THE IMPORTACE OF CO_2 CAPTURE AND STORAGE – A GEOPOLITICAL DISCUSSION

by

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The CO_2 capture and storage (CCS) technology is since more than ten years considered one of the key options for the future climate change mitigation. This paper discusses the implications for the further development of CCS, particularly with respect to climate change policy in an international geopolitics context.

The rationale for developing CCS should be the over-abundance of fossil fuel reserves (and resources) in a climate change context. From a geopolitical point, it can be argued that the most important outcome from the successful commercialisation of CCS will be that fossil fuel-dependent economies with large fossil fuel resources will find it easier to comply with stringent greenhouse gas reduction targets (i. e. to attach a price to CO_2 emissions). This should be of great importance since, from a geopolitical view, the curbing on greenhouse gas emissions cannot be isolated from security of supply and economic competition between regions. Thus, successful application of CCS may moderate geopolitical risks related to regional differences in the possibilities and thereby willingness to comply with large emission cuts. In Europe, application of CCS will enhance security of supply by fuel diversification from continued use of coal, especially domestic lignite. Introduction of CCS will also make possible negative emissions when using biomass as a fuel, i. e. in so called Biomass Energy CCS (BECCS). Yet, the development of BECCS relies on the successful development of fossil fuelled CCS since BECCS in itself is unlikely to be sufficient for establishing a cost efficient CCS infrastructure for transport and storage and because BECCS does not solve the problem with the abundant resources of fossil fuels.

Results from research and development of capture, transport and storage of CO_2 indicate that the barriers for commercialization of CCS should not be technical. Instead, the main barriers for implementation of CCS seem to be how to reach public acceptance, to reduce cost and to establish a high enough price on CO_2 emissions. Failure to implement CCS will require that the global community, including Europe, agrees to almost immediately to start phasing out the use of fossil fuels, an agreement which seems rather unlikely, especially considering the abundant coal reserves in developing economies such as China and India.

Key words: *carbon capture, CCS, geopolitics, CO_2, greenhouse gas*

Introduction

Climate modelling projects, such as those reported by the IPCC, suggest that reductions of 50-85% in global emissions of CO_2 (relative to the emission levels in 2000) are

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required to enable the stabilisation of atmospheric levels of greenhaus gas (GHG) at 440-490 ppm (~350-400 ppm CO_2), corresponding to a global temperature increase in equilibrium of 2.0 ºC to 2.4 ºC [1] In addition, state-of-the-art research indicates that 50% to 70% reductions in GHG emissions are required to limit the global temperature increase to 2 ºC; for this target to be met with >66% probability with further reductions required after 2050 and the emission levels should peak not later than 2015 [2]. It is therefore obvious that achieving the 2 ºC target represents a great challenge from the technical and political points of view. The GHG emission reductions achieved to date have been disappointing, principally due to the abundant resources of fossil fuels, the long turnover times for the capital stock of the energy infrastructures (*e. g.*, the technical life-time of power plants and the fossil fuel infrastructure is typically 20 to 40 years, *e. g.* OECD/IEA, 2005 [3]), the long lead times for the development and scaling up of low-carbon technologies and the increase in GDP. The global emissions have increased, and continue to do so and the CO_2 emissions increased by more than 5% in 2010 (although there was a 1% decline in 2009) [4]. Thus, it seems hardly likely that emissions will peak within a few years and negative emissions may therefore be inevitable in the long run in order to stabilize temperature at acceptable levels.

CO_2 capture and storage (CCS) represents a set of technologies which, if successfully implemented, would allow continued use of fossil fuels while reducing GHG emissions. CCS involves the capture of CO_2 from flue gases of large centralised emission sources, such as power plants and other industrial processes. The captured flue gas is then transported to a storage location located deep underground. In addition to reducing carbon emissions, CCS might also enhance the security of supply by allowing the use of domestic fuel resources, such as lignite and coal. In addition, application of CCS to processes using biomass as a fuel makes it possible to obtain negative emissions (provided biomass is supplied in a sustainable way).

The main reasons why CCS has attracted increasing interest over the last decade are: (1) the potentially large storage capacity for CO_2 that is available at many sites around the world, (2) the unlikelihood that the CO_2 will leak out, and (3) the expectation that CCS technology will be cost-effective, assuming that a price is established for CO_2 emissions.

The aim of the present paper is to discuss the development of CCS in a geopolitical context. The CCS technology is only explained briefly in this paper. For more detailed technical descriptions of the CCS technologies, there are numerous papers published on capture, transport and storage, the CCS special report from the IPCC (2005) [5], and information available from the IEA GHG R&D Programme [6], the European Technology Platform for Zero Emission Fossil Fuel Power Plants [7], the European Network of Excellence on the Geological Storage of CO_2 [8], and the US. Department of Energy [9]. The research and development within various aspects of CCS is reported at conferences within the IEA Greenhouse Gas Program and in the International Journal of Greenhouse Gas Control.

Carbon capture and storage

The capture and storage of CO_2 (often referred to as “carbon capture and storage”) involves three major steps: (1) the capture of CO_2 from large point sources, such as power plants, (2) the transport of the captured CO_2 to a storage site, and (3) injection of the CO_2 into the storage site, typically a geological formation located deep underground.

Currently, research and development studies of all three steps are underway. However, since the capture process is the most expensive part of CCS, it is generally considered to be the most critical element in efforts to control costs. Compared with a plant without CO_2 capture, the cost for a plant with CO_2 capture, *i. e.*, a CCS system, is higher due to an increase in investment costs, reduced plant efficiency (higher fuel consumption), increased maintenance costs, costs for transport of the captured CO_2 and costs for storage.

Typically, these factors will result in costs for CCS in the order of 25 €/tCO_2 avoided (capture, transport, and storage), although estimates given in literature vary greatly. As mentioned above, such cost is believed to be competitive in a carbon constrained world where there is a price tag on CO_2 emissions. CCS is expected in the first instance to be cost-effective in large (around 1,000 MW) coal-fired power plants that are running in base-load. In particular, lignite ("brown coal") is a low-cost fuel that is often burned in high-efficiency power plants with state-of-the-art flue gas cleaning, resulting in low levels of emissions of harmful products, such as nitrogen and sulphur oxides, albeit with high levels of emissions of CO_2. Typically, such power plants have an electric efficiency of around 43%, although this could be increased to some 48% using available technologies. Future plants may reach electric efficiency levels of around 50%. Considering the typical energy penalty from carbon capture of 7 to 8 percentage points, the first commercial application of CCS plants around 2020 may very well have an electric efficiency similar to that of current coal plants without capture (>40%). Yet, this requires research, development and demonstration of the capture technology.

Capture of CO_2 from biomass fuelled processes such as sugar cane-based ethanol mills, chemical pulp mills [10] as well as from power generation [11, 12] can, provided the biomass fuel can be regarded as climate neutral, provide negative CO_2 emissions ("carbon negatives"). The concept of BECCS is not straight forward or may even be spurious, depending on context. Firstly, it is likely that capturing CO_2 from biomass fired plants will be more costly than the cost of capturing CO_2 from large coal fired power plants. This, since biomass only fuelled plants have to be smaller in size due to fuel logistics and that the maximum steam temperature (determining the plant efficiency) may have to be limited to avoid alkali related high temperature corrosion on heat transfer surfaces. Second, until CCS has been applied to all fossil fuelled power plants and all other CO_2 emissions have been curbed, global CO_2 emissions are obviously not negative. Thereby, it is not straight forward why to favour BECCS technologies if these are more expensive than CCS from fossil fuel plants. It obviously does not matter which CO_2 emissions are captured and then these should be captured where most cost efficient. Yet, it makes sense that if a party is willing to capture CO_2 from biomass, they will be acknowledged with negative emissions (*e. g.* in an emission trading scheme). Thus, in an emission trading scheme which includes such negative emissions, the economic value of a tonne of carbon stored and thereby the value of negative emissions, will decide at which point in time BECCS will become commercially attractive. At the time of writing this paper, there is no regime on how to include negative emissions in existing emission trading schemes such as the EU-ETS (and, except for biomass co-firing in a CCS plant where total capture, including "negatives", is not more than 100%, such inclusion is not straight forward, [13]).

A more manageable way to introduce biomass in CCS power plant schemes would be to co-fire biomass with coal see [14, 15] for estimates on potentials for co-firing in the U. S. and in the EU). Co-firing would reduce the risk of high temperature corrosion (assuming the biomass fraction does not exceed some 10% of the total fuel input on an energy basis, although what is a "safe" biomass fraction depends on biomass quality and power plant technology). Typically, biomass co-firing in CCS plants can improve capture rate up to or near 100% (from some 90% which is what is expected, at least for the first generation of capture technologies). In addition, CO_2 capture may be applied to other biomass fuelled processes such as ethanol plants and combined heat and power plants. It can be concluded that when considering the slow pace in the work with changing the emission trends, it seems that it will be important to apply biomass as fuel in CCS schemes (BECCS) since negative emissions may be required to meet a 2 °C target.

The main options for transporting the captured CO_2 are pipelines and boat transportation or combinations thereof. Obviously, for a future large-scale CO_2 transportation infrastructure, given the large volumes to be transported, pipeline transportation is the preferred option from both the handling and cost perspectives. Initial projects may use boat transportation, as well as truck transportation, for smaller pilot projects, see [4, 16-20] for overview of CO_2 transportation issues.

The main target for the storage of CO_2 is deep geological formations, such as saline aquifers and depleted oil and gas reservoirs. Storage is also possible in association with enhanced oil recovery (EOR) and in deep unmineable coal seams, with enhanced coal bed methane recovery (ECBMR) offsetting some of the cost of storage. By far the greatest storage potential lies in deep saline aquifers, whereas EOR and possibly ECBMR could be important for the first phase of implementing CCS, in that they would offer less costly storage before an integrated transport and storage network could be put in place and also serve as examples of the storage safety. Assessments of national and global storage potentials reveal both on-shore and off-shore storage sites (see *e. g.*, [19-21 and references therein]).

Both in Europe and the US, several of the first CCS demonstration projects have met local opposition from the public and different interest groups ([22, 23], *e.g.* the so called *Greenville Project* in Ohio). It would probably be easier to get public and political acceptance for off-shore storage, but such storage will be more expensive and therefore difficult to apply for initial pilot and demonstration projects. Yet, there are also on-shore storage projects which have met no or little opposition by the public (*e. g.* [22], AEP-Mountaineer project in West Virginia and the FutureGen project in Illinois, USA, although recent development indicate some opposition with respect to the latter).

CCS as part of a European CO_2 mitigation portfolio

The EC several years ago adopted a target for limiting anthropogenic global climate change to 2ºC above pre-industrial levels [24]. To achieve this target, the EC proposed that mitigation levels of 30% reduction in GHG emissions by 2020 and 80% to 95% by 2050 should be targeted for developed countries when negotiating international treaties [25]. Considering the different possibilities and levels of willingness to pay for reductions in different sectors, one can expect the electricity generation system to take on more reductions than, for instance, the transportation sector [26]. In addition, electrification of the transportation sector (if such will take place at scale) will in part centralise the emissions from this sector (to the electricity generation system). Therefore, CCS offers a promising mitigation option for the part of the required electricity that is produced from fossil fuels. The alternative would be to apply hydrogen and other fuels produced from renewables. Due to the high cost of batteries, it is not obvious if and with what pace the transportation sector will be electrified.

Here, we exemplify the introduction of CCS with the European electricity generation system (*i. e.* not including the transportation system and with an exogenously defined demand for electricity). Thus, fig. 1 illustrates a possible development pathway for the European electricity generation system, applying a chosen target of 93% reduction in CO_2 emissions to the year 2050, relative to the level in 1990 (from [26]). Thus, the 93% reduction reflects the large share of the reduction assumed by the electricity generation system. The modelling applies models for each EU Member State individually, although it is assumed that the total electricity demand within the entire region (EU-27 countries plus Norway and Switzerland) will be met through a common electricity market, with import/export restricted to limitations in interconnections (current transmission capacity plus investments in new capacity when profitable in the model). Thus, it is assumed that emissions may be traded among the Member States in a manner similar to that used in the EU-ETS. National electricity demand, which is here defined as national electricity end use including distribution losses, for the model start year (2010) is taken from the Eurostat statistical data [28].

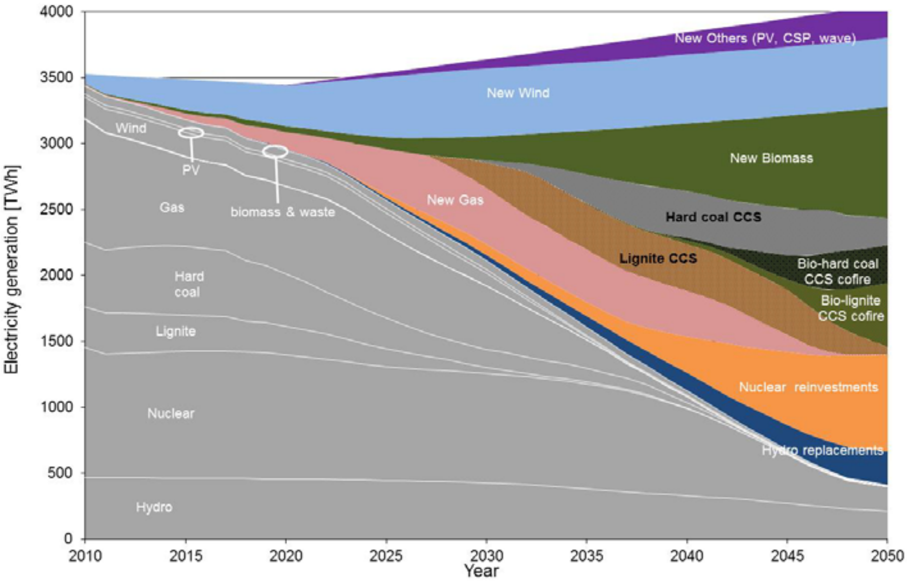

Figure 1. Electricity generation in the EU-27 countries, plus Norway and Switzerland, from the modelling work described in [27]. In the example, about 12 $GtCO_2$ is captured between 2020 and 2050. The marginal cost of electricity over the period ranges from 60 €/MWh in 2020 to around 85 €/MWh in 2050. This corresponds to a marginal cost of CO_2 abatement that ranges from 30 €/tCO_2 to 60 €/tCO_2 by 2030, with a steady increase to above 150 €/tCO_2 by 2050. In addition, the prescribed RES targets would require a support scheme of about 10 €/MWh RES-E from 2020, corresponding to a green certificate scheme. "Others" include PV, concentrating solar power, wave, small-scale hydro, and tidal power (color image see on our web site)

The scenario applied in fig. 1 represents a case in which energy efficiency measures proposed by the EU have been successfully implemented and for which there are RES targets, not only up to 2020 but also up to 2050. Thus, the national annual growth rates include an efficiency target of 20% relative to a baseline, which for the electricity sector is assumed to give a 13% reduction by 2020. The baseline corresponds to the national annual growth rates given by the EC [29]. CO_2 constraints to 2020 reflect the higher ambition expressed during the negotiation of international treaties, *i. e.*, an overall target of reducing GHG by 30% relative to the 1990 emission levels. According to Capros *et al.* [30], this implies that the reduction in CO_2 required within the power generation sector should be 40%. Assuming that the efficiency improvement will continue up to 2050 with a total reduction of 35% relative to baseline, this would mean 23% lower electricity consumption than the baseline [25]. RES-E fulfils the EU targets to 2020, and is assumed to grow in the same manner after 2020, assuming 45% RES-E by 2050. There are re-investments in nuclear power in existing plants, but not in Germany and Belgium, for which current (2010) political decisions are assumed to persist. The costs for CCS plants are derived from the European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP) [31]. Other costs and assumptions are based on those applied and described in World Energy Outlook 2011 [32].

The grey field at the bottom of fig. 1 is the contribution to generation from the present system, which also illustrates the long-lived nature of the capital stock in power generation systems (the model phases out plants when they are no longer profitable to run or when they have reached the assumed technical lifetime). Thus, the diminishing grey field represents the above mentioned need in the EU to replace old plants over the next decades. This requirement for significant investments in power generation is also valid between now and 2020, *i. e.*, before CCS becomes available (and this is also the case for North America). Without successful implementation of energy efficiency measures, there may be a continuous increase in the dependency on natural gas, depending on the penetration of renewable electricity generation [33].

After 2020, when CCS is assumed to become available, it can be seen that lignite and coal-fired CCS technologies will become cost-competitive mitigation options (fig. 1). Although gas-fired CCS technologies are included as options, these are not competitive in any MS due to the comparatively lower carbon intensity of natural gas and the fuel price relationship between coal and gas (taken from [32]). From fig. 1, it can be concluded that even if success is achieved in implementing energy efficiency measures, all presently known technologies are required on the large scale, including CCS. As a consequence, there is a strong ramping-up of CCS after 2020, which in reality may be significantly delayed as discussed below since, at present, it seems unlikely that the cost of CCS by 2020 is less than the price of an emission allowance in the EU-ETS. This is partly the result of the banking of emission credits in the previous period of the EU-ETS system, not making it probable that there will be a strong driving force for climate change mitigation before 2020, *i. e.*, there will be no strong driving force for real investments in large-scale demonstration or full-scale CCS projects before 2020. Although the cost of transport and storage is differentiated in the model, to account for differences in regional conditions, these costs reflect large-scale integrated systems for transport and storage, *i. e.* initial CCS projects may have to pay significantly more for transport and storage (per ton of CO_2 captured). In conclusion, fig. 1 represents the successful implementation of energy efficiency measures and a large expansion of renewable electricity generation. Yet, significant amounts of CCS are required. Failure to implement energy efficiency measures or to expand renewable, as in the example shown, obviously will exert even more pressure on CCS as well as on nuclear power (see [33] for such a scenario).

If the power sector is aiming for to become a more or less zero emitting system, CCS power plants configured as described in [31] cannot be used toward the latter part of the modelled period. This, since the normal configurations of CCS is assumed to have a 90% capture. Thus, with zero carbon emission as an objective much of the CCS power plants would have to go for either 100% capture or co-fire biomass. The results in fig. 1 indicate the requirement for biomass co-firing combined with CCS in the end of the period. In addition, a zero emission power system put pressure on new solutions for back-up and peak power for balancing purposes. The results in fig. 1 show virtually no gas power by 2050, which would imply other means to balance the system. This could be obtained by application of biomass gasification and continued use of gas turbines as well as by demand side management.

In Europe and other developed regions, CCS plants will most probably be built at existing power plant sites. It does not seem realistic that it will be politically possible to build new CCS coal plants at entirely new (greenfield) sites. Even if considering an increase in electricity consumption (as in fig. 1 or with a steeper increase in a case with less success in efficiency measures), there should still be a sufficient number of available sites [34]. In developed economies such as China there are plants built on new sites which therefore also should be the case for CCS plants, depending on when CCS is introduced).

CCS development

In most scenarios on the development of the energy system (globally and regionally) under a climate constrained future, CCS constitutes an important CO_2 mitigation options until year 2050 and beyond. Thus, CCS is recognized as an important part of a climate change mitigation portfolio in national and international contexts (*e. g.* [35]) and in future energy projections [1, 5, 36]. However, as indicated above CCS has not been applied at scale and the extent to which CCS will contribute to climate change mitigation depends on the successful implementation of climate-change policy measures (such as the EU-ETS) development and demonstration of capture technologies, as well as the ramping-up of a transportation and storage infrastructure for the captured CO_2. As indicated above, the barriers and challenges to implement CCS are most likely not technological (although cost must come down). This, since the entire CCS chain has been demonstrated or applied on a pilot or demonstration scale. Main barriers seems to be to reach public acceptance as well as to get a strong and clear climate mitigation policy in place which results in a steady increased cost to emit CO_2 (and other greenhouse gases). A key should be to get a number of CCS demonstration projects up and running, including the entire CCS chain–capture, transport and storage. It is a reasonable assumption that the first successful large-scale demonstration of the entire CCS chain, will have a high symbolic value, and once CCS is successfully implemented, it should be much more difficult to secure approval for building coal plants (and other high CO_2 emitting processes) without CCS. So far, only pilot projects have recently been put into operation such as the 30 MW Vattenfall oxyfuel fired Schwartze pumpe plant [37] and the CUDIEN 2×30 MW oxyfuel plants [38]. At the time of writing this (June 2012) it seems as several (if not all) of the six CCS demonstration projects to be in part funded by the European Economic Recovery Programme have more or less been put on hold, mainly due to problems with public acceptance and financial uncertainties. Thus, there is an urgent need for the EU climate change policy to find ways to deliver clear price signals and conditions so as to facilitate the initiation of these projects as well as the recently announced NER300 [39] CCS projects. If not, there is risk that the R&D efforts spent so far will not be taken to the next phase and the persons and business involved will redirect their efforts to other business areas.

A further challenge for commercialization of CCS is to establish an efficient infrastructure for transport and storage. The relatively low costs for transport and storage typically given (each some few € per tonne of CO_2 captured) only hold for a large co-ordinated transport and storage infrastructure. The costs for transport vary considerably with the amount transported and the mode of transportation used [16]. Thus, a transport and storage infrastructure that serves only one plant will have much higher costs, especially if the transported CO_2 has to be transported over long distances, such as to an off-shore storage location [16]. Yet, Dooley *et al.* [40] have shown that the historical growth of the US natural gas pipeline distribution system was at rates that substantially exceeded the growth projections for a future CO_2 pipeline network in the US. From this it can be concluded that construction of a large-scale CO_2 transportation network is possible from a technical and organizational point of view. However, an important difference is that the natural gas transportation infrastructure was developed to transport a product of high value to growing markets, whereas the transportation of CO_2 imposes a cost, which together with the cost for capture and storage must be less than the cost to emit CO_2. It is important to find integrated solutions that encompass different companies and countries. Possibilities and challenges for the establishment of such infrastructure are discussed in [41].

Capture of CO_2 can be implementing at existing plants if applying post combustion capture. This is an important option for demonstration of CCS as well as it can be important for some industrial processes where capture must be applied after the process. Yet, considering the rather long lead times for the development of CCS, it is the opinion of the authors of this paper that the bulk of CO_2 capture will be carried out in newly constructed power plants, which will be built in connection with the phasing out of old plants. New plants can be built with a design that maximises the thermal efficiency, which is important in order to get as low electricity generation cost from the plant as possible. In Europe, as well as in North America, there will, as mentioned, be a great need to replace old plants over the next decades.

The European Commission (EC) has acknowledged the challenge and urgency of implementing and scaling up the CCS technology. Thus, as mentioned above, the EU provides funding for the implementation of demonstration projects using two mechanisms: (1) within the EU-ETS, 300 million emission allowances will be set aside to fund up to twelve CCS demonstration projects (and to cover demonstration projects on innovative renewable energy technologies), and (2) the so-called European Economic Recovery Programme [39] has allocated approximately €1 billion to contribute to the funding of six CCS demonstration projects [42]. It is the opinion of the authors of this paper that the EU and North America should take the lead in demonstrating and implementing CCS and to intensify international co-operation on CCS development with developing economies, such as with China (*e. g.* [43, 44]). In Europe, Poland could play an important role in demonstrating CCS since Poland is overwhelmingly dependent on fossil (coal) for its electricity generation (*e. g.* [45]).

There is a need for a legal framework to regulate CCS. In Europe, there already exists a CCS Directive [46] for CO_2 storage in geological formations, which defines requirements for the storage site over its entire lifetime. This directive also contains amendments to other EU directives and regulations that regulate environmental impact assessment, the handling and transport of waste, and environmental liability, so that they include the handling of CO_2, including its transport. In addition, an amendment [47] to the EU-ETS directive [48] states that CO_2 emissions that are captured, transported, and stored will be considered as not being emitted.

As pointed out above, to reach public acceptance seems to be one of the main barriers for CCS. Yet, studies of public attitudes to CCS show that the general public is largely unaware of the CCS technologies [49-51]. As indicated above, several introductory pilot and demonstration projects have met local resistance (although others have not). It seems likely that the inhabitants of regions that are directly dependent upon fossil fuels will feel more positively about CCS than persons who live in regions that are not dependent upon or that are not perceived as being dependent upon these fuels. In regions that have deposits of coal (or lignite), the application of CCS may result in the replacement of an old power plant with a new one, thereby retaining jobs. The storage part will no doubt be controversial in certain cases, although significant storage potential exists offshore, far from inhabited areas. It seems clear that interaction with the local populace from an early stage of each project is important in order to gain confidence regarding the execution of CCS projects, although this is by no means a guarantee that local opposition will be assuaged. For the successful implementation of CCS, it will be important to engage with the communities where CO_2 is to be stored; work aimed at building confidence among public and local authorities on these issues has been initiated during the last years (see WRI [52] for a description of such efforts and programs). It is important to mention that deployment of new technologies often meets resistance from the public, *i. e.* not only for CCS (*e. g.* wind power has met considerable public resistance in several regions as well as there is the well-known resistance among public on nuclear power).

Discussion – Geopolitical rationale for CCS

Although, it is obvious that the large reserves and resources of fossil fuels represent the major threat to the climate [53], this fact seems to sometimes be forgotten in the public debate on GHG mitigation strategies, which often focus on choosing or ranking the technologies and measures available for curbing emissions. Considering the drastic cuts in emissions required over the next decades and the competitiveness between economies, the security of supply, the continuous development of exploiting the fossil fuel reserves and resources (including those in the arctic regions, becoming more available due to global warming) and differences in local conditions, CCS should be a key technology unless there is a global consensus in stopping the deployment of the fossil fuels. Yet, CCS is only one option and all other mitigation options are required such as illustrated from the modelling results shown in fig. 1. Clear and strong policies are crucial to the large-scale deployment of technologies and measures (*e. g.*, [54]). The probability that the political system will introduce strong policies, such as a tax on GHG/CO_2 emissions or a trading scheme for which the levels of the allowances are reduced to comply with required reductions, depends on the technologies that are available and the associated cost.

Given the strong dependence upon fossil fuels, most notably coal, the availability of technologies that allow for continued use of these fuels while curbing emissions should facilitate the transition towards a more sustainable energy future while maintaining economic competitiveness and security of supply also in regions with fossil fuel resources. The societal cost for curbing emissions cannot differ too much between different economies in order to maintain regional competitiveness. Or, the other way, it seems likely that only if the cost and conditions for curbing GHG emissions is similar in different regions there will be any chance to achieve binding targets which can meet the reductions required to meet a 2 °C target. Thus, since there obviously are many fossil fuel dependent and fossil fuel rich economies and since fossil fuels are abundant (especially coal), it is important that there are options which allow for its continued use at the same time as emissions can be cut drastically, at least in the medium term before the cost for using fossil fuels exceeds that of other forms of energy.

In summary, it is rather obvious that there cannot be large differences in energy policies between regions [55]. The global economy together with the international markets of fossil fuels and security of supply issues makes it hardly likely that one region will apply CCS and others will not (provided similar resources of fossil fuels). Thus, although EU and North America may take the lead in developing and demonstrating CCS it seems unrealistic that CCS will only be applied at scale in these regions (or only in EU) while coal is continued to be used without CCS in developing economies. Consequently, for a global large scale diffusion of CCS there must be a price on CO_2 emissions in all regions. This is of course a challenging task from a geopolitical point of view, considering the slow development of binding targets within the UN driven climate change negotiations. A geopolitical question can thus be if successful demonstration of CCS may enhance the chances of getting a widespread price on CO_2 emissions, although not necessarily within the same regime for the entire globe. The first successful large-scale demonstration of the chain of capture, transport, and storage will have a high symbolic value, and once CCS is successfully implemented, it probably becomes much more difficult to secure approval for building coal plants without CCS even in regions where CCS was not demonstrated. In other words, it may very well be that its success of CCS in one region will make it politically impossible to build plants without CCS also in other regions. Thus, provided successful large scale demonstration of CCS (in for instance EU), the probability of successful global diffusion of this technology (followed by regional emission policies making it impossible to build coal plants without CCS) may be higher than the success of first reaching a global agreement on emission reductions.

It is important that there is a strong political consensus behind the necessity of pushing CCS forward. EU should be able to play a key role in this respect and, developing CCS should be seen as a an opportunity since a success of CCS in Europe will most likely make other economies to follow, at the same time as this will make European technology providers to get a competitive advantage in a global market. As should be clear from above, the political momentum in the CCS development seems rather weak with the development rather governed by local opinions than from a strong climate policy (which is lacking). Indeed, there are demonstration projects under planning but they have not reached that far and seems to – in spite of receiving funding from the European recovery funds – still be pending on additional support. Thus, without a predictable and high enough cost to emit CO_2 imposed by the EU-ETS system, the European development of CCS (as well as other carbon mitigation technologies) will depend on technology specific support. For CCS, such support is likely to be more controversial than for renewable technologies. However, as mentioned above, before CCS has been demonstrated at large scale, it seems unlikely that there will be a high enough cost to emit CO_2 in fossil fuel dependent regions. Hence, a hypothesis from the discussions in this paper is that EU cannot count on that other fossil fuel dependent economies will impose a cost high enough for CCS to be developed, but EU has to rely that a full demonstration of CCS value chain will diffuse to other regions.

In summary, the following points with geopolitical implications, can be made with respect to the future development of CCS:

- in various scenarios and projections of the future development of the energy system, at both the regional and global levels, CCS is generally assumed to account for a significant share of CO_2 reductions in the stationary energy system (mainly electricity generation) from 2020-2025 and beyond,
- in these future developments, the roll-out costs for CCS are typically estimated to be in the order of 25 €/tCO_2 avoided (capture, transport, and storage), *i. e.*, less than the costs expected to be associated with emitting CO_2 (*e. g.*, as in the European Emission Trading Scheme, EU-ETS),

- the potential for CO_2 storage is large, which is one of the major (and essential) motivations for the great interest in CCS,
- the first successful large-scale demonstration of the chain of capture, transport, and storage will have a high symbolic value, and once CCS is successfully implemented, it is likely that it will be much more difficult to secure approval for building coal plants without CCS, and
- perhaps the most important outcome of the successful commercialisation of CCS will be that it will become easier to get fossil fuel-dependent economies to comply with stringent GHG reduction targets. Therefore, it is important for the EU and North America to take the lead in demonstrating and implementing CCS. Failure to implement CCS will mean that the global community will have to agree more or less immediately on starting to phase out the use of fossil fuels, an agreement on which seems more unlikely than reaching a global agreement on stringent GHG reductions.

There are, however, a number of uncertainties regarding the near-future prospects for CCS, and several challenges must be overcome to ensure the successful commercialisation of CCS by 2020. Although CCS may help reaching a global agreement on climate change mitigation, clear and long-term policy measures are required for ensuring that CCS is developed, demonstrated, and commercialised over the next decade. Here, the EU and North America should be able to take a leading role (which is to some extent already the case, but as indicated above the work with developing CCS needs to be intensified).

It can be concluded that at present it seems *unlikely* that *CCS will significantly contribute to climate change mitigation before 2025*. If a significant CCS contribution is to take place already in 2025, activities to develop CCS globally and to find integrated ways to build up a transport and storage infrastructure are required from now (2012) onwards. An obvious condition is the successful large-scale demonstration of CCS within the next five years. The following conclusions can be drawn in this context.

- Failure to implement CCS will be a tremendous challenge from a geopolitical view, if the global community at the same time will try to comply with climate mitigation such as wanting to limit global temperature increase to 2 °C. Such a scenario will require that the global community, including Europe, agrees to almost immediately to start phasing out the use of fossil fuels, an agreement which seems rather unlikely, especially considering the abundant coal reserves in developing economies such as China and India.
- Key issues in achieving the commercialisation of CCS are that an integrated transportation and storage infrastructure is established in a timely manner (planning must be commenced within a few years) and that market regimes are identified (*e. g.*, public-private partnerships). This is a geopolitical challenge with respect to cooperation between regions which could benefit from a coordinated transport and storage network.
- Most of the available storage estimates rely on rather rough estimates, which mean that firstly the most prospective areas will have to be singled out wherein site-specific investigations are required in order to arrive at the actual storage capacity. Ways and policies to stimulate site-specific investigations of storage capacities must be found. This will require international co-operation if to be successful.
- Although the above-mentioned estimates of roll-out costs appear to be attractive, the costs incurred during the first years after commercialisation may be significantly higher. Thus, it is important to find CCS support schemes and concerted actions for building up the CCS infrastructure, so as to minimise the time before the roll-out costs are reached.

- It is of the utmost importance to ensure that the planned large-scale demonstration projects are successfully implemented. For the EU, it is important that the six projects that have recently received economic support from the EU recovery funds will be successfully carried through, so that the experiences gained can be used efficiently in subsequent projects.
- Regarding the above point, the banking of credits within the EU-ETS system is problematic, making it likely that the cost for emitting CO_2 will not exceed 20 €/tCO_2 before 2020. This means that there will be a lack of a strong driving force for building large-scale demonstration plants and the first "near-commercial" CCS plants.
- An alternative "Plan B" should be developed in case CCS introduction is delayed or the CCS technology fails. An obvious geopolitical challenge in this case is how the international community should handle the large resources of fossil fuels (which could not be used to the same extent as compared to the situation in which CCS became available on a large scale or in the case of CCS failure, had to be phased out completely over a few decades).
- For the EU, investments made during the period until CCS is available may increase the dependence on natural gas for electricity generation. For Europe, this is obviously negative from a security of supply point of view although exploiting of unconventional gas in North America and (perhaps) in Europe, may moderate these negative effects.

Conclusions

The implications for the further development of CCS have been discussed, particularly considering climate change policy in an international geopolitics context. From the discussion, it can be concluded that that successful commercialisation of CCS is crucial to mitigate climate change, especially considering the likelihood of countries and regions that are heavily dependent on fossil fuels (especially coal) reaching agreement on strict CO_2 emission reductions. Thus, with respects to geopolitics CCS may moderate tensions between fossil fuel dependent and non-fossil regions with respect to how to meet strong targets on CO_2 reductions. The main challenge for CCS is reaching the estimated roll-out costs around or shortly after 2020. Clear and long-term climate change mitigation policies are important in terms of sending clear signals to the market that investments in developing CCS will be rewarded in the long run.

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