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Embedding CCS infrastructure into the European electricity system: A policy coordination problem

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Abstract:
Carbon dioxide capture and storage (CCS) has recently been receiving increasing recognition in policy debates. Various aspects of possible regulatory frameworks for its implementation are beginning to be discussed in Europe. One of the issues associated with the wide use of CCS is that it requires the establishment of a carbon dioxide (CO_2) transport network, which could result in the spatial restructuring of power generation and transmission systems. This poses a significant coordination problem necessitating public planning and regulation. This paper reviews the recent literature on energy system modeling pertaining to the problem of installing CCS-related infrastructure throughout Europe and also discusses the policy issues that need to be addressed for a potential wide implementation of CCS in the next decades.

Keywords: CCS (carbon dioxide capture and storage), the European Union, climate policy, energy system models, cost effectiveness

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1. Introduction

Since the publication of the IPCC Special Report in 2005, carbon dioxide capture and storage (CCS) increasingly attracted policymakers' attention due to its potential as a major option to reduce carbon dioxide emissions in the next decades. This recognition is supported by a few recent leading studies of climate change policy (Pacala and Socolow, 2004; Lackner and Sachs, 2005; Stern, 2006). A recent IEA report (2008a) also estimates that a substantial proportion of long-term CO_2 emission reduction is ascribed to CCS. In some regions of the world, where climate policy is already in place, such as Europe, policy debates are beginning to look at practical issues of CCS's deployment should it be embedded into the energy system in the near future.

An essential perspective for understanding CCS policy debates is that they are built on mixed views on this technology. On the one hand, CCS is not a fully established technology yet – particularly, no demonstration has yet verified the viability of carbon dioxide (CO_2) storage in underground reservoirs over decades or longer. This is the most important concern held by the critics of this technology. In this sense, all long-term assessments of CCS lack solid factual foundations. On the other hand, it is relatively easy to find some positive evidence of the viability of long-term CO_2 storage. The positive information includes the general knowledge of geology about some mechanisms that could seal gas in selected geological structures (trapping), the existence of a range of geological analogues and element technologies (e.g., geologically stable oil and gas fields, natural gas storage, gas pipeline, and gas separation techniques), and the experiences made by demonstration projects[3], such as the Sleipner project in Norway, or the

[3] A list of demonstration projects is available at the ZEP ETP website (http://ec.europa.eu/environment/climat/ccs/docs_en.htm).

practices of enhanced oil recovery (EOR), which have existed since the 1960s. With these pieces of information, along with other reasoning, many now think that CCS could technically handle a substantial proportion of human carbon dioxide emissions over the next decades. However, uncertainty is still rampant with regard to effectiveness, safety, and future cost level (including efficiency), not to mention the public perception on this technology, which is yet to be formed. Therefore, in the policy debates, CCS tends to be regarded not as the ultimate solution to the climate change problem but as a "bridge technology" to an energy system based on more revolutionary alternatives. In presence of the mixed views, the tentative position taken by policymakers could be summarized by de Coninck et al.'s (2009) aptly phrased statement that at the moment "there are no compelling scientific, technical, legal, or economic reasons why CCS could not be widely deployed" in the future.

Policy discussions of CCS need to be construed as a reflection of such mixed prospects regarding this technology. Despite this unclear character of CCS, however, policy discussions are already shifting towards practical considerations because of the long time horizon associated with investment in CCS research and development activities and its deployment. An aspect that has become evident throughout the policy discussions of CCS is that its implementation should be preceded by massive investment in relevant infrastructure, especially in CO_2 transport pipelines, the potentially dominant mode of CO_2 transport in CCS operations. It is worth noting that pipeline installation, while principally conducted by private firms, poses a problem of network externality. It is efficient for multiple CCS operators to share CO_2 pipelines, but due to the spatial complexity of the network (upstream-downstream structure) the private market cannot find the efficient pricing levels of pipeline use, and by extension, the socially optimal structure of pipeline network. When coupled with other externalities, such as the externality of research and development and the carbon (climate change) externality, the externality problem of pipeline network design poses a substantial need for coordination – this is, in fact, a problem that needs a public solution.

In this article we review the recent literature on the installation of infrastructure for CCS. We mostly refer to studies of numerical modeling with a cost minimization approach (spatially or one-dimensional) for either CCS use or CO_2 pipeline installation, but we also pay attention to the context of the problem within the entire system of electricity supply and regulation. Indeed, the installation of CCS transport infrastructure is not only a question of technical or economic feasibility but one subjected to various external factors, such as emission targets, environmental safety regulation regarding transport and storage, and the (economic) regulatory system of electricity markets, each of which has both national and international dimensions. We primarily consider the context of Europe (more specifically, the European Union, EU, plus Norway), which is at the forefront of policy debates on this issue. However, the general lessons should essentially be the same in other regions and countries as well. In this way, it is meant to not only summarize recent academic contributions but also provide guidance on a policy question that is expected to be more prominent in the coming years. The paper is organized as follows. In Section 2 we summarize the currently emerging regulatory schemes within the EU regarding CCS and CO_2 transport. In Section 3 we review scenario analyses on future CCS deployment throughout Europe as well as factors that influence it, namely CCS system cost, storage potentials, emissions and energy mixes. Moreover, we review the findings of numerical modeling studies that deal with optimizing the installation of CCS infrastructure in Europe. Section 4 sketches the necessary perspectives for policy discussions of the CO_2 transport issue in Europe. Section 5 concludes.

2. CCS in the EU: Developing a regulatory framework

With the growing recognition of CCS as a potentially important mitigation option, policymakers are beginning to pay attention to possible policy frameworks in order to legalize and regulate CCS operations. This section reflects on recently emerging regulatory schemes on CCS, which mirror the mixed positive and negative prospects with regard to this technology, as mentioned in Section 1.

CCS is beginning to be included in policies as a recognized mitigation option, but the establishment of a regulatory framework for its deployment involves some difficult issues. One difficulty is the complexity of jurisdictions regarding CCS operations. Each process of CCS - capture, transport, and storage –touches specific legal issues that necessitate different types of regulation. As a response to the issue of regulatory coherence, the EU drafted a legal framework dedicated to CCS in 2007, which is an attempt followed by that of the US and Australia (Kerr et al., 2009). In June 2009, the EU enacted the Directive 2009/31/EC on the geological storage of carbon dioxide (CCS Directive) as part of the EU Climate and Energy package. The CCS Directive determines the processes of CO_2 storage in geological formations to guarantee environmental safety, but it also includes provisions for the processes of capture and transport. As for storage, the Directive includes, inter alia, regulations on storage site assessment, selection and permitting process, monitoring and reporting requirements, long-term responsibilities after storage site closure and on liability for leakages[4] (IEA, 2008). It is important to note that the Member States (MSs) have the right to decide whether they allow for storage within their

4 Leakage is regulated according to Directive 2009/29/EC (ETS Directive), which ensures the inclusion of CCS into the EU ETS: emissions that are captured, transported, and securely stored have to be considered as not emitted – otherwise ETS allowances have to be surrendered.

territory or not (Article 4 (1)). In addition to those specific storage regulations, the CCS Directive guarantees third-party access to transport networks and storage facilities in order to prevent competitive distortions in the electricity and heat market (Article 21).[5] This becomes particularly important when a potential regional transport network expands and transboundary issues (such as transport between two MSs) arise. In this case, provisions are required to enable MSs to cope with those issues in a harmonized way. The Directive also states that an operation of enhanced hydrocarbon recovery (which includes EOR) is subject to the Directive only if geological CO_2 storage is simultaneously pursued. It also amends six other Directives and one Regulation[6] in order to account for and to facilitate the whole process of CCS (EU, 2009a).

In fact, some of these amendments include processes of CCS, whilst others exclude it from their scope. For example, the amendments of the Environmental Impact Assessment (EIA) Directive and of the Regulation on Shipments of Waste are concerned with the process of transporting CO_2 for the purpose of geological storage. While the EIA Directive regards CO_2 pipelines of over 8mm diameter and over 40km length as significantly affecting the environment and, therefore, demands a mandatory EIA for them, the Regulation on Shipments of Waste, which determines

5 Depending on the CO_2 price and costs for CCS, access to transport networks and storage facilities could become a precondition for market entry.

6 Council Directive 85/337/EEC (Environmental Impact Assessment Directive), European and Council Directives 2000/60/EC (EU Water Framework Directive), 2001/80/EC (Large Combustion Plants Directive), 2004/35/EC (Environmental Liability Directive), 2006/12/EC (Waste Directive), 2008/1/EC (Integrated Pollution Prevention and Control Directive) and Regulation (EC) No 1013/2006 (Regulation on shipments of waste). In addition, the European Commission is currently finishing an amendment to Directive 2007/589/EC in order to ensure uniform monitoring of captured CO_2 across Europe (http://europa.eu /rapid/press ReleasesAction.do?reference=MEX/ 10/0608& type= HTML).

the supervision and control procedures for the shipment of waste, excludes the transport of CO_2 from its scope.

Individual MSs have to transpose the CCS Directive into national law by June 2011. At present, the process of drafting national legislation is underway in most MSs, but not complete. For example, in June 2009 the German Parliament sought to pass an act[7] for the deployment of CCS, which included provisions for each CCS process. However, a consensus on the draft act was not reached. By the end of this year, the German Parliament plans to vote on a new draft jointly proposed by the Federal Ministries of Economics and Environment, which only legalizes demonstration projects and entails a comprehensive review in 2017 about the viability of commercial-scale CCS (BMU, 2010). Another example is the UK's CCS regulatory framework. The regulations on offshore storage were already clarified by the Energy Act of 2008, but the governmental funding for demonstration projects was only provided two years later by the Energy Act of 2010. Both examples illustrate the difficulties in setting up a comprehensive regulatory framework for CCS and reflect the ambivalence towards CCS as a not yet fully established technology. Still, the regulatory issue exists as a present policy problem since development of energy infrastructure necessitates a future-oriented perspective given the long lifetime of power plants as well as the long time span of the design and construction of plants.

3. Deployment of CCS in Europe: Existing estimates

The idea of CCS's potentially significant use in the future is closely related to the perceived need of climate stabilization. The European Union states that the increase of global average surface temperature should be kept within 2°C compared to the pre-industrial level, and in fact, as

[7] "Gesetz zur Regelung von Abscheidung, Transport und dauerhafter Speicherung von Kohlendioxid" (CO_2 ATSG).

observed in the Copenhagen Accord, this 2°C benchmark is also becoming a global policy consensus. This target, however, means a substantial tightening of climate policy for Europe throughout the next decades; to a level of 60-80% reduction of greenhouse gas emissions in relation to 1990 by mid-century for developed countries (EC, 2007). With this recognition, the European Commission has agreed upon the unilateral emission target of 20% emission reduction by 2020, with which the carbon price in Europe could easily reach 50 EUR per ton CO_2 or higher, as a recent comparison of integrated assessment models confirms (Böhringer et al., 2009) – this level of carbon price would justify a variety of new mitigation options including CCS. Indeed, a recent IEA analysis (2008a) estimates that CCS would be used extensively as an option of CO_2 emission reduction if the worldwide emissions are halved by 2050 (the BLUE scenarios).

3.1 Overview of cost estimates for the individual components of the CCS system

This section presents an overview of the cost related to the three key components of a CCS system, namely capture (including compression), transport, and storage (including benefits from EOR). Over the past years a number of CCS cost studies have been conducted (e.g. Anderson and Newell, 2004; IPCC, 2005; Davison, 2007; Rubin et al., 2007; Hadjipaschalis et al., 2008; Giovanni and Richards, 2010). Most of the cost studies focus solely on capture, excluding transport and storage costs from their calculations, although these components should be added to the total costs of a CCS system. Capture costs are mostly expressed as CO_2 avoidance costs (cost/t CO_2 avoided)[8], whereas transport and storage costs are often expressed as costs per ton of CO_2 transported and stored, respectively. The total cost of employing a full CCS system is

[8] Capture costs can also be expressed as costs per ton CO_2 captured or as the costs of electricity (COE). This has to be taken into account when comparing and aggregating cost estimates (IEA, 2008b).

dominated by the cost of capture (IPCC, 2005). According to the results from the GESTCO project, which aggregates cost estimates derived from 17 European case studies, the capture cost (including compression) amounts to 78% of the average total CCS costs, which are estimated to be 54 EUR/t CO_2 (Fischedick et al.; 2007, see also Figure 1).

(Insert Figure 1 here)

3.1.1. Capture costs

Capture costs are determined by three factors: additional required gross power capacity, capture equipment, and additional fuel costs. This results in additional investment costs for coal-fired power plants with carbon capture technology compared to a plant without it. These additional investment costs range between 50% and 100% (US$ 600/kW to US$ 1700/kW), depending on the type of power plant (IEA, 2008b). Depending on the assumptions made in the respective cost studies, e.g. on generating technology, capture technology, and fuel price, CO_2 avoidance costs (US$/t CO_2) vary significantly (see Table 1).

(Insert Table 1 here)

3.1.2. Transportation costs

Captured CO_2 can be transported via pipelines, ships or road tankers. In practice, only pipeline and ship transport are cost-effective options due to the high volumes involved in commercial-scale CCS operations (IEA, 2004). According to IPCC (2005), pipelines are the most cost-effective option for transporting large quantities of CO_2 up to distances of 1,000km for offshore pipelines and of 1,600km for onshore pipelines transporting 6 Mt CO_2 per year.[9] Svensson et al. (2004) also argue that pipelines are the only cost-effective means of CO_2 transport onshore, whereas water carriers might be also cost-effective for offshore transport. In the context of CCS applications within Europe, only pipelines would therefore be relevant from the standpoint of cost effectiveness.

Pipeline transportation costs can be divided into the costs for construction, operation and maintenance, and other costs, such as right-of-way-costs. Pipeline material costs depend e.g. on the length and the diameter of the pipeline, and on the amount of CO_2 to be transported (IPCC, 2005). The maximum possible flow of CO_2 increases more than proportionally to the pipeline diameter, which crucially influences transportation costs. Table 2 gives an overview of pipeline transportation cost estimates for different assumptions on distance and mass flow rates. Pipeline transportation costs also depend on the geography of the land, which is characterized by the population density, mountains, natural reserves, physical obstacles such as rivers and highways, as well as land use patterns. Offshore pipelines can be 40 to 70% more expensive than onshore pipelines (IPCC, 2005).

(Insert Table 2 here)

[9] Costs increase linearly with the distance for pipeline transport while they increase less than proportionally to the traveling distance for ship transport. Therefore, transport by ship is the most cost-effective option for distances over 1600km.

3.1.3. Storage costs

Storage costs include capital expenditures for drilling and surface facilities as well as operational expenditures for maintenance and monitoring. The main determinants of the level of costs are storage option, location, depth, and other characteristics of the storage reservoir (IPCC, 2005). Offshore costs, approximated by costs for offshore drilling of oil and gas wells, can be four times as high as onshore costs, even in shallow waters, and would be even higher in deeper waters. One option is to store CO_2 in connection with enhanced oil recovery (EOR), which could be particularly relevant to the North Sea because of its proximity to large anthropogenic CO_2 sources and oil fields. The revenues from EOR operations depend on the oil price, the price of CO_2, and the injection rate of CO_2, but also on the time frame of its implementation and the condition of the existing infrastructure (IEA, 2008b). A summary table of storage cost estimates for CCS deployed in Europe including EOR is found in Table 3. Note that the cost of oil and upstream operations such as drilling, completion and production rose significantly between 2000 and 2007, i.e. the cost index approximately doubled due to an increase in material prices and a shortage in material (IEA, 2008b). In this sense, the listed figures might be upwardly rescaled with the latest price indices.

(Insert Table 3 here)

3.2 Scope of CCS deployment in Europe

Here, we discuss a few aspects that may influence the regional distribution of CCS utilization in Europe, namely, the potential storage capacity in a country, its share of coal and lignite in the power generation mix, and its CO_2 emissions from the power generation sector.

3.2.1. Storage potentials in Europe

IPCC (2005) documents various estimates of the global and regional potential for CO_2 storage in geological formations. This comprises storage in oil and gas reservoirs, unmineable coal seams, and deep saline formations, which seem to be the best options for CO_2 storage in the medium term (IEA, 2008b). For Europe, the studies taken into account in the IPCC Special Report include Holloway (1996) and Wildenborg et al. (2005). As a more recent attempt of estimation by the EU, the GeoCapacity project (GeoCapacity, 2010) extends and updates the data provided by an earlier assessment, the GESTCO project (Christensen and Holloway, 2004).[10]

Conservative estimates for storage capacities across Europe provided by the GeoCapacity project are: 20 gigatons (Gt) CO_2 in depleted hydrocarbon fields, 1 Gt CO_2 in unmineable coal beds, and 96 Gt CO_2 in deep saline aquifers. These estimates are lower or in the lower range of those sampled by IPCC (2005). 25% of Europe's total storage capacity is located offshore from Norway, mainly in deep saline aquifers. Following Norway, the largest storage capacities are located in Germany (17.1 Gt), United Kingdom (14.4 Gt), Spain (14.2 Gt), Romania (9 Gt), and

[10] GeoCapacity widens the group of countries for which the storage potential is estimated and updates the GESTCO data for some countries (UK, Denmark, Germany, Netherlands, France, Greece). Some of the figures presented in the GeoCapacity report have not been updated but taken from the GESTCO project and adjusted to create conservative estimates (Norway and Belgium). Details can be found in the GeoCapacity reports.

France (8.7 Gt). Together, these six countries comprise 64% of the total potential storage capacity of CO_2 in Europe (GeoCapapcity, 2010). Note that the reported storage capacities are still subject to large uncertainties, particularly those located offshore. To manage the problem of uncertainty, the conservative estimates by the GeoCapacity project apply large discounts to offshore storage sites, e.g. in the North Sea (GeoCapacity, 2009).

3.2.2. Power generation mixes, CO_2 emissions, and emission reduction targets

As CCS is so far mostly considered in the context of combined use with a coal-fired power generation system, it might correspond to the circumstances of some EU Member States where a high share of electricity production is coal-based. Countries with a major share of coal and lignite in their electricity generation mix are Estonia (93.7%), Poland (91.4%), Czech Republic (61%), Greece (54.6%), Bulgaria (51.7%), and Denmark (50.8%) (EEA, 2010a). However, the majority of CO_2 emissions from power generation are found in other countries. In 2005, the top six emitters were Germany (325Mt CO_2), UK (173Mt CO_2), Poland (169 Mt CO_2), Italy (120 Mt CO_2), Spain (110 Mt CO_2), and the Czech Republic (62.4Mt CO_2), altogether accounting for 70% of all CO_2 emissions in the power generation sector in the EU27 (EEA, 2010b). In addition to the current emissions, the stringency of European climate policy and the distributions of reduction requirements among European countries are likely to influence the future deployment of CCS. As an example, Poland is likely to deploy CCS in the future due to its high share of coal and lignite in power generation and high absolute emissions, although it will be allowed to emit 14% more greenhouse gases in 2020 compared to 2005 (EU, 2009b).

(Insert Figure 2 here)

The distribution of CO_2 emission sources and potential storage sites throughout Europe can be inferred from Figure 2. Regional heterogeneity with respect to storage capacities and electricity generation mixes implies that cross-border transport of CO_2 is likely to happen and may indeed improve the cost-effectiveness of CCS in Europe. This also highlights the necessity for cooperation within Europe to establish the necessary infrastructure and effectively employ CCS in the future.

3.2.3. Scenario analyses of CCS's utilization in Europe

A number of studies conduct a modeling analysis regarding CCS's future deployment, and a couple them specifically analyze Europe. Energy system models estimate the future share of power generation (or other energy uses) equipped with CCS, utilizing cost minimization calculations including different power generation techniques and some emission reduction policies. These models have different assumptions in terms of the cost structure of power generation techniques, including CCS, of socioeconomic projections, and of regional and sectoral decompositions. Therefore their results differ. However, most of the results share a common view: Regarding CCS's future deployment, they agree that a significant, though not dominant, proportion of power generation will be CCS-equipped in the next decades – and provided that CCS's technical capacity and institutional frameworks are established, the studies hint that, to some extent, CCS could be operated in a cost-effective fashion from the next decade onward. Many of these modeling studies are either global or country-based (major studies include the following: Ha-Duong and Keith, 2003; Riahi et al., 2004; Smekens and van der Zwaan, 2006;

Gerlagh and van der Zwaan, 2006; Gilotte and Bosetti, 2007; MIT, 2007; van der Zwaan and Gerlagh, 2008; Keller et al., 2008), but a small number of regional analyses for Europe also exist.

Van der Zwaan and Smekens (2009) employ the bottom-up energy model MARKAL to examine long-term (up to 2100) energy system scenarios for Europe[11]. They show that under the assumption of a stringent climate stabilization target, CCS is deployed, but its scale depends on the assumed leakage rate of CO_2 from geological storage reservoirs. In most scenarios the deployment of CCS begins in 2030. Another scenario analysis study on the European energy system is the Eureletric's Power Choices. This study is based on the energy system model PRIMES and simulates the EU27 energy system up to 2050 with the 40% CO_2 emission reduction target in 2030 and 75% in 2050, both relative to the 1990 levels. They conclude that CCS will be commercially deployed from 2025 onwards, and that it should be considered as a main mitigation option of emission reduction in the long run. Capros et al. (2007) also employ the PRIMES model in order to investigate the utilization of CCS technology in the European energy system under various policy assumptions, such as the mandatory CCS deployment for fossil power plants and the targets for renewable energy along with the general emission target. They show that the deployment of CCS in 2020 is low in most scenarios due to the immaturity of the technology but increases significantly by 2030, and that CCS is eventually deployed in all their scenarios that meet an emission target. In their results most CCS activities take place in Central and Eastern Europe; Germany, Poland and Czech Republic are the largest users of CCS. Meanwhile, Odenberger and Johnsson (2010) report a different cross-country pattern of CCS use in Europe. They examine the potential contribution from CCS to reaching the EU's emission reduction target of 30% for its power generation sector by 2030 and of 85% by 2050 relative to

[11] Western Europe, including EU 15 countries, expanded by Norway, Switzerland, and Iceland.

the 1990 level. Their model includes detailed information on the existing European[12] electricity generation system such as location and age structure of power plants as well as potential storage sites. They show that the current top six CO_2 emitting MSs – Germany, Italy, the Netherlands, Poland, Spain, and the UK – are also the countries that most extensively use CCS.

3.3 Spatial optimization analyses on the size of costs required for CO_2 transport infrastructure in Europe

Taking together the estimated deployment rates of CCS and the cost estimates of CCS infrastructure, one can infer that massive investment in CCS-related infrastructure would occur throughout the next decades even if CCS's adoption remains at a modest scale relative to the total electricity production. While transport is expected to be a relatively minor cost element in the CCS system, the installation of a CO_2 pipeline network creates an especially complex coordination problem at the national or regional level, as the pipelines would be built and function most effectively when multiple relevant companies share some of the infrastructure. It should also be noted that the spatial distribution of pipelines is subject to the spatial distribution of CO_2 storage sites, which is determined based on their own cost effectiveness as well as their geological suitability. Along with the general analyses of energy system modeling mentioned above, several studies have specifically discussed the issue of building a pipeline network for CCS in a European-specific context. Hints could be drawn from these studies as to the expected scale of the pipeline installment issue in the next decades if CCS is introduced in Europe according to mainstream predictions.

[12] EU27 plus Norway.

The spatial analyses of CO_2 pipeline network are mostly based on a common framework of spatial optimization discussed by Chrysostomidisa et al. (2009). They consider two types of systems, the point-to-point and backbone pipeline systems: the former is a set of pipelines directly linking individual sources and sinks, and the latter is a system where sources and sinks are connected to short pipelines branching out from a main pipeline. They argue that the backbone pipeline system is preferable under high capacity utilization because of the shared use of the backbone line by multiple operators. They also point out that the external factor of carbon prices is a very important determinant for the optimality of the network. Consistent with the general idea of optimal design of a pipeline network, some authors attempt to develop spatial optimization methods, which are useful for cost estimations of a CCS pipeline network. Middleton and Bielicki (2009a,b) develop a numerical tool to spatially optimize the design of a CO_2 pipeline network for integrated CCS systems (Bielicki (2009) applied this approach to California). A similar attempt to build a numerical tool is Kazmierczak et al. (2009).

As a multi-country analysis of the establishment of a pipeline network in a European context, Kjärstad and Johnsson (2009) make basic estimates of CCS transport infrastructure costs (without spatial optimization of pipeline network design) up to 2050 in Germany and the UK. They estimate that 3,300 to 3,700km of pipeline would be built in Germany, while 2,200 to 2,600 km of pipeline would be built in the UK, costing 6.1 to 7.8 billion EUR for the former and 6.7 to 10.1 billion EUR for the latter. This builds upon the previous analysis of Odenberger et al. (2009), who estimate that roughly 13Gt of carbon dioxide may be processed by CCS systems between 2020 and 2050 in Northern Europe.

There are also some studies on the CCS transport issue for a single country in Europe. Van den Broek et al. (2009) investigate the future installation of CO_2 pipeline network in the Netherlands by using a combination of a geographical information system with spatial and routing functions

(ArcGIS) and an energy bottom-up model (MARKAL). While they do not report figures as to the total costs of infrastructure construction and the resultant size of CO_2 pipeline network, they do imply that the installation of pipeline network would pose a significant problem of spatial coordination, as, according to their results, CCS would, on average, contribute 13-26% to CO_2 emission reductions in the Dutch electricity and cogeneration sector by 2050. Meanwhile, Kemp and Kasim (2010) investigate the costs of CCS deployment in the UK by using a spatial optimization approach. They estimate that 1755 to 2583km of pipelines would be built for CO_2 transport by 2037, and that their capital expenditure would amount to 3.5 to 5.2 billion pounds (approximately 4.2 to 6.3 billion EUR).

So far, the most complete cost study of CCS infrastructure focusing on Europe is Morbee et al. (2010a,b), which estimates the CCS infrastructure costs through spatial optimization of pipeline routing for entire Europe with multiple time steps up to 2050. Building on Middleton and Bielicki's (2009a,b) spatial optimization approach, they realize their spatially and temporary vast estimation by limiting their computation to interactions between spatially contiguous nodes only (the k-means approach). Basing their analysis on the Eurelectric Power Choices scenario, they estimate that 18,728km of CO_2 pipeline would be built in Europe by 2050, resulting in a cumulative investment of 28.2 billion EUR until then.

While it is necessary to recognize that those analyses are produced by assuming certain predetermined portfolios of future power generation based on fairly thin empirical evidence, they can still provide some illustration of the size of problem that Europe will face. Figure 3 compares the estimated CCS infrastructure costs with a couple of reference figures. Kjärstad and Johnsson's (2009) lower estimate for the combined infrastructure costs for Germany and the UK (12.8 billion EUR) almost matches the total amount of capital expenditures (CAPEX) and net aquisition of EDF, Europe's (and in fact, the world's) largest utility company (12.4 billion EUR:

EDF, 2009). Morbee et al.'s (2010a,b) pan-European estimate is more than twice this level. Again, it is worth emphasizing that the estimates are for the transport infrastructure only, not the entire investment costs for CCS systems, let alone all other costs for maintaining the total power generation system. All the estimates of CCS infrastructure costs dwarf the EU`s current 1 billion EUR fund for demonstrations of CCS under the EU-financed framework of the European Economic Recovery Program. It is important to note that the eventual size, geographical distributions, and pace of CCS deployment are conditioned by various other factors of the European energy policy and energy market. This issue will pose a large spatial coordination problem for Europe over the next decades.

(Insert Figure 3 here)

4. Policy issues to be considered regarding installation of CCS-related infrastructure

4.1 Integrative evaluation of CCS transport pipelines with other energy infrastructures

The modeling studies of pipeline installation discussed in the previous section are essentially built on given scenarios of power generation and other socioeconomic factors besides CCS use and pipeline construction. In reality, however, the development of CCS-related infrastructure interacts with various aspects of the entire energy system, and the issue needs to be seen in this broad context.

First, the construction of coal-fired power plants in Europe peaked in the early 1970s (IEA, 2004), and, given their typical lifespan of 40-50 years, this means that a large fraction of coal-fired power plants either needs to be terminated or replaced by around 2010-2020. Provided that CCS becomes available in that time frame, location decisions should take the construction of CCS infrastructure into account. Second, the expected significant expansion of renewable electricity generation is likely to shift spatial distributions of power generation capacity and power grid capacity. For example, offshore wind farms would be sited in areas far away from load centers and where conventional power plants do not exist. These two issues imply that a wide adoption of CCS in Europe in the next decades is likely to take place alongside a spatial restructuring of power grid capacity. Indeed, the installation of CO_2 pipeline network and the spatial restructuring of power grids could to some extent substitute each other, i.e., instead of building a CO_2 pipeline, a utility company might choose to locate its power plant next to the CO_2 storage site and lay new power transmission lines. In other words, the optimization analyses discussed in Section 3 are not complete in the sense that the pipeline installation and the grid restructuring are not considered together. This possibility is briefly highlighted by Kjäarstad and Johnsson (2009) in the European context but is not investigated in depth. One attempt to carry out an integrative optimization analysis of CCS infrastructure and power grids is Newcomer and Apt (2008)[13]. They show that the distances from the power plant to the storage site, the load centre, and the fuel delivery site are all important for facility siting decisions made by private utility companies that operate CCS. A profit-maximizing utility company will locate its power plant nearer to the load center if transmission costs outweigh CO_2 piping costs and fuel delivery costs.

[13] Newcomer and Apt consider one generator with varying facility sizes in the US Midwest. Note that their analysis does not consider strategic interactions with other firms, in other words, the problem of dual spatial allocation of CO_2 pipelines and power grids could exist both as a problem of social optimality as well as of private investment decisions.

There are also other factors in infrastructure development, which concern the temporal dimension of coordination. For example, when CCS is operated as a form of EOR, the economic feasibility of these operations depends on the temporal path of oil extraction profitability, which is affected by the conditions of existing facilities as well as the future trend of oil and CO_2 prices (IEA, 2008b; Holt and Lindeberg, 2009; Gozalpour et al., 2005). Also, it should be noted that the total storage potential in geological formations, which could be as large as 117 Gt CO_2 as we showed earlier, far exceeds the annual CO_2 emissions from the European power generation sector (which could be in the range of 1.1 Gt CO_2 in 2020). Thus, the potential storage sites that are detected today will not be used all at once, but consecutively. A determinant for the temporal sequencing of storage site selection is the cost of CO_2 transport associated with those sites (IPCC, 2005); in turn, temporal decisions on storage site selection affects the allocation decisions of pipeline network as well. Note that in a general sense, storage sites are also subject to uncertainty regarding geological integrity and possibly also regarding complex ownership structures of underground spaces or sea floors.

4.2 Institutional mechanisms

In practice, the resolution of the spatial and temporal coordination problems described above depends on the design of institutional mechanisms that streamline investment decisions. A couple of authors mention potential institutional issues regarding the pipeline infrastructure for CCS in Europe. Haszeldine (2009) highlights the issue of pipeline installation as one of the technical and institutional challenges for the large-scale use of CCS. He illustrates a potential CO_2 pipeline network in the area of the North Sea basin and discusses the issue of devising appropriate contractual links between different types of entities. Meanwhile, Coleman (2009) identifies several key issues for the implementation of CCS transport infrastructure in the EU. He notes that safety would become a primary concern in constructing and operating pipelines and the pipelines would straddle the jurisdictions of various MSs of the EU. In this respect, he emphasizes the importance of establishing an EU-wide administrative organization that could identify relevant areas and oversee the implementation of CCS.

A major determinant for CCS investment decisions is the expected long-term CO_2 price trend. In Europe, this price is currently determined by the EU ETS, which will be in place at least for the next 10 years as declared by the EU's climate and energy package. However, there is uncertainty regarding the institutional structure of CO_2 markets and the CO_2 price after 2020. Thus, companies are faced with uncertainty about the CO_2 price pathway but nevertheless have to form expectations to take investment decisions. In the time of a low carbon price, firms might be struck with pessimism about future carbon prices as well and refrain from or delay large investment in CCS. Assuming that a high future CO_2 price is necessary from a societal perspective, it might be meaningful for the government to use additional incentive mechanisms to promote investment.

Another institutional factor that is relevant to the infrastructure development is the charging mechanism of CCS infrastructure, which could be shared by multiple companies. The pipeline network could be owned and operated by one or by several companies as long as they allow for non-discriminatory third-party access for its use. The corresponding pricing mechanism should be subjected to regulations that have to ensure an economically efficient pricing scheme. In fact, the design of charging mechanisms on the electricity and CCS infrastructure could influence firms' investment decisions. For example, if the charging mechanism for electricity transmission was distance-independent (the so-called postage stamp system), distance costs to the load center would be external to generators' cost-effectiveness appraisal. If the same distance-independent charging system applied to CO_2 pipelines, a profit-maximizing generator would only take into account the fuel delivery costs for its siting decision but not the distance to the storage site and to the load center.

5. Conclusion

As this paper's discussion shows, the current body of estimates indicates that CO_2 storage opportunities and the location of coal-fired power plants are spatially dispersed throughout Europe, suggesting the necessity of a region-wide CO_2 pipeline network. The analyses of CO_2 transport in Europe are still far from complete. In particular, analysis of CO_2 transport infrastructure in combination with other energy infrastructure is still lacking, at least in the European context. The reviewed studies imply that consistent policy and regional coordination would be needed to embed CCS infrastructure in a changing European electricity system. The need for spatial coordination also implies that the prohibition of CCS made by some local governments, as in the case of the State of Schleswig-Holstein in Germany, could hinder efficient CCS utilization across Europe. However, the current EU's CCS Directive leaves the decision to allow carbon storage on their territory to individual MSs and makes no provision for limiting local bans of CCS. The economic arguments reviewed in this paper suggest that such EU policy should be reconsidered. It is worth stressing that the issue of building CCS-related infrastructure is rather an imminent policy question. Although CCS is not yet a fully established technology, steps for setting up a policy framework should be taken at present given the long time frame of investment in CCS-related infrastructure and power generation facilities.

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Table 1. Estimates of capture costs

Capture cost (US$/t CO_2 avoided)	PC (Pulverized coal plant)	IGCC (Integrated gasification combined cycle plant)	NGCC (Natural gas combined cycle plant)
Rubin et al. (2007) Review of cost studies	29-51 (41)[a]	13-17 (23)[a]	37-74 (53)[a]
Rubin et al. (2007) Own results	49.7	22.6	62.6
Davison (2007)	28-36	20-39	39-102
Hadjipaschalis et al. (2008) Review of cost studies	32-63.90	18-52.80	26-158
Hadjipaschalis et al. (2008) Own results	32.72	17.25	132.81

[a] Range and representative value (in parentheses)

Source: Rubin et al., 2007; Davison, 2007; Hadjipaschalis et al., 2008

Table 2. Pipeline transportation costs.

Pipeline transportation costs	Ecofys 2004 (€/t CO_2)[a]		IPCC 2005 (US$/t CO_2)[b]		IEA (2008) (US$/t CO_2)[c]	
Distance (km)	Min	Max	Min	Max	Min	Max
100	1	6			1	3
					2	6
250			1	8		

[a] Source: Hendriks et al. (2004). Pipeline transport costs per 100 km for flow rates of 25 kg/s (high end) and 250 kg/s (low end) and for velocities of 1 m/s (high end) and 3 m/s (high end).

[b] Source: IPCC (2005). Pipeline transport costs per 250 km for mass flow rates of 5 (high end) to 40 (low end) MtCO_2/year.

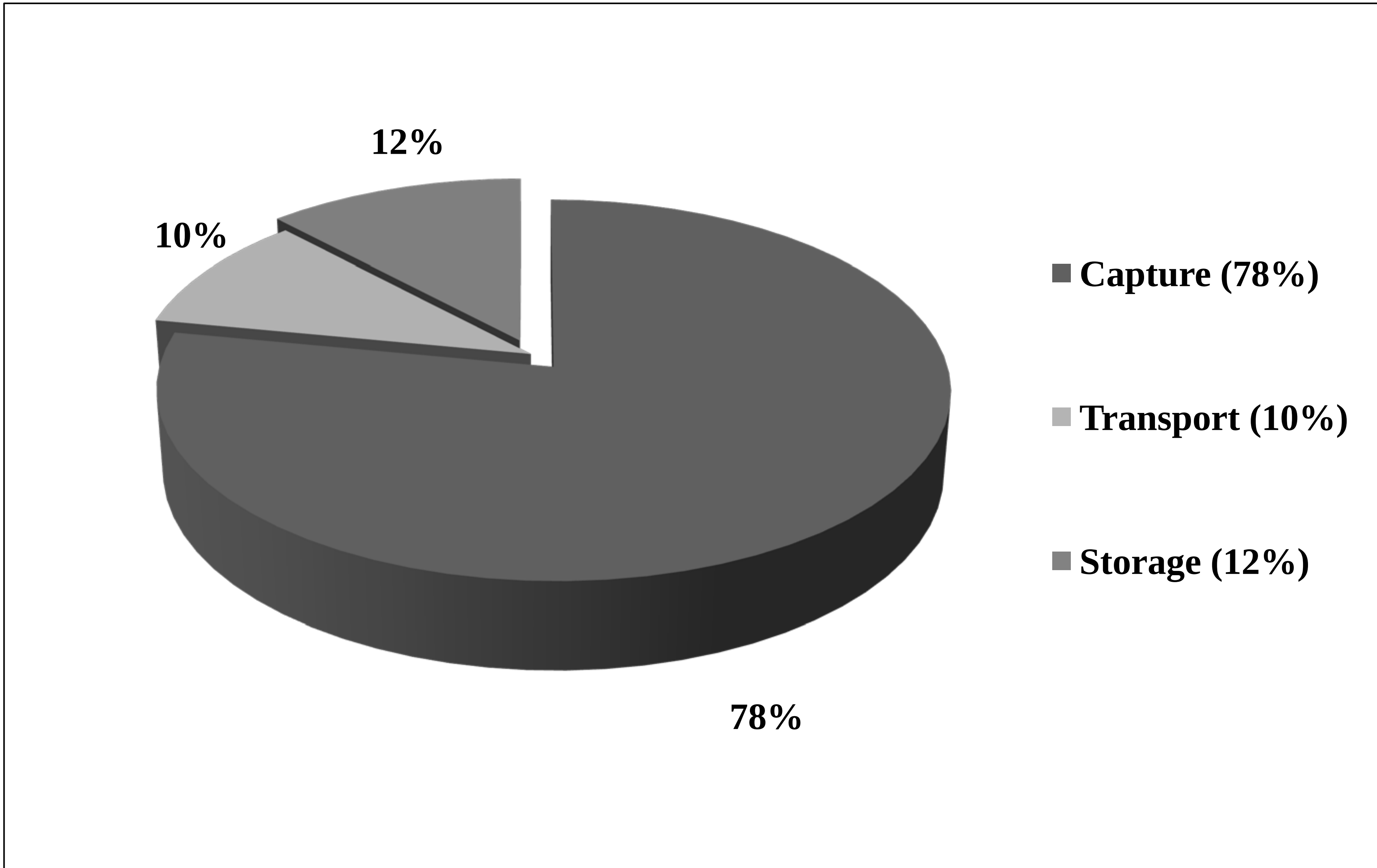
[c] Source: IEA (2008). Pipeline transport costs per 100 km. Higher range for mass flow rates of 2 Mt CO_2/yr, lower range for mass flow rates of 10 Mt CO_2/yr.

Table 3. Estimates of CO_2 storage costs for Europe.

Storage cost (Europe)	Ecofys 2004 (€/t CO_2)[a]	
	Low	High
Oil and gas fields (North Sea)	3,6	7,7
Aquifers (North Sea)	4,5	11,4
Oil and gas fields (onshore)	1,1	3,6
Aquifers (onshore)	1,8	5,9
Storage with EOR (offshore)	-10	20

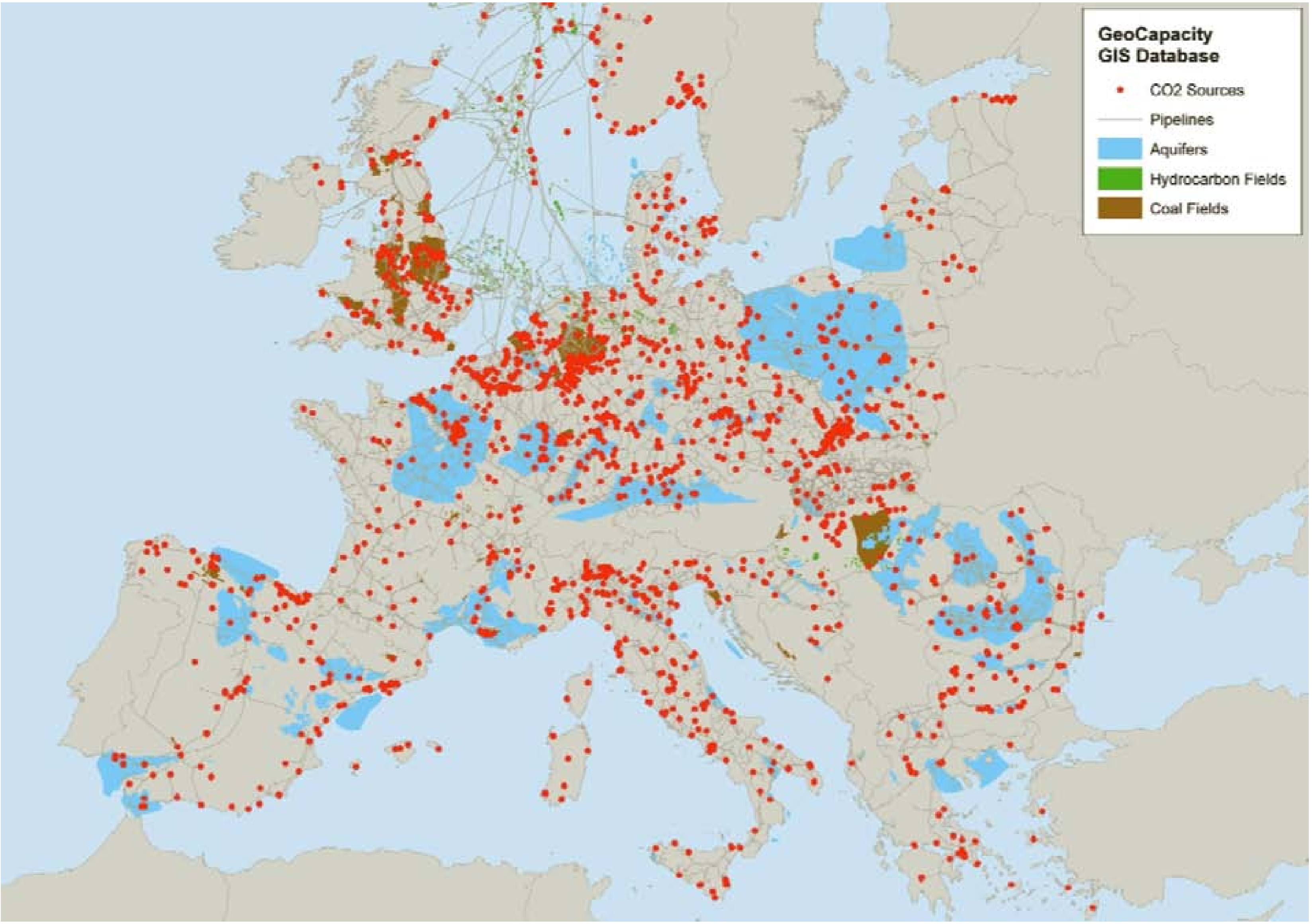
[a] Source: Hendriks et al. (2004). Lower estimates for storage depths of 1000m, higher estimates for storage depths of 3000 m.

Figure 1. Composition of CCS cost.



Composition of average CCS cost from the GESTCO project, which includes case studies from the power generation sector as well as from the industrial sector. Capture costs encompass pure capture costs (63%) as well as compression costs (15%). Figure modified from Fischedick et al. (2007).

Figure 2. CO2 emission sources, storage sites and existing pipelines in Europe as collected in the GeoCapapcity database.



Source: Vangkilde-Pedersen et al. (2009).

Figure 3. Estimates of CCS infrastructure costs in Europe.