-volumes being captured at industrial sites. This is however not the case in the Netherlands and in the Slovak Republic. In the Netherlands, the industrial sources are so close to the existing system already designed for the power sector that there is only a marginal addition in total pipeline length while at the same time the transported volume increases substantially. Additionally, pipeline Systems 2 and 3 have a shorter offshore section (around 60 km) starting from Corus steel in Ijmuiden as opposed to System 1 where the offshore section starts from Rotterdam. In the Slovak Republic, the industrial sites have large emissions and are located close to the storage sites.

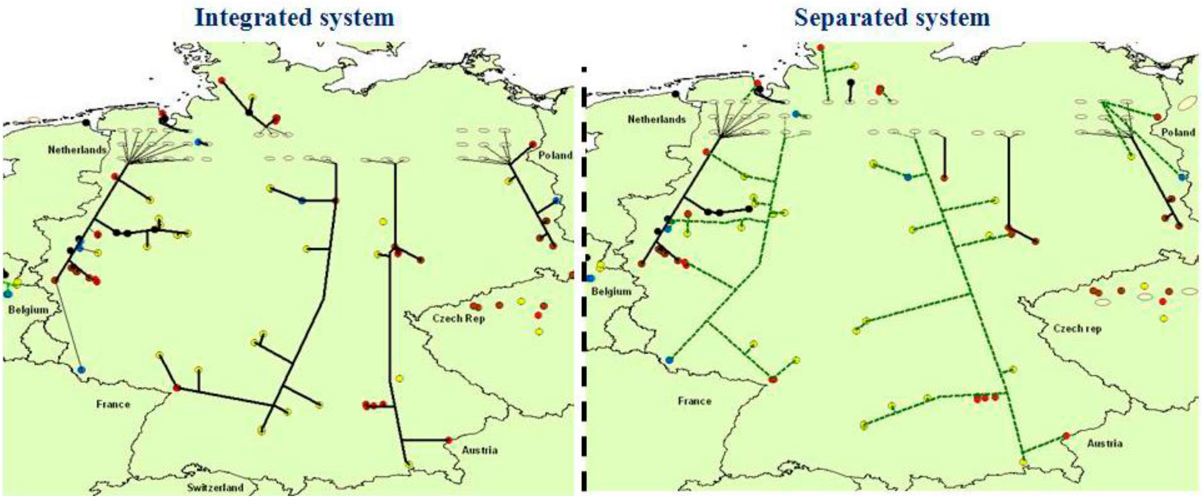
Transport costs are considerably higher for System 3 for one main reason; the average volume captured and transported per capture site is reduced further compared to System 2. Applying System 3 in Belgium, increase costs almost six times compared to System 1 (power sector only) and by 250% compared to System 2 (shared system power + industry). The reason for this is a combination of many small industrial emitters, long transport distances and the need for offshore transport.

Comparing specific cost in the three systems, in most countries there seems to be little to gain for the power sector by integrating transport network between the power and industry sectors, at least for the costs applied in the

[7] McKinsey [5] also claims that transport cost would benefit from scale and network effects once CCS is more broadly rolled out and that this would act to offset the likely increase of average transport distances.

ELIN modeling with CCS at lignite based power plants preferred over CCS at coal plants. The opposite is of course the case for the industry sectors and a combined pipeline system for several sectors would also cause less impact on the surroundings. However, and as already mentioned, the geographical distribution of sources and sinks in the Czech Republic, Poland and the Slovak Republic is such that there are very few pipelines for which there is anything to gain by a shared system between the two sectors. Also, the number of capture sites is considerably higher in Systems 2 and 3 than in System 1, which certainly will make it even more challenging to achieve integrated systems across several sectors. The length of the various pipeline systems ranges from 90 km in System 1 in the Slovak Republic to 4,600 km in System 2 in Germany. As a comparison it can be mentioned that the four German gas importers in 2006 had a combined natural gas pipeline net of 23,000 km [30].

The single most decisive factor affecting the design of the various pipeline systems is the phasing in of capture plants over time, i.e. which plants that will apply capture, what volumes that will be captured at each individual site and when capture will be implemented on each individual site. The less the number of potential sites and actors, the easier it will be to design a system in advance and to achieve a centralized system. In this paper it has been assumed that all sources that eventually will connect to a system over time is known in advance which will minimize pipeline length and therefore also impact on the surroundings under any given storage scheme. Such a system will also be "overdesigned", i.e. the system will be utilized at less than full capacity over a number of years until all relevant sources have been connected. While the first factor will drive down cost the second factor will raise cost. In previous work by the authors, the cost for bulk pipelines was compared with the cost for smaller pipelines under a ramp-up of 10 years, i.e. the bulk pipeline is gradually reaching full capacity over a period of 10 years as opposed to smaller pipelines being built as the system requirements expand. The previous work clearly showed that bulk pipelines would be the most cost efficient solution [31]. A factor that may facilitate centralized pipeline systems in the power sector is the ownership concentration geographically which is apparent in all countries investigated in this study. Ownership concentration is not at all equally apparent in the industry. Figure 1 shows pipeline Systems 2 and 3 in Germany, i.e. a combined transport system for the power sector and the industry (Figure 1a) and a separated system (Figure 1b).



a b

Figure 1: The CO_2 transportation and storage system in Germany in the case of a) a fully integrated network between the power and industry sectors (System 2) and b) a separated system, i.e. one system for the power sector and one system for the three industry sectors (System 3). In b) the pipelines connecting industrial sources are shown as green dotted lines while the pipelines connecting power plants are shown as black lines. Power plants are shown as black (coal) and brown (lignite) circles while refineries are shown as red, cement plants as yellow and steel plants as blue circles. The yellow ellipses illustrate possible location of storage sites in the North German basin.

Assuming that onshore storage will be difficult to implement or that actual storage capacity in countries like the Czech Republic, Poland and the Slovak Republic is considerably less than what has been estimated, it will be costly to find alternatives. Belchatow lignite power plant in Poland emitting almost 31 Mt CO_2 in 2008 will require a 1,000 km long pipeline across Germany and the Netherlands and then another 150 km offshore pipeline before reaching the southern gas basin in the UK part of the North Sea. Similarly, US Steel's facility in Kozice, Slovakia which emitted 9.7 Mt CO_2 in 2007 will require a pipeline of around 1,200 km before reaching the west coast of the Netherlands while Prunerov and Pocerady lignite plants in the Czech Republic, each emitting between 6 to 7 Mt CO_2 per year, will require a pipeline of more than 600 km. The large lignite plants in eastern Germany will require pipelines of more than 650 km before reaching the Dutch west coast. Assuming instead storage in the Norwegian part of the North Sea, the offshore section of the pipeline would be anything between 400 to 700 km long. Therefore, a closer alternative for these countries would be to identify suitable reservoirs in the Baltic Sea. The power sector alone in the Czech Republic, Poland and the Slovak Republic emitted 235 Mt CO_2 in 2007 [3] and at least Poland is planning for a continued use of its lignite resources both up to and beyond 2050 (see for instance Footnote 6) while the Czech Republic prepares for coal consumption at least up to 2030[8] [32]. This cannot be done without CCS if long-term emission reduction goals are to be met.

4. Conclusions

The build-up of a CCS transportation infrastructure in six European countries have been analyzed and discussed for three different domestically based CCS systems transporting in total between 1.8 and 9.0 Gt CO_2 up to 2050 of which 7.2 Gt from the power sector and 1.8 Gt from the industry sector.

Specific transport cost for the power sector only (System 1) is estimated to range from € 1.0/ton CO_2 in the Czech Republic to € 4.06/ton in the Netherlands. The low cost in the Czech Republic are mainly caused by favorable distribution of storage sites relative to capture sites while the high cost in the Netherlands are related mainly to the requirement of offshore transport. Adding industrial sources to the system increases specific transport cost in all cases apart from in the Netherlands where specific cost decreased from € 4.1 to € 3.6 per ton. The reason for this is that the lower volumes being captured at industrial sites drive cost upwards. Comparing transport systems 2 and 3 there seems to be little to gain for the power sector on an integrated network for the power and industry sectors. The main reason for this is the geographical distribution of sources and sinks and that the industry sources generally account for a minor share of the total CO_2-volume being transported. The single most decisive factor affecting the various pipeline systems is the phasing in of capture plants over time while a factor that may facilitate centralized pipeline systems in the power sector is the ownership concentration which currently is substantial in all the countries investigated, except for the Netherlands. If onshore storage proves difficult or if countries like the Czech Republic, Poland and the Slovak Republic have less storage capacity than anticipated, these countries may conclude that CCS is not an economically feasible option for emission reductions simply because of the long transport distance to alternative storage sites.

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