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# Environmental Impacts of Carbon Capture Technologies

An overview of the state of development, potential side effects and current challenges for science and society

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# Abstract

We are addressing the current critical issues around carbon capture with particular focus on the environmental side effects of the technologies for capturing CO<sub>2</sub> from point sources. For various carbon capture technologies we have surveyed their state of development and potential impacts on the environment. For the amine scrubbing technology, which is considered to be the most mature CO<sub>2</sub> capture technology, we have identified several potential side effects resulting from unintentional emissions of amines to the atmosphere during the capture process. In the atmosphere, amines lead to the formation of secondary aerosol and degrade into carcinogenic nitramines and nitrosamines. Also they can lead to the production of tropospheric ozone. The quantitative investigation of these potential side effects is still insufficient and represents a key challenge for current research activities around carbon capture technologies.

Finally, we have identified critical research questions that need to be addressed in the near future in order to ensure a thorough assessment of the environmental impacts of the different CO<sub>2</sub> capture technologies.

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# Introduction

The stabilization and possibly the reduction of atmospheric concentrations of greenhouse gases, particularly CO<sub>2</sub>, represent a key challenge in the attempt to mitigate climate change. One of the possible technologies that could help reduce anthropogenic CO<sub>2</sub> emissions is the concept of carbon capture, widely known rather as carbon capture and storage (CCS).

The concept of CCS describes the idea of separating CO<sub>2</sub> from the flue gas of emission sources obtaining highly concentrated CO<sub>2</sub> which could then be stored e.g. underground in geological formations. It offers the possibility of reducing CO<sub>2</sub> emissions from new and existing fossil fuel sources. It appears particularly promising because it could ensure a further use of fossil fuels while reducing anthropogenic CO<sub>2</sub> emissions at the same time. This in turn would postpone the fade out of fossil fuel based power generation and give mankind additional time for the development of a clean and sustainable energy supply. CCS may therefore provide an important contribution to the transition towards a low-carbon economy.

While in this context the fate of CO<sub>2</sub> – once it has been captured – is being discussed controversially, there are also important open questions concerning the capture process itself.

At the moment, it is still unclear to what extent the technologies currently available will be able to meet the high expectations in terms of the total climate impact of CCS. Also the risks and side effects associated with the different CO<sub>2</sub> capture technologies need to be assessed thoroughly before a large scale deployment of carbon capture can become a realistic option in the climate change mitigation portfolio.

This paper provides an overview on several of these aspects. Firstly, we survey the overall role CCS is expected to play in climate change mitigation scenarios. Secondly, we give an overview over the CO<sub>2</sub> capture technologies that are currently being developed and their respective future prospects. Then, the main focus of this paper is to survey the potential environmental risks and side effects that could arise from the different CO<sub>2</sub> capture technologies. Based on this survey we formulate research questions that need to be addressed in the near future to allow a thorough assessment of carbon capture.

# 1. Future scenarios and challenges for an implementation of Carbon Capture

## *The global role of CCS in climate change mitigation scenarios*

In its Special Report on CCS from the year 2005 the IPCC expected CCS to contribute a share of about 30% to climate change mitigation scenarios. The ETP analysis from 2010 now estimates the role of CCS to about 20% in the BLUE-Map scenario. In this scenario, CO<sub>2</sub> emissions of 9.4 Gt are expected to be captured by CCS in the year 2050. 55% of the captured CO<sub>2</sub> reside in energy production, 21% in industry and 24% in the energy conversion sector.<sup>1</sup>

According to these predictions, the deployment of CCS in energy production has to be limited not only to fossil fuel plants but also biomass plants have to be included. In the future, CCS will also become relevant in non-OECD countries particularly if emissions from new coal-fired power plants built in emerging economies are to be tackled. To meet the emission reductions of the scenario, China and India alone will need to account for around 36% of global CCS deployment in power generation by 2050.<sup>2</sup> Up to now, however, the deployment of CCS is not progressing as fast as expected.

## *Relevance of CCS for the power sector*

A special time pressure for the deployment of CCS arises from the fact that large amounts of CO<sub>2</sub> emissions are already locked-in by existing CO<sub>2</sub> emitting facilities. The today proved resources of fossil fuels

account to about 2800 Gt CO<sub>2</sub>. Roughly 1800 Gt out of these total 2800 Gt are associated to emissions from coal, 600 Gt due to emissions from combustion of oil and 400 Gt due to emissions from gas.

Presently, the installed capacity for energy production from coal is around 1650 GW and is expected to rise to 3005 GW in 2035 with current policies. Assuming new policies an installed capacity of 2327 GW is expected for the year 2035. 47% of the new coal fired power plants will be built in China and 20% in India. These new-built plants in China and India have the potential to produce the largest total amounts of CO<sub>2</sub> because they will be operating for long time periods (at least 40 years). These new power plants are therefore considered to be ideal candidates to be equipped with CCS. CO<sub>2</sub> emissions associated to the use of coal, however, should be reduced not only in the energy sector but also in the industrial sector, which presently accounts for about 26.4% (40% including indirect CO<sub>2</sub> emissions from the use of electricity) of the total CO<sub>2</sub> emissions worldwide.<sup>1</sup> Also to the industrial sector CCS could be applied similarly to the power sector.

In the U.S. a carbon pollution standard for stationary sources was developed and will be applied to new coal power plants in the near future. This standard, however, also needs to be applied to the existing plants and has the potential to incur higher emission reductions than current clean car standards are doing.

<sup>2</sup> *Energy Technology Perspectives (ETP), IEA, 2010*

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## *Costs of CCS*

Carbon capture is a cost and energy intensive technology. Currently the costs are estimated to about 60 USD/ton captured CO<sub>2</sub> which may generally decrease in the long-term future with technological advancement. Due to these high costs, only adequate economical-political conditions, which are currently missing, may ensure a large-scale deployment of CCS.

Presently, the carbon prices within international and national regulations like the European Emission trading Scheme, ETS, (<5 USD/ton CO<sub>2</sub>, end of May 2013) or the carbon-pricing scheme in Australia (22.17 USD/ton CO<sub>2</sub> in July 2013) are considerably lower than the estimated costs for carbon capture. At the moment it seems not to be possible to create a global carbon market but rather only regional/local markets. If these regional/local markets included OECD countries as well as China, however, this might be sufficient to drive CCS even without a global carbon market.

The high costs of CCS and the uncertainty in CCS price development are currently a drawback for its deployment. At this moment it is difficult to make any projection for future prices since on the one hand technological enhancement could lead to lower costs but on the other hand increasing future energy costs and costs for steel would also make CCS more expensive. As a consequence, other mitigation options like, e.g., the increase of energy efficiency or renewable energies would become competitive. If on the other hand CCS was not deployed due to its high costs, other climate change mitigation measures would have to contribute to a higher degree and the related costs would increase as well. In this context, the deployment of CCS might be important particularly for the industrial sector because so far there are no other options to reduce CO<sub>2</sub> emissions in this sector significantly. The exact evaluation of this aspect, however, depends essentially on a realistic estimation of the CO<sub>2</sub> capture costs, which are probably underestimated in the industrial sector so far.

## *Policy requirements*

Apart from the technological feasibility three main criteria need to be fulfilled for a large-scale implementation of CCS whether in industry or energy generation: i) a solid regulatory framework for CCS development and application, ii) CCS supporting business conditions and iii) public acceptance.

Economic incentives in CCS can only develop if governments create appropriate political framework conditions. The political support, however, can only be guaranteed for a longer term future if it is backed by public acceptance. Experience shows that public acceptance, in turn, depends crucially on an open and trustful interaction of the different stakeholders with the broader public.

For the realization of reliable political-economic conditions it is necessary to establish economic incentives for a reduction of CO<sub>2</sub> emissions. Different economic incentive systems are already in place or will be installed in the near future as for instance the carbon trading market in the EU and Australia, carbon pricing and performance standards for new-built plants in the U.S., and fixed and future warranted prices for energy from plants applying CCS in the UK. Even though the carbon price is presently still very low the following incentive measures are expected to be fundamental to CCS in the future: i) carbon pricing as a first step, ii) performance standards for first new-built but later also old plants and iii) standards for long-term competitive prices.

Future projections for CCS show that its deployment will take place mostly between 2050 and 2100. At the moment, however, it seems not to be possible to make any reliable predictions for CCS implementation. One of the biggest challenges in implementing CCS is for example that the new-built and retrofitted plants will have to be able to compete with the old fleet of power plants. As long as there are no reliable political framework conditions which allow a reliable estimation of the economic feasibility of CCS no concerted driving of CCS can be expected.

### *Public acceptance*

As already mentioned above, public acceptance of CCS plays a key role for the deployment of carbon capture. In most OECD countries public consensus is a precondition for any government action. Also the success of individual carbon capture projects depends crucially on the perception and support of the people who might be affected directly due to health and environmental risks in the capture, transportation and storage chain of CCS.

In order to achieve public acceptance several points seem to be particularly relevant. Firstly, CCS needs to be communicated as climate change mitigation tool particularly with its relation to other strategies in the climate change mitigation portfolio. In Germany, for example, investments in CCS are perceived skeptically, among other reasons also because it is feared that they could cause a reduction of investment in renewable energies. It thus seems to be important to

point out CCS as additional measure complimentary to other climate change mitigation efforts. Generally, public acceptance can only be achieved if the people can truly trust the information they receive. An honest, transparent and upfront communication based on independent expertise is essential for this trust development. Potential risks must not be concealed but should be communicated openly and addressed early. Ideally, all relevant data should be made publicly available as early as possible. All scientists involved in the risk assessment around carbon capture need to be financially and intellectually independent. Also the public needs to have the chance to express questions or concerns that are seriously taken into account by the responsible scientists. Only if the public is engaged at an early stage and has the chance to contribute to the overall development a thorough acceptance seems likely.

## 2. Environmental Impacts of Carbon Capture Technologies

A thorough assessment of all technologies relevant for CCS is crucial for the development of future predictions on the deployment and implementation of CCS as a climate change mitigation tool. Since the IPCC Special Report on CCS in the year 2005 the maturity of nearly all technologies is now judged slightly more conservatively.

For the capture process itself, oxy-fuel combustion is now considered to be in the research/demonstration state. Post-combustion with chemical solvents and pre-combustion with physical/chemical solvents are

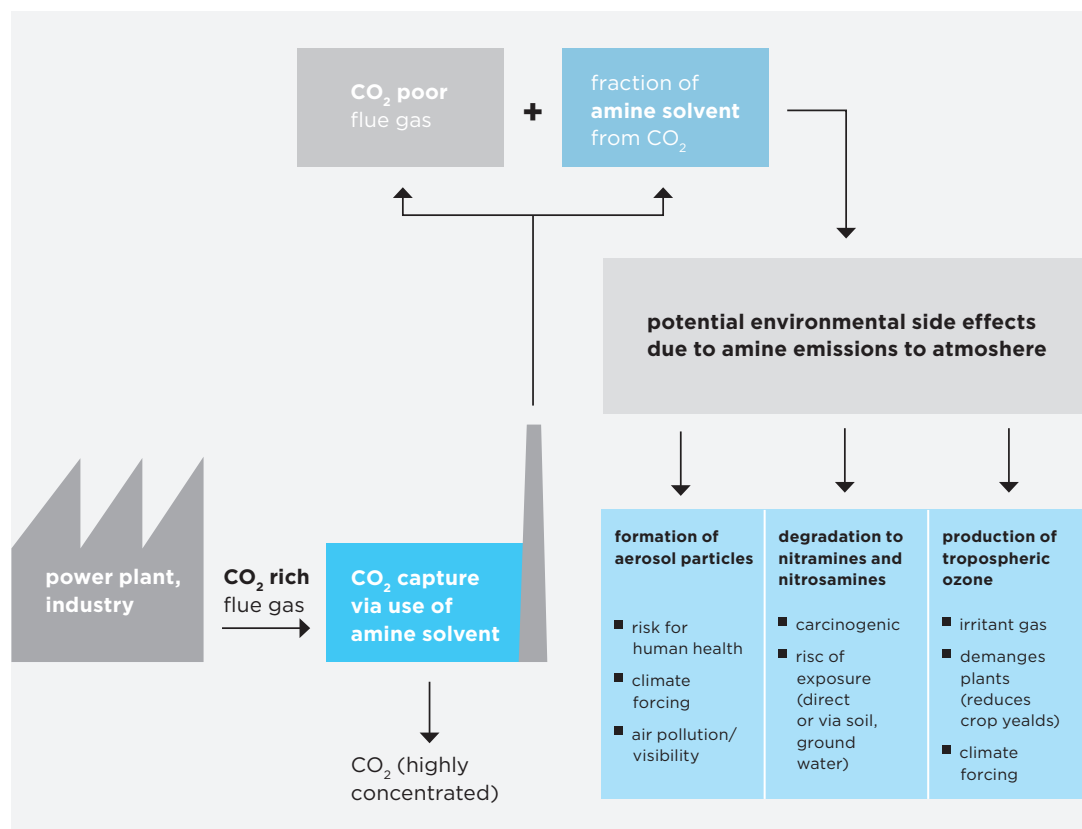
judged to be in the demonstration phase and to be economically feasible for certain applications and under certain conditions. Air capture has entered into the debate but is seen at the very beginning of its development. Most mature post-combustion capture technologies that may even be used for retrofitting existing plants are particularly amine scrubbing and also the chilled ammonia technology. In this section the potential environmental impacts will be discussed only for technologies that can be suitable for retrofitting existing plants.

## 2.1 Amine scrubbing - Unintentional emissions, fate and degradation of amines

At present, amine scrubbing is considered to be the most mature CO<sub>2</sub> capture technology with a long history of experience and is expected to be the first technology to be deployed. Amine scrubbing was invented around 1930 using an amine absorber solvent for the capture of CO<sub>2</sub>. As side effect of the amine scrubbing process, a small fraction of the amine solvent is released to the atmosphere. Amines themselves are considered not to be very dangerous. In the

atmosphere, however, these unintentional emissions of amines can lead to a variety of environmental side effects. Here, we will discuss four aspects of potential side effects in detail:

- 1) the formation of carcinogenic nitramines and nitrosamines,
- 2) the formation of secondary aerosol,
- 3) the production of tropospheric ozone and
- 4) the risks from hazardous amine solvent waste.



**Fig 1:** Schematic overview over potential side effects of CO<sub>2</sub> capture via amine scrubbing. During the capture process a fraction of the amine solvent is released to the atmosphere where amines can lead to the formation of aerosol particles and the production of tropospheric ozone and where they can also degrade into carcinogenic nitramines and nitrosamines.

### *Formation of nitrosamines and nitramines*

There is broad interest in understanding the degradation of amines to nitramines and nitrosamines. Nitrosamines are known to be potent carcinogens. Also nitramines are expected to be carcinogenic, but detailed studies on the health impacts of nitramines are still insufficiently available. At the moment a very conservative safety limit for nitrosamine concentration (e.g. in Norway) lies at 0.1 ppt. This safety level, however, is too low to be measured. Therefore, detailed modeling calculations are highly relevant. For nitramines the safety limits are unclear due to the insufficient studies on their health impacts.

In the atmosphere the formation of nitrosamines and nitramines depends on the availability of  $\text{NO}_x$ . Directly in the plume of a power plant, however, no formation of nitrosamines and nitramines is expected because the high  $\text{NO}_x$  concentration in the plume scavenges the OH radicals, which are necessary for the amine degradation. Recently, amines in the atmosphere were also shown to degrade partially into imines. In order to assess the degradation products of amines thoroughly, therefore, not only the direct degradation products of amines need to be considered but also the further fate of imines.

Additional to their formation in the atmosphere, nitramines and nitrosamines could also be formed in the scrubber before evaporation to ambient. The processes in the scrubber leading to such nitramine and nitrosamine formation and their potential impacts are still unclear and need to be addressed in the future. Despite their carcinogenicity nitrosamines are expected to have limited impact because they photolyse efficiently which limits their atmospheric lifetime significantly. Nitramines, in contrast, do neither photolyse nor hydrolyse and will therefore end up in soil and ground water where they could potentially represent risks to human health and the environment.

### *Formation of secondary aerosol*

Recent results from the CLOUD project at CERN show that amines can contribute very effectively to the formation of secondary aerosol particles. The amount of particles that can be formed will be higher

at lower ambient temperatures and will also depend on the relative humidity. It is expected that lighter amines will go to the gas phase while the heavier ones will rather lead to the formation of secondary aerosol. The availability of nitric acid seems to play a minor role for the formation of secondary aerosol compared to the presence of amines. However, the formation of secondary aerosol could vary significantly between day and night because the availability of sulphuric acid that underlies diurnal and seasonal variations boosts the aerosol formation.

The newly formed particles can potentially even become large enough to serve as condensation nuclei for cloud formation, which in turn could influence cloud properties and climate. An important open question remains how fast the formation of aerosol will happen and particularly whether this process will happen faster than the amine degradation to nitramines and nitrosamines.

So far, all experimental investigations have only been performed for one amine namely DMA. Similar experiments for further species and also at different temperatures are planned particularly for those amines used in carbon capture solvents.

### *Production of tropospheric ozone*

As a third side effect amines emitted to the atmosphere are expected to lead to the production of tropospheric ozone very rapidly and very effectively. A big uncertainty regarding the potential ozone production remains because amines were found to degrade also into imines. The atmospheric chemistry of imines, however, is still unclear to a large extent. The total ozone production potential of amines will therefore likely depend also on the atmospheric fate of imines formed from the emitted amines. Further the production of ozone will depend on the background  $\text{NO}_x$  and VOC levels and the formation of aldehydes at the location of the facility could boost the reaction and enhance the production of ozone. It is still unclear how the production of ozone competes with the other atmospheric reactions. These questions will need to be clarified by future box modeling calculations particularly in order to identify the processes that can be neglected compared to the processes that dominate the atmospheric fate of amines.



## Hazardous amine waste

Beside the potential side effects from amines being emitted to the atmosphere, also the hazardous waste from the amine solvent could lead to adverse environmental effects. In total, the capture of 1 million tons of CO<sub>2</sub> will result in around 3500–4000 tons of amine waste. With improving technologies this amount is expected to go down to 1 kg waste per 1 t CO<sub>2</sub> captured. Still the impact of amine incineration is unclear in terms of a potential formation of CO<sub>2</sub>, H<sub>2</sub>O and potentially even N<sub>2</sub>O and needs to be addressed by experimental investigations.

## 2.2 Other technologies

In this section we give a brief overview over several other post-combustion technologies, namely chilled ammonia, amino acid salts, carbonate cycle, membranes, cryogenic separation, metal-organic frameworks (MOFs), and ionic liquids. Also the oxy-fuel technology, which recently was demonstrated to be suitable as well for retrofitting, is briefly discussed.

## State of development of different carbon capture technologies

Table 1 reports the current state of development of various technologies and the respective time scales for large-scale deployment. For comparison the state of the amine scrubbing technology is also reported.

Currently only chilled ammonia, amine scrubbing and oxy-fuel combustion technologies are technologies at demonstration stage. Globally, 18 new demonstration post-combustion projects are planned including chilled ammonia and ammonium scrubbing technologies and six oxy-fuel projects. Only these technologies are ready to be demonstrated in the power generation sector. However demonstration is still at the beginning. According to the time table reported in table 1 first commercial plants could start to operate by 2023–2025. Commercial plants with 2<sup>nd</sup> and 3<sup>rd</sup> generation technologies could be ready for operation earliest around start 2028–2030 and 2030 respectively assuming that the reported time schedule will be kept.

State of Development	Idea	Basic R & D	Pilot/Field plant	Validation	Scale-up/demonstration	Commercialisation
Plant size			100 kW–1 MW	50–100 MW	200 MW–1 GW	
Lapse of time		2 years	3 years	5 years	5–7 years	5 years*
Technologies and current state of development	<ul style="list-style-type: none"> <li>MOFs</li> <li>Ionic Liquids</li> <li>Carbonate cycle, allothermal</li> </ul>	<ul style="list-style-type: none"> <li>Membranes</li> <li>Cryogenic</li> </ul>	<i>3<sup>rd</sup> generation</i> <ul style="list-style-type: none"> <li>Oxy-fuel with chemical looping</li> <li>Carbonate cycle, externally heated</li> </ul>	<i>2<sup>nd</sup> generation</i> <ul style="list-style-type: none"> <li>Amino acid salts</li> </ul>	<i>1<sup>st</sup> generation</i> <ul style="list-style-type: none"> <li>Amine scrubbing</li> <li>Chilled ammonia</li> <li>Oxy-fuel</li> </ul>	

\* time from start of construction until operation

**Table 1:** State of development of CO<sub>2</sub> separation technologies and lapse of time of the different development stages

## Potential environmental impacts and open questions concerning risk assessment

No data are available on the environmental impact of amino acid salts when used for CO<sub>2</sub> capture from flue gas of power generation units. There is little public information available on volatile degradation products from the amino acid-salt based capture process.

Environmental impacts of this technology have to be investigated for the several amino acid salt candidates. Liquid waste from the reclaimers is of similar nature to the liquid waste generated by the amine scrubbing technology. Furthermore, some of the amino acid salts are used in combination with amines as promoters. In this case, environmental impacts will be similar to those of pure amine mixtures.

The Alstom **chilled ammonia technology** demonstrated at TCM Mongstad, Norway, generates a moderate loss of ammonia to air which was calculated to amount to 0.08 g/s  $\text{NH}_3$  at base case and 2.4 g/s  $\text{NH}_3$  at worse case. The worst case emission was calculated to result in a maximum hourly concentration of 55  $\mu\text{g}/\text{m}^3$ .<sup>3</sup> Base case hourly concentrations thus should be about 18  $\mu\text{g}/\text{m}^3$ . In its gaseous form,  $\text{NH}_3$  has a short lifetime of about 24 hours and usually deposits near the point source.  $\text{NH}_3$  is a precursor to the formation of small particles via the reaction with acidic gases. In particulate form ammonia can travel large distances impacting a larger area. Both gaseous and particulate ammonia contribute to eutrophication of surface waters, soil acidification, fertilization of vegetation, changes in ecosystems, and smog and decreased visibility in cities and pristine areas impacting human health.  $\text{NH}_3$  is deposited via wet and dry processes. The current critical level for ammonia ( $\text{CLE}_{\text{NH}_3}$ ) in Europe is set at 8  $\mu\text{g}/\text{m}^3$  as an annual average concentration. This limit, however, was recently reported to be most probably overestimated by a factor of 2–8 depending on the respective type of vegetation.<sup>4</sup> There is evidence that the current annual  $\text{CLE}_{\text{NH}_3}$  does not protect vegetation in Europe because the Critical Load CLO for N deposition would be exceeded in most ecosystems from the dry deposition of  $\text{NH}_3$  long before any direct effects would be expected to occur on the basis of the current annual  $\text{CLE}_{\text{NH}_3}$ . For lichens and bryophytes a new  $\text{CLE}_{\text{NH}_3}$  of 1  $\mu\text{g}/\text{m}^3$  as a long-term (several years) average concentration and for herbaceous species of higher plants a  $\text{CLE}_{\text{NH}_3}$  of  $3 \pm 1 \mu\text{g}/\text{m}^3$  is proposed. The authors claim that the value of  $3 \pm 1 \mu\text{g}/\text{m}^3$  is likely to exceed the empirical critical load for N deposition for the most forest ecosystems.<sup>3</sup> Considering that the base case emissions for the Alstom chilled ammonia demonstration facility at TCM were estimated to amount to an hourly concentration of about 18  $\mu\text{g}/\text{m}^3$ , it appears likely that ecosystems could be influenced negatively by the additional  $\text{NH}_3$  emissions. Since  $\text{NH}_3$  emissions can be lowered sufficiently by acidic wash down to even less than 1 ppm in the flue gas, we suggest discussing the necessity of  $\text{NH}_3$  abatement

installation in the framework of  $\text{CO}_2$  scrubbing with chilled ammonia. The reported base line and worse case emissions correspond to respectively 5 and 149 ppm in the flue gas and could therefore be most probably sufficiently abated.<sup>3</sup>

**Oxy-fuel technology** with chemical looping in addition generates particle emissions from the air reactor. Indirect environmental impacts of oxy-fuel and chilled ammonia technologies are related to the high energy consumption of both technologies including the energy penalty for producing the large amounts of energy required for ammonia production.

$\text{CO}_2$  capture via **carbonate looping** mostly generates particle emissions. Promising approaches with an indirect fired calciner are currently being investigated and could require significantly less energy in the  $\text{CO}_2$  capture process than other technologies which in turn would also reduce their environmental footprint. The more mature directly fired carbonate looping technology will have an energy consumption similar, even if somewhat lower, to oxyfuel technology.

The environmental impacts of **cryogenic separation** are mainly related to the high energy demand of this technology.

The environmental impacts of **membrane** use will depend on the membrane type and absorption material implied. The use of membrane technologies will require an energy intensive pre-treatment of the flue gas. Further membranes require a pressure differential. Therefore either the flue gas has to be compressed or a vacuum has to be established at the permeate side. In summary the total energy consumption of membrane capture systems will be most probably only slightly lower than for aqueous systems.

<sup>3</sup> T.F. Berglen, D. Tønnesen, C. Dye, M. Karl, S. Knudsen, L. Tarrasón, *CO<sub>2</sub> Technology Centre Mongstad – updated air dispersion calculations, OR 41/2010, Update of OR 12/2008, Norwegian Institute for Air Research, NILU*

<sup>4</sup> J.N. Cape, L.J. van der Erden, L.J. Sheppard, I.D. Leith, M.A. Sutton, *Environmental Pollution* 157 (2009) 1033–1037

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## 3. Open research questions

For the technologies surveyed above, particularly amine scrubbing and chilled ammonia technology, the following research questions need to be addressed:

- Real emission measurement data of amine and ammonia emissions need to be obtained to lay the basis for further quantitative research.
- A detailed understanding of the atmospheric chemistry of imines is required to allow for addressing the entire atmospheric life cycle of amines.
- The formation and distribution of nitrosamines and/or nitramines under different meteorological conditions should be quantified by the help of regional 3D modeling.
- The ozone production potential of amines needs to be quantified by box modeling.
- The aerosol formation from MEA and other amines used as CO<sub>2</sub> capture solvents needs to be investigated experimentally.
- Deployment scenarios need to be developed in order to estimate the total environmental impacts resulting from large scale deployment of CCS in different regions of the world.
- The exact impacts of nitramines on human health need to be investigated in toxicological studies.
- The critical limits for NH<sub>3</sub> exposure to different ecosystems need to be reassessed.

## Summary

In this perspective paper we have given an overview on the current critical issues around carbon capture. We have surveyed the state of development of various carbon capture technologies and discussed their potential environmental impacts. Particularly for the amine scrubbing technology which is considered to be the most mature CO<sub>2</sub> capture technology, we have discussed the potential side effects arising from emissions of amines to the atmosphere. Amines are

known to lead to the formation of nitramines and nitrosamines and secondary aerosol. Also they can lead to the production of tropospheric ozone. In this context we have compiled a list of research questions which should be addressed in the near future in order to ensure a thorough assessment of the respective carbon capture technologies. ■



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