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Communicating scientific uncertainty for decision making about CO_2 storage

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Abstract

As the severity of the global CO_2 problem gradually is becoming clear to everybody, decisions will have to be made concerning permitting of carbon storage projects. Fossil fuel based power plants can produce energy at competitive prices with other energy sources even if equipped with capture facilities. Thus, the fossil fuel industry is ready to implement carbon capture and storage (CCS) once a CO_2 tax regime or its equivalent is introduced. Questions associated with accounting for leaky storage reservoirs over millennial time scales in a carbon credit regime and estimating impacts of CO_2 on climate and ocean ecosystems will then have to be addressed in order to estimate the benefits and possible damage from any given storage project. Available environmental models for such questions have only limited validation data but are foreseen to play a key role, and acquisition of required site specific data may be costly. Experience from the past 15 years of research on CO_2 storage options and the associated science – policy interface suggests that uncertain models tend to be trusted too much by policy makers. In some cases, good intentions for environmental protection lead to a compartmentalized approach that is unsuitable for global problems where tradeoffs may be inevitable. In conclusion, the likelihood of poor environmental management decisions on carbon storage is large and the actual need for alternative solutions to the CO_2 problem is larger than proponents of CCS may like to think.

Keywords: climate change, carbon storage, carbon capture, oceans, energy, fossil fuels, CO_2 injection.

1. Introduction

The CO_2 problem may well be the most severe environmental challenge facing mankind. The amount of CO_2 that has already been emitted to the atmosphere will affect the earth system for thousands of years. The emissions are still rising and are very likely to do so for several decades. An option which has been proposed to curb the effective emissions is that of direct storage of CO_2, mostly from large

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fossil fuel power plants, into geological reservoirs or the deep ocean. This raises several questions where environmental modeling has been used and will have to be used in decision making. One key question is whether the stored CO_2 can be expected to remain in place permanently or for long enough so that leakage to the atmosphere or ocean will not give significant climate change or ocean acidification effects for future generations. Carbon credits should only be given if this can be assured. Associated questions are what certainty is needed to make decisions, and whether it is acceptable to make trade-offs between impacts in different compartments of the earth system (ocean, atmosphere) and between impacts experience at different times (*e.g.,* this century and a thousand years later).

Modeling inevitably enters this arena primarily because of the long time scales involved and partly because of the complexity of the earth system response that needs to be understood when making globally significant perturbations to cycles of a key element like carbon. There is no way to make a global carbon emission and storage experiment like the present one with large emissions to the atmosphere and associated indirect storage in the ocean, and then afterwards decide on long term policy by learning from the measured response. There also seems to be no past event in earth history that is sufficiently similar to the present situation to be of much use. If there were, the observations of earth system response from that time would be indirect by proxies and very incomplete in spatial and temporal coverage. In effect there is no good way to test or validate the environmental models needed for present day decision making. For reasons that are somewhat obscure and probably go well beyond natural science, public trust in relevant modeling results may however be high.

Particularly for geological storage, the porous media in which CO_2 is planned to be stored are notably heterogeneous with relevant properties such as permeability varying by many orders of magnitude on centimeter scales. The lack of detailed data from any long term storage experiment in such a reservoir precludes model history matching, not to mention prediction for other reservoirs. Yet projects are being planned based on not much more data than those typically involved in exploring for oil and gas: seismic profiling from the surface supplemented by core data with rock and fluid properties from a single well cutting through the formation. When such data are used as a basis for field development decisions, the stakes are the money spent on exploration costs, and the potential revenues are those associated with the market value of the oil and/or gas. A 50% success rate is acceptable. When such data are used for decision making about CO_2 storage however, an annual leakage rate of 0.1% of the CO_2 stored in place can be shown to be unacceptable from a global climate perspective, *i.e.,* even without considering any local environmental impact. Can we have sufficient confidence in the models to make predictions at such accuracy for several millennia into the future?

CO_2 is not only a greenhouse gas, which alters the radiative balance in the atmosphere, but it also acidifies ocean waters after ocean uptake. Adding CO_2 to seawater leads to a shift in the balance between carbonate and bicarbonate ions with the indirect, but rather immediate effect that the availability of calcium carbonate is reduced. Many marine organisms including both warm and cold water corals make their shells of calcium carbonate. Thus their growth rate is reduced and with increased CO_2 pressure they will even start to dissolve. For cold water corals at high latitudes where the effects happen faster and penetrate deeper into the water column than in warm water at lower latitudes, such dissolution is expected in the present century for almost all conceivable carbon emission scenarios. In case of direct deep ocean storage or leakage from subseabed geological storage, high carbon concentrations may also lead to additional acute effects in a range of organisms, but only on the local scale.

The present paper is intended to provide an introduction to carbon storage emphasising aspects relevant to environmental models and their use in decision making. The following section gives a short primer on carbon (dioxide capture and) storage. Thereafter comes a somewhat personal tour through 15 years of interaction with researchers and policymakers on development of direct carbon storage in oceans as well as in geological reservoirs. The problem of estimating and ultimately costing damage to the climate system from future leakage is addressed in section 4, followed by a critical discussion of the role of environmental modelling envisaged in present guidelines for permitting subseabed carbon storage. The windup in section 6 includes some prospects for development of carbon storage decisions in the near future.

2. Carbon storage: what is it?

The Kaya equation (named after Professor Yoichi Kaya, Japan) gives CO_2 emissions as:

$$CO_2 = N \times (GDP/N) \times (E/GDP) \times (CO_2/E), \qquad (1)$$

showing that one or more of the four factors population (N), wealth (GDP = Gross Domestic Product), energy intensity (E/GDP where E is energy use) or carbon intensity (CO_2/E) has to be reduced in order to reduce total emissions (Kaya, 1995). Experience has shown that there is limited scope for reducing energy intensity as countries improve their standard of living. Historically there are only a few cases where it has been possible to reduce carbon intensity, notably in countries which have emphasized nuclear energy such as France. However, the abundance of cheaply available fossil fuel reserves has so far limited development of alternative energy sources. Coal is the most carbon intensive of the fossil fuels and available in such large quantities that it alone could supply the world energy for several centuries. The available amounts of oil are more limited also by political factors, but with the present oil prices (around 100 USD/barrel), it begins to become economically attractive to produce liquid fuels from other fossil sources. Natural gas is the least carbon intensive fossil fuel, abundantly available in many locations, although in smaller energy-equivalent quantities than coal. In addition there are potential huge reserves bound in methane hydrates.

About 40% of the global CO_2 emissions occur in the energy industry, mainly by burning coal in public electricity and heat generation plants. Transport is the second largest source, growing faster than the other sectors and now approaching 25% (IPCC, 2005). Other industries, manufacturing and construction, and other sectors including residential fuel use account for the rest. The IPCC Special Report on Carbon Dioxide Capture and Storage (IPCC, 2005) contains a wealth of reference and background material for sources, capture, transport and storage and cost estimates for these options as well as properties of CO_2, and may be consulted for information not given with specific reference information in the present text.

Technologies for CO_2 capture are mainly focussed on large stationary sources because of the economy of scale, the need to run complex chemical processes often at high pressures and the need for a receiving system for handling the CO_2. In order to decarbonize the transport sector, capture at each mobile unit is not considered feasible. Fuel switching *e.g.,* to hydrogen which may be produced from fossil fuels at large stationary plants is considered more realistic. Thus, if large scale capture and storage is to become a key part of future global energy supply, the capture will still take place at large power plants retrofitted or designed for capture. CO_2 captured at an industrial site would normally be pressurized and/or cooled to a liquid (or supercritical) phase suitable for transport by pipeline or ships. The two types of storage options which have volumetric capacities relevant for the scale of the global CO_2 problem are the deep ocean and underground geological storage.

Geological storage involves injection of liquid CO_2 at high enough pressures to displace the fluids which are naturally present in the geological formation, normally saline water (brine), but possibly also oil in which case enhanced oil recovery may result. The injectivity depends on porosity and permeability of the formation, typically sandstone. Low permeability reservoirs are less suitable because of the high injection pressures required and the possibility for formation damage. Because of the high temperatures encountered when drilling hundreds and thousands of meters below the surface, CO_2 will in almost all cases be less dense than the fluids in the formation and tend to penetrate upwards. Structural properties, such as availability of low permeability seals above the formation, and the properties of faults and fractures are therefore important for the fate of injected CO_2.

Direct ocean storage involves either injection of CO_2 droplets in the open water column with rapid dissolution and transport by ocean currents, or deposition on the deep sea floor. For depths of the order 3000 m and at the relatively cold temperatures of seawater, liquid CO_2 is denser than seawater and would tend to stay near the disposal site, particularly if confined in topographic depressions at the seafloor. Formation of CO_2 hydrate at the interface between CO_2 and water and interaction with sediments on the seafloor could further delay the dissolution into the water column above.

In addition to the economic costs of making and running facilities for carbon capture and storage (CCS), there is an energy penalty associated with the operation. Capture, compression and transport require energy input which in turn requires more fossil fuel to be burnt, captured and stored. The penalty is highly dependent upon the type of power plant, suitable and available technology, transport distance etc. A typical assumed range is 5–20% energy penalty. This is the expected increase in total CO_2 produced in a facility with CCS compared to the CO_2 emitted if no CCS was implemented for the same production of electricity and heat.

3. Development of storage options and perceptions

Capture and storage of CO_2 (CCS) is often considered as a possible bridge from a fossil based energy sector towards carbon-free alternative energy sources. If sufficient economic incentives were provided, *e.g.,* by avoidance of a CO_2 tax which would otherwise apply, available technologies could be applied rapidly in some cases by adding capture facilities to existing power plants. More efficient, energy-saving and economically attractive technologies could be implemented in the design of new plants. However, the typical lifetime of heavy infrastructure in the energy sector is several decades and CO_2 emissions are growing rapidly also from other sectors. Even if the political incentives and technology were to develop favourably and the environmental aspects of CCS could be handled satisfactorily, there are therefore some inherent hard limitations on how fast CCS could handle a large fraction of present and future CO_2 emissions. A key question is whether environmental concerns should or will further limit its application, at least as a short term bridge. If so, the CO_2 problem is even harder and the need for alternative solutions even larger.

Modern studies of carbon capture and storage started with Cesare Marchettis proposal to inject CO_2 from European power plants in the Gibraltar outflow of saline dense water which would transport it deep into the Atlantic (Marchetti, 1977). During the past 30 years, a wide range of capture technologies have been developed although not yet applied to full size power plants due to lack of incentives. Transport of CO_2 in pipelines and by ship is mature technology already applied for enhanced oil recovery and industrial use of CO_2. The longest (since 1996) and largest (1 million tonnes of CO_2 per year) geological storage operation is that of StatoilHydro at the Sleipner gas field in the North Sea. The stored CO_2 in this case does not come from a power plant, but is naturally present in the produced natural gas from the field. The CO_2 is separated from the natural gas (mostly methane) at the offshore platform and injected into the highly permeable Utsira saline aquifer formation situated above the gas field but approximately 1000 m below the seafloor. The operation is motivated by purity requirements for the market value of the natural gas, making it necessary to separate much of the CO_2 anyway, in combination with a Norwegian carbon tax that would be applied to the CO_2 if emitted offshore. A similar operation is now coming onstream for the Snøhvit field in the Barents Sea north of Norway. Onshore storage occurs in several locations worldwide including the In Salah field in Africa and Weyburn in Canada. In the latter case, injection occurs in oil bearing formations and prospects for enhanced oil recovery is a prime motivation.

Even if the ocean has been seriously considered since the 1970s as a primary possible storage reservoir for CO_2 and research on direct ocean storage was performed both experimentally and theoretically throughout the 1990s, the largest purposeful ocean disposal experiments that have been performed so far amount to less than one ton of CO_2 in total and time scales of hours to days for each individual experiment. This is if we exclude the largest CO_2 experiment of all, the release of CO_2 to the atmosphere, the subsequent uptake by gas exchange to the global ocean of between one third and one half of the cumulative emissions since the start of the industrial revolution and the expected final uptake of close to 90% over a time scale of millennia into the future. As mentioned in the introduction, the subsequent ocean acidification has potentially large detrimental effects on marine life. Public attention to this "second", but not necessarily secondary, CO_2 problem has developed slowly and serious scientific efforts to elucidate the effects are only now beginning to be organized and widespread beyond a few pioneering research groups.

Against this background, the development over time of the scientific knowledge and public perceptions of different storage options may illuminate aspects of science-policy interaction. The following is not at all intended as a balanced history of carbon storage science being heavily biased towards references to work that the author has been involved in. Rather it is a collection of cases where interesting responses from the scientific and/or decision making community have been registered.

In 1992, my co-author Helge Drange and I published a paper entitled "Sequestration of CO_2 in the deep ocean by shallow injection" (Haugan and Drange, 1992). The paper dealt with fundamental physical and chemical properties and processes related to CO_2 in seawater. The implications of the study in effect transformed the Marchetti (1977) proposal of using the Mediterranean outflow into a technical option that could be applied anywhere with access to the deep ocean but with need for only shallow water facilities. The publication occurred shortly before the 1992 Rio meeting and created considerable attention. At the time, it had already been realized that simple release of single bubbles or droplets of CO_2 in the upper water column (upper 500 m) would not, except in special cases like Gibraltar, provide a conduit to the deep ocean. This was also before the development and demonstration of large and relatively cheap deep ocean pipelines, so deep ocean storage was considered by many to be prohibitively expensive. While we made important caveats about biological effects in the paper, such aspects received little attention. Technological optimism prevailed and many believed that if the climate problem became sufficiently serious, one could elaborate and roll out CCS as a fallback option. But strong action was not yet called for.

In 1996 we published a paper on "Effects of CO_2 on the ocean environment" (Haugan and Drange, 1996) contrasting the rapid anthropogenic pH reduction (acidification) in global ocean surface waters due to emissions with the localized effects of direct storage. Primarily we pointed out the global character of the largest of all CO_2 ocean storage experiments (via emissions to the atmosphere) and how different and unique this is compared to all known glacial to interglacial environmental changes in the ocean. The paper was hardly noticed. Admittedly it was a short and relatively simple paper, published in a less visible journal, and our limited expertise made us stick to chemical environmental changes, their measurable amplitudes, spatial scales and rates. But even when skilled ocean biologists and ecologists started to publish alarming reports on measured effects of increased CO_2 on organisms, there was a very slow development of awareness.

Finally the Intergovernmental Commission (IOC) together with the non-governmental Scientific Committee on Oceanic Research (SCOR) hosted an important conference in Paris in 2004 on "The Ocean in a High CO_2 World". Interestingly it was the appointed science committee which initiated a change in the focus for the conference from potential direct storage projects in international waters which was the prime concern of governments to acidification due to atmospheric emissions, which the scientists felt was a much more pressing issue. International science programs now have ocean acidification on the agenda and a followup conference was held in Monaco in 2008. The volume and topical breadth of research activity on ocean acidification is however still limited, indicated by the fact that 4 years is considered an appropriate time to develop sufficient amounts of research results to justify a new conference.

Government interest in ocean acidification due to emissions boosted temporarily in Norway in 2005/2006 when this second CO_2 effect was seen as another argument for allowing and stimulating subseabed geological storage projects (Haugan *et al.*, 2006, a commissioned report within the Oslo-Paris convention on protection of the North-East Atlantic, OSPAR). We will return to OSPAR in section 5, but for now just note that government interest in potential negative effects of CO_2 emissions on the oceanic environment has not yet had any measurable effect on stimulating any other technologies or options than CCS.

The ocean holds a special and sacred status for many people and many cultures throughout the world. It is a global commons and the precautionary principle has been used in many cases to limit or prohibit pollution and negative influences. From 1997 to 2002/2003 an international project (Japan, USA, Canada, Australia and Norway) on direct ocean storage of CO_2 was executed involving laboratory and field studies and modelling. The final culmination of the project was planned as an experiment releasing up to 5 ton of CO_2 at intermediate depths in the ocean (800 m; too shallow for long term storage but deep enough for hydrates to form and relevant lessons about spreading and dissolution to be learnt). First, public opposition prevented the planned experiment from taking place at the Kona coast of the Big Island of Hawaii. A combination of indigenous population religious concerns specifically about the planned experiment site, more general interests of international pressure groups, and complicated and time consuming US permitting procedures, forced the project to move the experiment elsewhere. Then just a few weeks before a re-designed experiment was to take place off the mid-Norwegian shelf, permits given by the Norwegian State Pollution Control Authority to run the experiment were overruled and withdrawn by the Norwegian minister of

Environment. Thus the project had no controlled experiment as basis for the models, but was left to make best possible use of measurements of existing natural seepages of liquid CO_2 through the seafloor which ironically do occur at large rates on the other side of the Big Island of Hawaii.

Returning to Norway, the reasoning presented by the minister is interesting. He stated that it is uncertain whether international law and regulations will permit large scale application of ocean storage of CO_2. Therefore it would not be appropriate to perform scientific experiments to learn more about this option and its potential impacts. While such decision is unfair and illogical, it was probably politically correct for a minister wishing to preserve an impression of protecting the ocean environment. (See Haugan, 2002, for further background and interpretation). Later it was confirmed that OSPAR, which was explicitly referred to by the minister, can not be applied to stop or prohibit scientific experiments. But by that time, the project had run out, the money was used up, and many scientists, both those directly involved in the project and others with interest in ocean storage, had turned away from the subject, realizing the extreme sensitivity of direct ocean storage in many influential decision making parties.

So, nobody takes the responsibility for the greatest ocean CO_2 storage experiment of all, that which has been going on for 200 years via emissions to the atmosphere. But being associated with small scale experiments in a localized site is considered to be so harmful for the public image of the responsible government that permission is not granted. In the present context, we note that the main objective of the experiment was to provide observations of phenomena (dissolving droplet plume dynamics, effect of hydrates and turbulence on dissolution, density effects on “peeling” etc.) which presently are represented in models with only theoretical parameters that cannot be determined in small scale laboratory tests. Thus, for estimating the efficiency and impacts of direct ocean storage we still have to rely on environmental models with untested process parameters.

At present, focus in Europe and mostly also in North America has turned to geological storage. Japan however which is plagued by high seismic activity and therefore hosts considerable public scepticism towards geological storage, maintains a substantial research programme on direct ocean storage. Interestingly this occurs in a country and culture with strong ties to the ocean and a genuine interest in preserving and utilizing the ocean environment. Key issues in geological storage in addition to capacity, efficiency and injectivity, are potential leakage pathways through abandoned wells, faults, fractures and imperfect seals as well as potential seismic events on time scales of millennia. Most of these issues require site specific data and future seismic activity is difficult to predict. In contrast ocean storage occurs in a medium of known properties and relatively uniform conditions at least in the deep sea. Thus, the challenge of developing credible process and prediction models for the fate of CO_2 disposed on the deep sea floor seems scientifically more tractable than developing similar models for any given geological reservoir. Both however, have to face the issue of leakage into the water column (if the geological site is subseabed) and into the combined atmosphere-ocean carbon repository.

4. Estimating environmental damage from leaky reservoirs

Haugan and Joos (2004) noted that there are several different metrics which may be used to estimate the damage of leaky reservoirs. Perhaps surprisingly, many of these metrics may be produced by global climate models which are reasonably well validated. This applies to ocean as well as geological storage. The main problem may be that it is hard to decide which metric to use and the choice may matter for estimating the value of any particular storage scheme.

5. Environmental regulations and the use of models

The IPCC Special Report (IPCC, 2005) gives an overview of relevant international law for both geological and ocean storage. Since then some important developments in the OSPAR Convention have taken place. A very similar process is ongoing with the global London Protocol. Due to space limitations, since the two conventions develop in so similar ways, and the first storage projects are expected to be in the OSPAR area, we here concentrate on OSPAR.

In 2007, OSPAR was amended at a ministerial meeting so that industrial scale subseabed geological storage in principle is allowed. Previously the “dumping” of any industrial waste except some materials explicitly included on a reverse list, in the water column or subseabed was prohibited. We note in passing that the CO_2 from the mentioned Sleipner and Snøhvit fields originates in the subseabed. Even if these storage projects have not been tried for OSPAR, they are likely to be formally acceptable. At least they are in principle quite different from any project involving CO_2 from a power plant or other industry. Thus it was clear that an amendment of OSPAR would be required in order to be able to offer geological storage facilities for industrially produced CO_2 in the subseabed in the OSPAR area regardless of whether the industrial CO_2 is produced onshore or offshore and whether it is to be transported by ship or pipeline.

The timing of this is crucial for the present political regime in Norway as several gas fired power plants are being built along the Norwegian coast and promises have been made that these shall shortly become CO_2 free, *i.e.,* with CCS implemented. As a short term solution a capture test facility which is being built at Mongstad close to Bergen on the west coast of Norway plans to deliver CO_2 for ship transport all the way to the Barents Sea in the north, capitalizing on the injection facility used for the Snøhvit field. In the meantime the Utsira formation and another formation closer to shore are being evaluated as possible storage sites for larger amounts of CO_2 to be transported by pipeline once the main power plants come on stream (Publicly available information from Gassnova SF, Norway, 2007; only in Norwegian).

So which procedures are envisaged to test whether these or any other subseabed storage project should be licensed by OSPAR? The political decision already made stipulates that a set of "Guidelines for Risk Assessment and Management of Storage of CO_2 Streams in Geological Formations" should be adopted and used against the individual projects. CO_2 streams from capture processes can be stored into a sub-soil geological formation if:

- The streams consist overwhelmingly of carbon dioxide.
- No wastes are added for the purpose of disposing.
- They are intended to be retained permanently and will not lead to significant adverse consequences for the marine environment.

The guidelines have not yet been formally adopted, but are likely to contain the following modeling-relevant elements taken from draft documents:

- From part 1, Problem formulation: Problem formulation is the scoping of a risk assessment and includes the collection of information that will be used to develop a site-specific conceptual model to direct a site-specific risk assessment.
- From part 2, Site selection: The site selection will typically include a reservoir simulation to assess a potential storage site, *e.g.,* by a three dimensional geological model.
- From part 3, Exposure assessment: The probabilities of the exposure processes, the amount of CO_2 and the spatial and temporal scale of fluxes may be assessed using appropriate numerical modelling tools.
- From part 6, Risk management: Predictive modelling of injection of CO_2 streams should include both flow (reservoir) simulation, prediction of fracturing and fracture propagation, *e.g.,* induced by CO_2 injection, and modelling of geochemical rock-fluid interaction. … These will establish the transport and fate of the injected CO_2 stream and provide the operator with an integrated knowledge sufficient to manage the injection process in an environmentally protective manner. The modelling should provide predictions during the operational injection period and an assessment of the residual pressure fields during the period after shut-in of the injection well and prior to decommissioning. … Modelling should be updated in the light of monitoring results.

An immediate comment to this is that there is an apparent confidence in models to be useful in assessment of the suitability of proposed storage sites and the movement of CO_2 as well as the general conditions in the subseabed. All models for geological storage will depend on site specific data, possibly history matching or 4D assimilation of flow data (*e.g.,* repeat seismic), *i.e.,* updating model parameters after project start. One may ask what level of certainty will be required to shut in an expensive storage operation once it has started, and how such decisions would be reflected back on the carbon credits given.

Papers on subsurface fluid migration, rock properties and interaction between reservoir rocks and fluids including CO_2 in the relevant geological storage chapter of IPCC report are mostly non-peer review oil and gas company reports. Data requirements for site specific subsurface flow models are immense. However, site specific data can be costly to obtain, particularly offshore. Drilling wells also increases the number of potential leakage pathways, and decisions may be difficult.

The limited experience that exists from Sleipner-Utsira shows that reservoir description of this extremely favorable high permeability reservoir had to be updated after a few years since repeat seismic revealed that injected CO_2 penetrated surprisingly rapidly through what was considered impermeable shale layers. No account has so far been taken of effects of pressure buildup on fracturing or the possibility for enhanced release of shallow occurrences of natural gas, nor effects of natural seismic events on millennial time scales.

Present proponents of subseabed geological storage estimate a very low cost of monitoring compared to capture and transport. Capture is to be paid by the companies but storage costs have been accepted as a Norwegian government responsibility allegedly in order to stimulate the development of carbon free fossil fuel power. This cost sharing has yet to be accepted by the European Union and may be problematic to them since it can be seen to affect competition between different power suppliers.

This case illustrates the hurry with which storage projects are being brought forward and need to be brought forward if CCS is to play a significant role in the global CO_2 problem.

6. Conclusions and outlook

It would be easier if environmental impact assessment could be made more generic rather than site-specific. Thus if CCS is needed, storage in the ocean or in sediments just below the deep seafloor where CO_2 is negatively buoyant (House *et al.*, 2006) may be a better option than the geological options which presently seem to be favoured at least in Norway and Europe. Experimental data could be obtained, but legalities are uncertain and there are potential problems with public acceptance. Some other yet unexplored options such as injection into high salinity brine water in deep depressions, *e.g.,* the Red Sea, or injection into anoxic basins, *e.g.,* the Black Sea, could also play a role.

A CO_2 concentration in air of 1000 ppm is the legally determined maximum acceptable level in Norwegian primary school classrooms since higher levels give an unpleasant and ineffective learning environment. Present emissions would lead to similar levels in the global atmosphere before the end of this century. This is just one illustration of the severity of the CO_2 problem and the time scale over which we need to act. Ocean acidification and the multitude of climate changes expected are others.

In order to find ways out of this situation, public perception and its variation across cultures and conditions play significant role in decision making. It is to be hoped that there is also a role for the scientific method in making policy choices.

Burning of biofuels with CCS may be necessary to effectively pull CO_2 out of the atmosphere even if other energy sources are developed rapidly, but a significantly changed attitude towards stimulating and developing the necessary good science to underpin environmental models for carbon storage is required.

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