Status and prospects for CO_2 capture and storage

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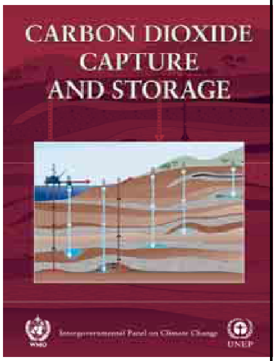
- Introduction to Carbon Dioxide Capture and Storage (CCS)
- Knowledge base in the IPCC Special Report on CCS from 2005
- Some updates and significant recent developments
- A little about science – policy interaction
  (+ possibly even less about
  Climate impact of leaky reservoirs &
  Technology for leakage monitoring)



CARBON DIOXIDE CAPTURE AND STORAGE

www.gfi.uib.no,
www.bjerknes.uib.no
www.bergenmarine.no

Bjerknes Centre
for Climate Research

The CO_2 problem

The Kaya equation (after Professor Yoichi Kaya, Japan, 1995):

CO_2 emissions = N x (GDP/N) x (E/GDP) x (CO2/E),

i.e. four factors:

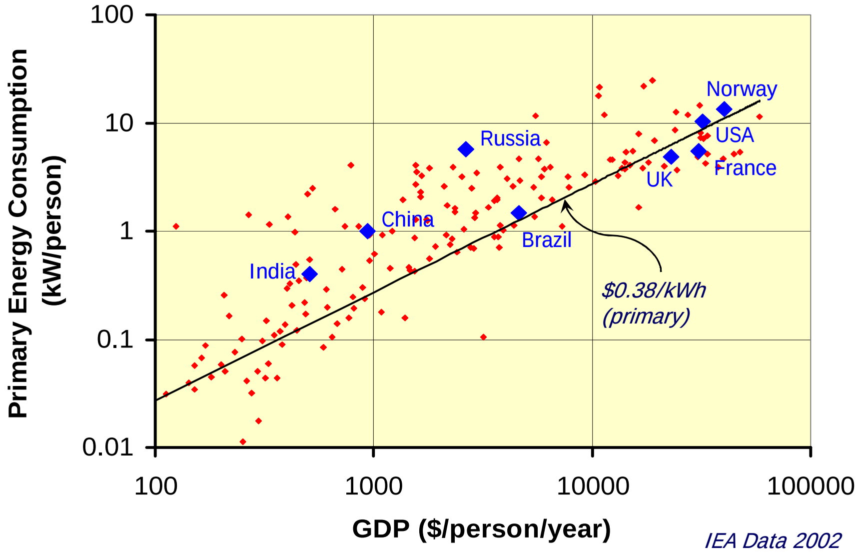
Population, wealth, energy intensity, carbon intensity

Improvements in energy efficiency may reduce the energy intensity in developed economies, but:

Improvement in standard of living in developing countries will increase energy use considerably over the present century

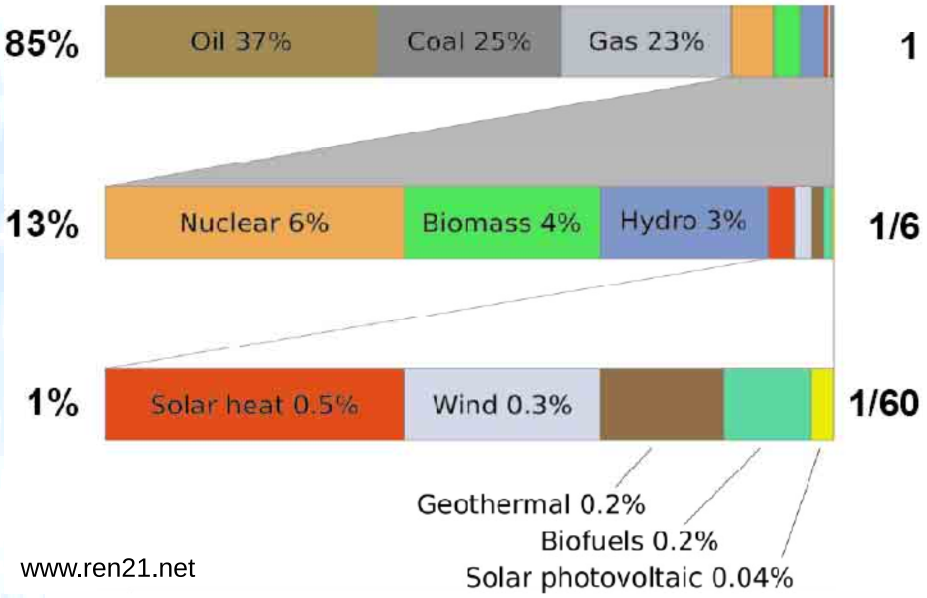
=> Present emissions of 1PgC/yr per capita (3 Gt CO_2) will rise unless carbon intensity can be drastically reduced.

Energy use versus wealth



IEA Data 2002

World energy supply 2005



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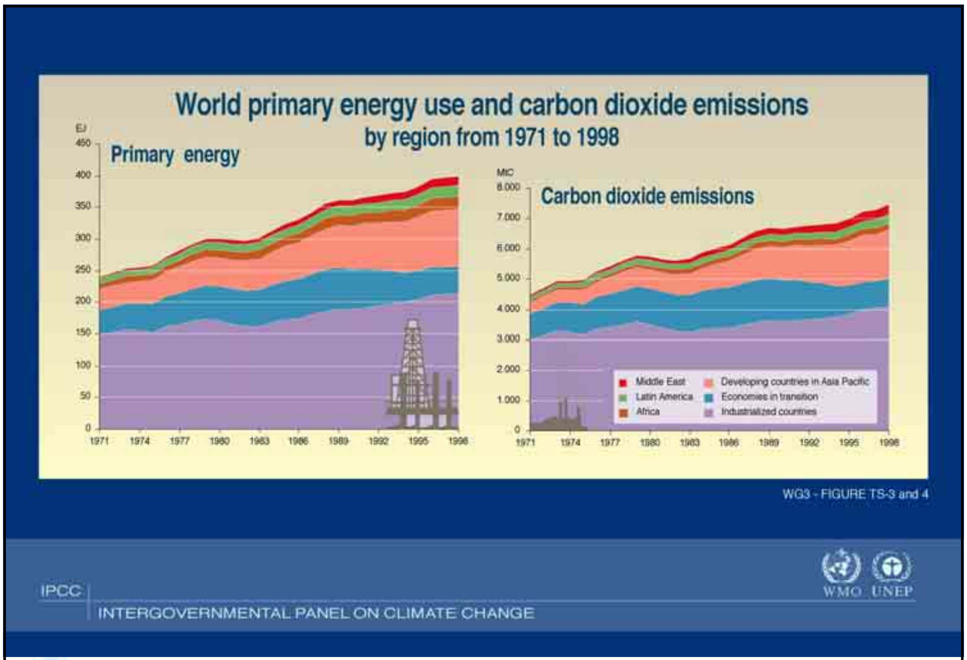


World primary energy use and carbon dioxide emissions by region from 1971 to 1998

WG3 - FIGURE TS-3 and 4

IPCC | INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

It has not been possible to decouple energy use from carbon emissions

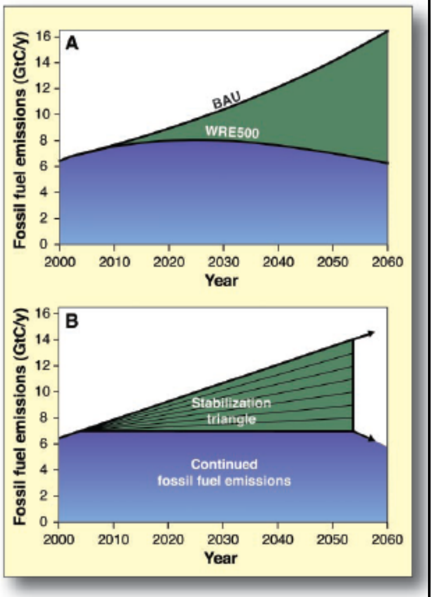
What to do with CO_2 ?

Pacala & Socolow (Science, 2004) introduced 14 potential 1 GtC/year wedges of which 7 are needed to achieve stabilization.

Three involve Carbon Capture and Storage (CCS):

- Baseload power plants (800 GW coal or 1600 GW gas)
- H_2 plant (250-500 Mt H_2 /year)
- Coal-to-synfuel plant (30 million barrels per day)

These would require 3500 storage facilities of the size of one presently existing and in use (Sleipner field - Utsira formation in the North Sea)



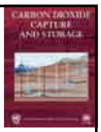
Options and obstacles

Is carbon capture and storage a useful option? - topic of an IPCC Special Report from December 2005

- *Sources, capture, transport, storage, costs, …*
- *Geological including subseafloor storage, but also*
- *Ocean storage:*
  - *Dissolution at intermediate depths in the ocean*
  - *Storage in depressions on the deep sea floor ("lake")*
  - *Ocean options with* $CaCO_3$ *compensation*

Both geological and ocean storage options need to address permanence (leakage, how long is long enough?), costs, environmental issues, public perception, regulation, safety (e.g. geological storage in populated areas)

Sources, capture, transport, costs



CCS applies only to large stationary sources – 40% of present emissions. Transport sector (25%) must first be decarbonized in order to become a target.

Range of technologies for capture depending on type of plant. Some can be retrofitted, cheaper if included in design of new plants.

[Power sector infrastructure lifetime is several decades.]

Tremendous economy of scale in pipeline transport.

Reasonable geographical match between sources and perceived storage sites.

Costs are typically 20-70 USD/ton CO_2 *avoided for coal fired plants, dominated by capture. This applies to both geological and ocean storage (low monitoring costs).*

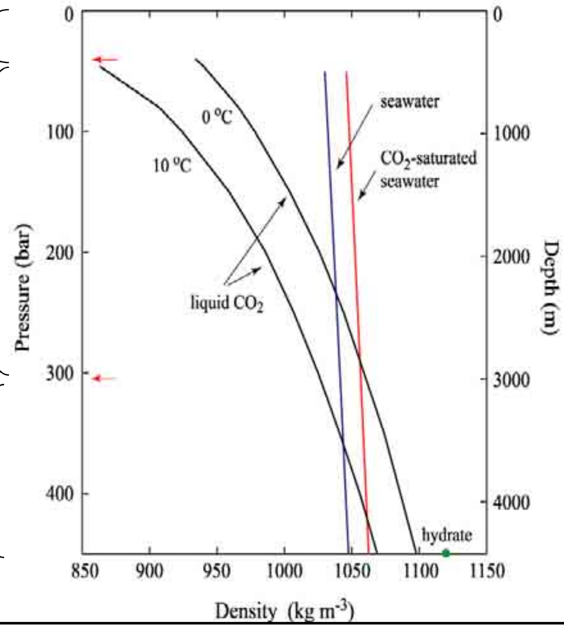
[Personal comment: Except the ocean chapter, most of the authors could be seen as proponents of the technology. Literature base quite different from IPCC WG I.]

Density of liquid CO_2, seawater, CO_2-enriched seawater and CO_2 hydrate

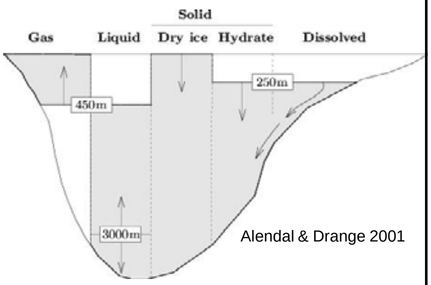
Gas

Buoyant liquid

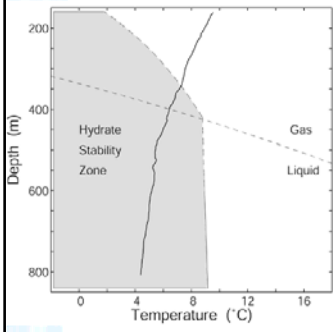
Negatively buoyant liquid

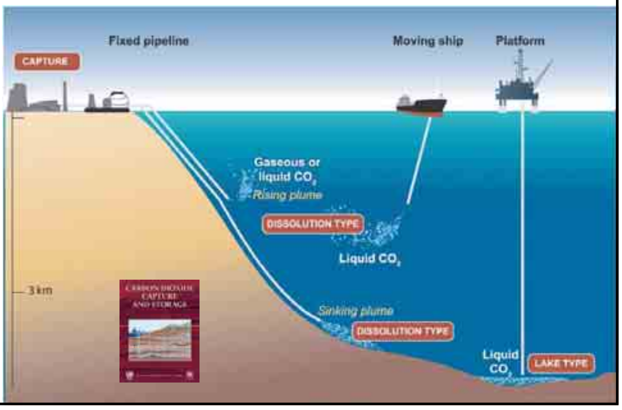


CO_2 properties in relation to seawater and corresponding storage options

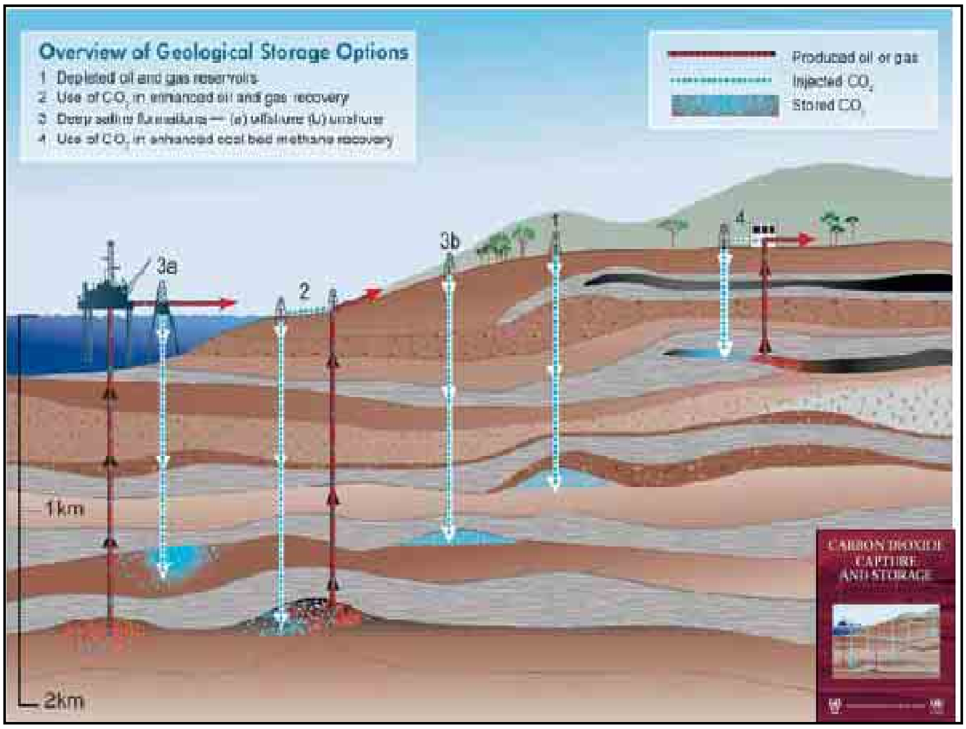


Alendal & Drange 2001





Hydrates are only
metastable,
but hydrate
skin reduces
dissolution
rate



Geological storage

Depleted oil and gas reservoirs and enhanced oil recovery projects have estimated global volumetric capacity up to 1000 Gt CO_2.

Deep saline aquifers: Widespread on continental shelves and on land, estimated to allow at least 1000 Gt CO_2.

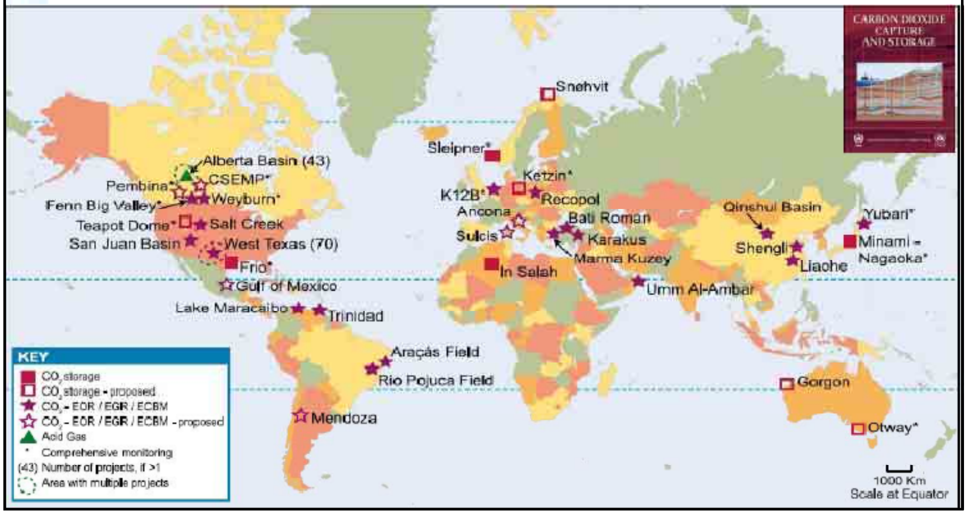
Much smaller expected contributions from unminable coal beds and largely unexplored options like basalts.

Injectivity requires high permeability, overpressuring can compromise structural seal (”cap rock”).

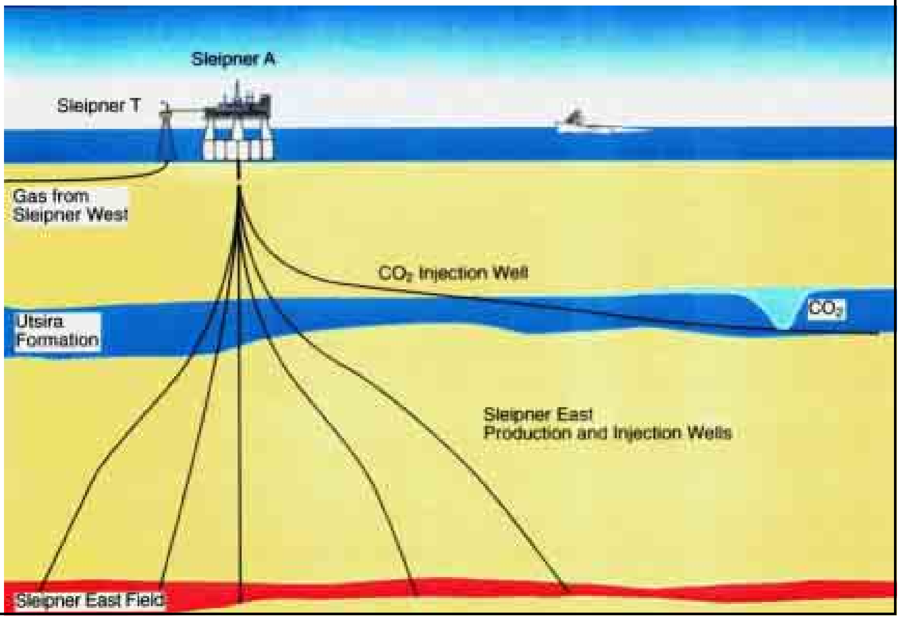
CO_2 is almost always lighter than in situ fluid because of high temperature, so tends to move upwards.

Dissolution in brine and mineralization can occur on longer time scales.

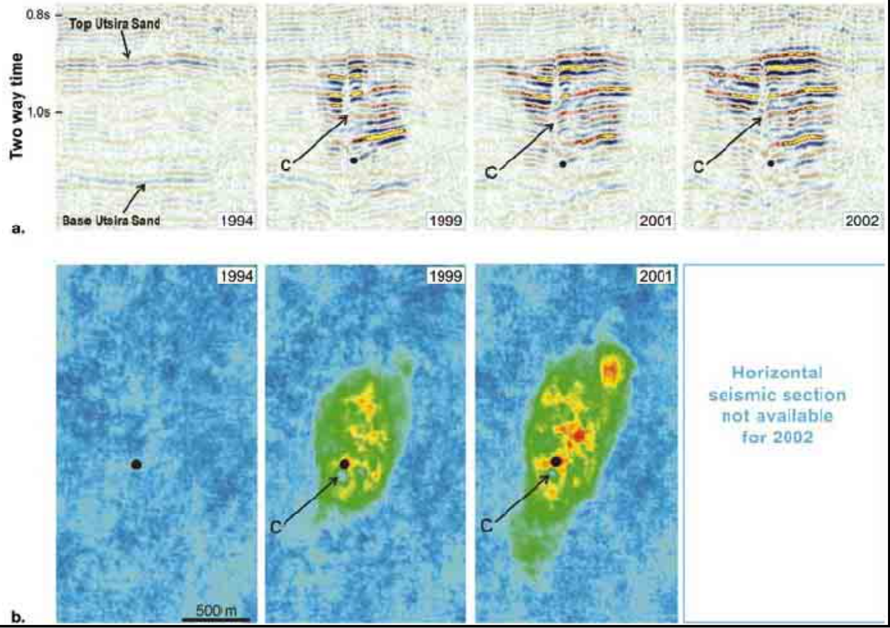
Ongoing and planned CO_2 storage, Enhanced Oil Recovery and Coal Bed Methane projects



Norway ongoing: Injecting 1 Mt CO_2/y from natural gas production at Sleipner into Utsira formation in the North Sea since 1996



Vertical and horizontal seismic sections at Sleipner-Utsira

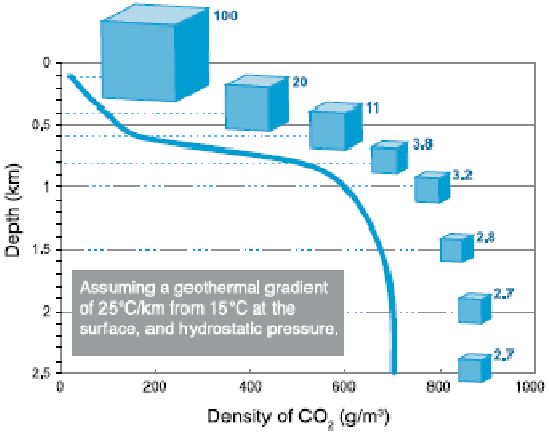


Depth of Utsira close to CO_2 phase boundary

=>Hard to estimate CO_2 in place

Other parts of Utsira are quite clearly in CO_2 gas regime and should be avoided; previous capacities over-estimated.

Still Utsira is probably the most suitable formation in the North Sea because of high permeability and porosity.



Assuming a geothermal gradient of 25°C/km from 15°C at the surface, and hydrostatic pressure.

Ongoing CO_2 storage and related projects

About 3 Mt CO_2/year is presently being stored in aquifers globally.

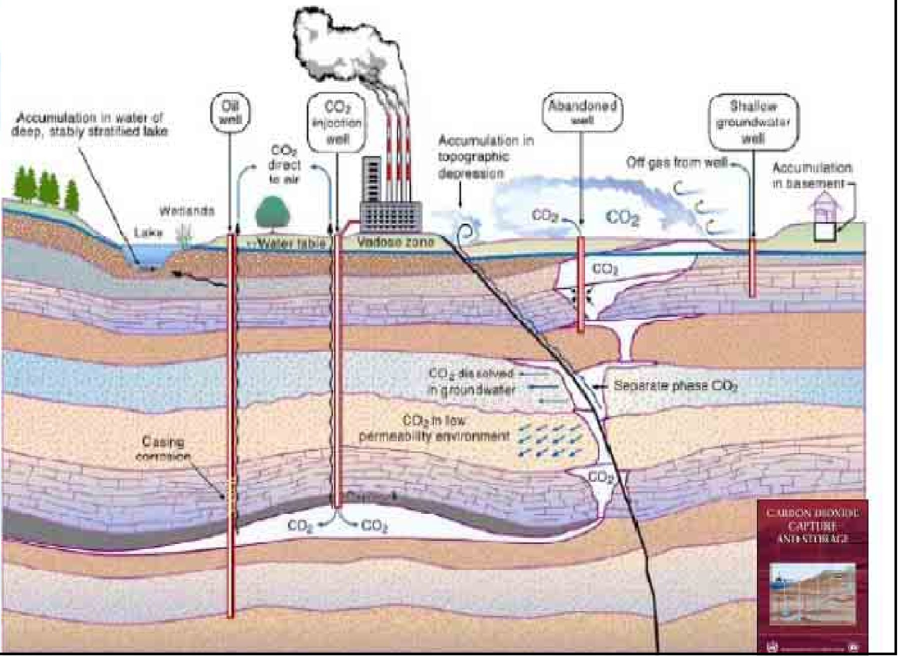
Experience base:

Including Enhanced Oil Recovery projects, a cumulative total of 0.5 Gt CO_2 has been injected up to now.

- Acid gas injection projects
- Natural gas storage projects
- Disposal of brines and contaminants

Numerical petroleum reservoir fluid flow models are being adapted to treat CO_2 including fluid-fluid and fluid-rock interactions. Normally dependent upon production data for history matching (data assimilation) to estimate spatially heterogeneous rock properties.

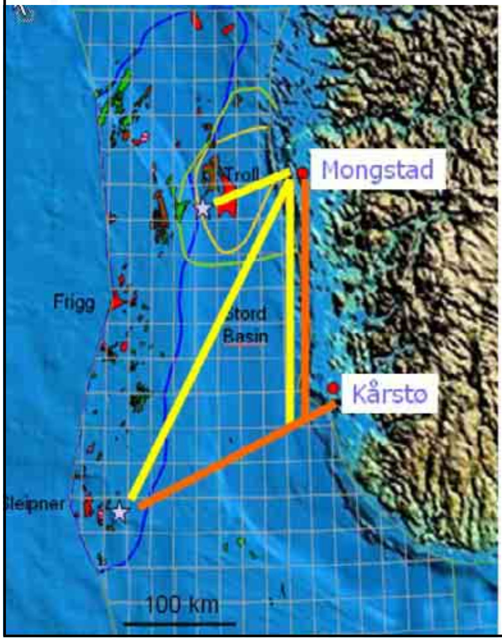
Conditions and processes affecting leakage



Recent trends and developments

- Price of oil soon passing 100 USD/bbl
  - Cost of CCS a decreasing fraction of energy costs.
  - Liquid fuel and transportation fuel may soon be produced cost effectively from other fossil fuels than oil.
- Extremely rapid political acceptance of subseabed storage in OSPAR and London Dumping Convention/Protocol.
- At TCCS-4 conference in Trondheim, Norway, October 2007, there was recognition of surprises at Sleipner and emerging studies of the need for multiple barriers to leakage, yet:
- Almost zero public debate about the possibility for leakage,
- Norwegian government spends at least 1 billion NOK (120 MEuro) in 2008 on CCS, more than 90% on capture, very little on storage and environmental aspects,
- EU is likely to approve the planned Norwegian government paying for storage costs even if this may be seen as subsidies to power companies.

New Norwegian plans 2007

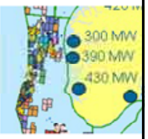


Government position on CO_2

- ”no new powerplants without CO_2 capture”
- Focus on technology developement and demonstration
  - Gassnova
  - CLIMIT : R&D&D program
- Obligations for fullscale realisation
  - Gasfired powerplants with Capture- Kårstø and Mongstad
  - CO_2 transport and storage

Fullscale CCS

- Gas fired power plants Kårstø and Mongstad
  - Kårstø 1,1 Mt/CO2 pr year from 2007, capture 2011/12
  - Mongstad
    - 1,3-2 Mt/y CO2 y from 2014
    - 0,1 Mt/y from 2010
- Capture plants and storage solution under planning
  - Investment decision end 2008



Amendment to the OSPAR convention 2007

(Oslo – Paris Convention on the Protection of the Northeast Atlantic)

CO_2 streams from capture processes can be stored into a sub-soil geological formation[1] 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 London protocol is being amended along a very similar path.

---

[1] The amendment applies only to shelf areas (not deep ocean) and only to storage several hundred meters below the seafloor.

Draft OSPAR risk assessment/management framework

1 Problem Formulation
  Defines the boundaries of the assessment.
2 Site Selection and Characterisation
  Suitability of a site proposed for storage (and the surrounding area)
  Baseline for management and monitoring.
  Capacity and injectivity.
  Design and operation of the injection project.
  Plan for site-closure.
3 Exposure Assessment
  Movement of the CO_2 stream within geological formations.
  Potential leakage pathways
  The amount of CO_2 and the spatial and temporal scale of fluxes.
  Additional substances already present or mobilised by the CO_2.

4 Effects Assessment

Effects on the marine environment, human health, marine resources and other legitimate uses of the sea from leakage.

5 Risk Characterisation

Integrates the exposure and effects to estimate of the likelihood for adverse impacts.

Distinguish between processes relevant to characterizing risks in the nearterm and long-term

Level of uncertainty

6 Risk Management (incl. Monitoring and Mitigation)

Safe design, operation and site-closure.

Monitoring requirements, during and after CO_2 injection.

The performance of the storage.

Monitoring to assist the identification of additional preventive and/or mitigative measures in case of leakage.

After site closure, the monitoring intensity may gradually decrease.

Summary of present state of affairs

Present proponents of subseabed geological storage (Norway, …) estimate a very low cost of monitoring compared to capture and transport.

No proper account has so far been taken of effects of pressure buildup on fracturing of cap rock and enhanced natural (shallow) gas release, microbial reduction of CO_2 to CH_4, or effects of natural seismic events on millennial time scales.

Obtaining site specific data can be costly in particular offshore (drilling wells also themselves constitute leakage pathways), so decisions on whether to allow storage may be made on basis of untested models.

It would be easier if environmental impact assessment could be made more generic rather than site-specific. However geological formations are notoriously heterogeneous.

Carbon sequestration becomes a reality: Significant for 21st century ocean carbon storage?

Present projects are only order 0.01 Gt C/year, but are increasing rapidly, so maybe…

OR

the projects may turn out to be environmentally unacceptable, unreliable or too slow to provide a bridge, in which case the net effect is probably higher emissions because of false beliefs.

Status and future of ocean storage

Less than one ton CO_2 in total has been used in ocean experiments which typically last hours to days.

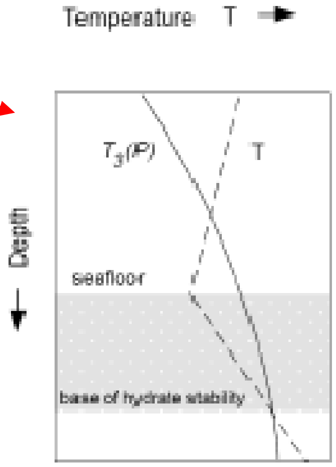
The probably most environment friendly ”versions” are still prohibited.

Only the deep ocean provides cold temperatures and high pressure.

Focus in Europe and US is on geological, but Japan has an active research program on ocean storage.

If geological falls out of favor for cost or environmental reasons, deep ocean may come back.

In a desperate world, CCS from biofuel may be launched. [Included in Norw. geo-project, combined with natural gas.]



House et al., 2006

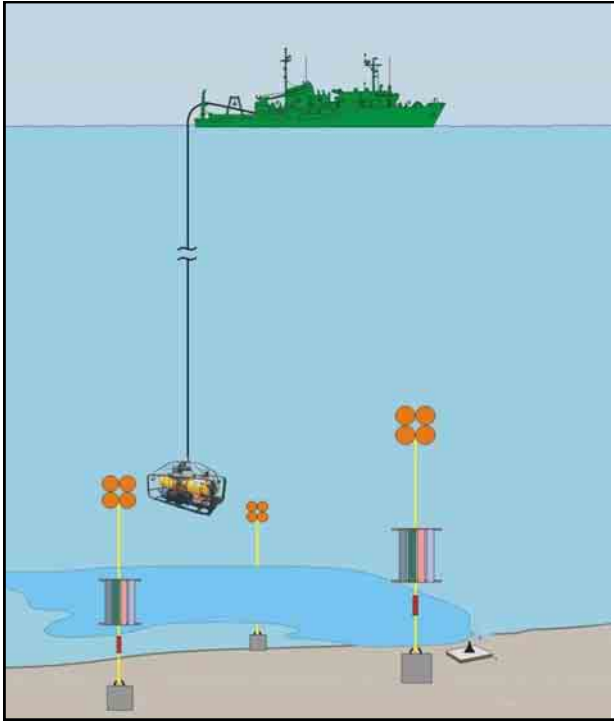
Ocean issues related to CCS

-> dissolution, spreading, acidification and potential biological damage, communication to atmosphere.

In addition to the options studied so far there are some yet unexplored versions:

- Inject into high salinity brine water in deep depressions, e.g. the Red Sea, or
- Inject into anoxic basins, e.g. the Black Sea.
- Inject in deep sea sediments in the negative buoyancy zone where dense phase CO_2 is denser than formation water and hydrates are stable (House et al., 2006)

+ Perhaps others will be found, but time is running out.



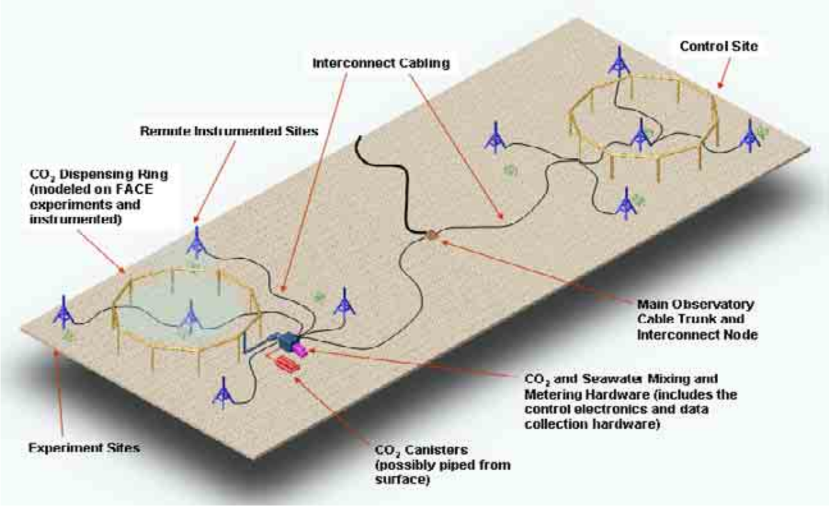
Experiments?

Needed to resolve if CO_2 would be dissolved near the seafloor and create high benthic impact or spread towards the sea surface

Technology for monitoring of leakages and for use in exposure experiments ->

Lars Golmen, NIVA

The Free Ocean CO_2 Experiment (FOCE) Concept



Bill Kirkwood, MBARI, see also Haugan et al GHGT-7

Present state of FOCE

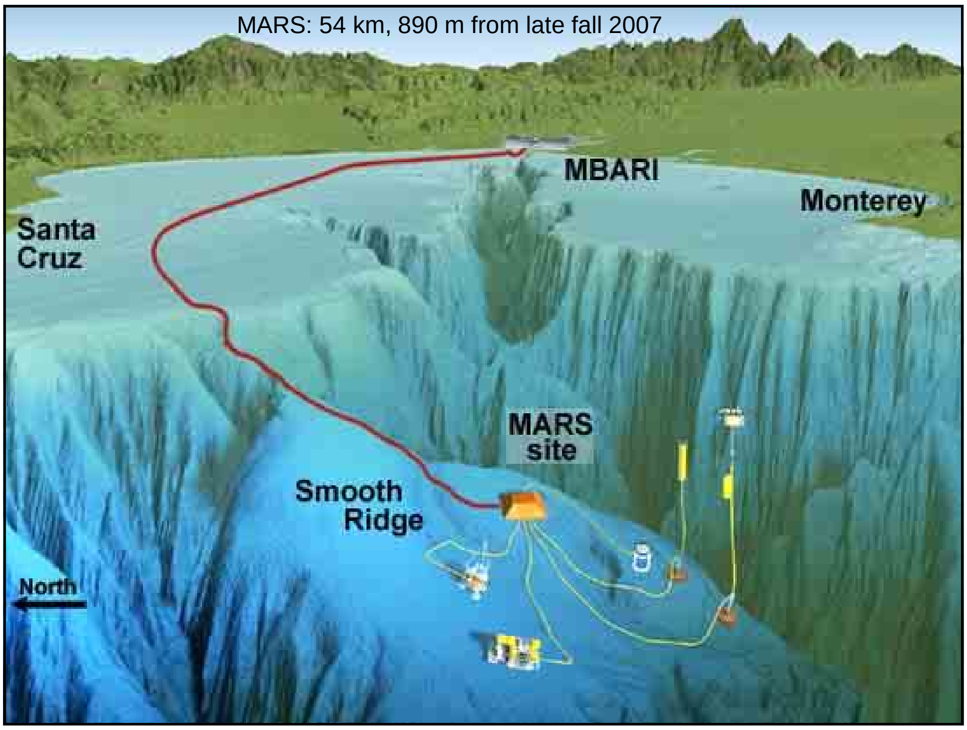
Tests have been done:
- Short term order 1 day
- ROV-based
- Limited amounts of CO_2

Needs to be run longer term with steady CO_2 supply, perhaps in conjunction with cable observatory

Needed for assessment of deep ocean storage, geo-leakage as well as acidification from atm.

Peter Brewer, MBARI

MARS: 54 km, 890 m from late fall 2007



Personal experience with (lack of) public interaction

Direct storage:

- Publication in Nature in 1992 on “Sequestration of CO_2 in the deep ocean by shallow injection” on physical and chemical properties and processes received much attention, Rio meeting, …, but biological effects received much less attention.
- Norwegian Minister of Environment stopped 5 ton ocean experiment in 2002 after Greenpeace/WWF involvement despite approval.

Acidification:

- Very slow development of awareness, finally IOC/SCOR conference in 2004 on “The Ocean in a High CO_2 World” where the science committee initiated change from focus on direct storage (governments) to general acidification.
- Government interest in general acidification due to emissions boosted in Norway/UK in 2005/2006 when this effect was seen as another argument for allowing and stimulating CCS and subseabed storage (Haugan/Turley/Poertner (2006), a commissioned report within the Oslo-Paris convention on protection of the North-East Atlantic)


Directorate for **Nature Management**

Utredning 2006-1

Effects on the marine environment of
ocean acidification resulting from
elevated levels of CO_2 in the atmosphere

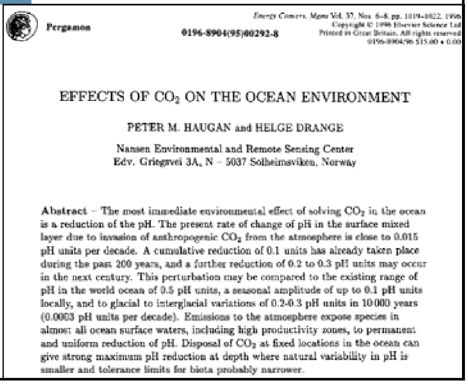
Report (ab)used to push for OSPAR amendment,

not used to push any other carbon reduction

OSPAR report March 2006

Politically neglected paper(s) on acidification

Publication 1996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EFFECTS OF CO_2 ON THE OCEAN ENVIRONMENT

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Abstract – The most immediate environmental effect of solving CO_2 in the ocean is a reduction of the pH. The present rate of change of pH in the surface mixed layer due to invasion of anthropogenic CO_2 from the atmosphere is close to 0.015 pH units per decade. A cumulative reduction of 0.1 units has already taken place during the past 200 years, and a further reduction of 0.2 to 0.3 pH units may occur in the next century. This perturbation may be compared to the existing range of pH in the world ocean of 0.5 pH units, a seasonal amplitude of up to 0.1 pH units locally, and to glacial to interglacial variations of 0.2-0.3 pH units in 10 000 years (0.0003 pH units per decade). Emissions to the atmosphere expose species in almost all ocean surface waters, including high productivity zones, to permanent and uniform reduction of pH. Disposal of CO_2 at fixed locations in the ocean can give strong maximum pH reduction at depth where natural variability in pH is smaller and tolerance limits for biota probably narrower.

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Geological Storage of CO_2;
the marine component

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A review project funded by Climit and executed by

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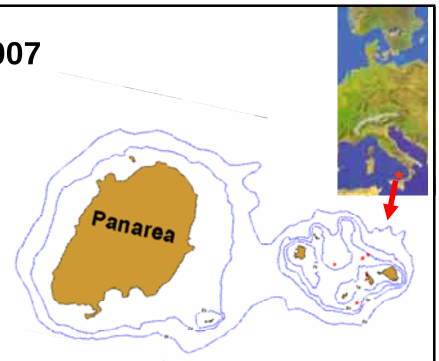
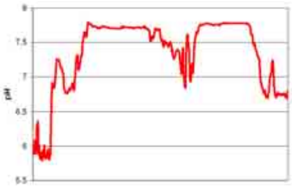
[2]Christian Michelsen Research (CMR),
University of Bergen;
  [3]Geophysical Institute,
  [4]Department of Mathematics,
Unifob;
  [5]Bergen Center for Computational Science

Panarea field studies, Sep 2007

Work at the Panaera area so far:

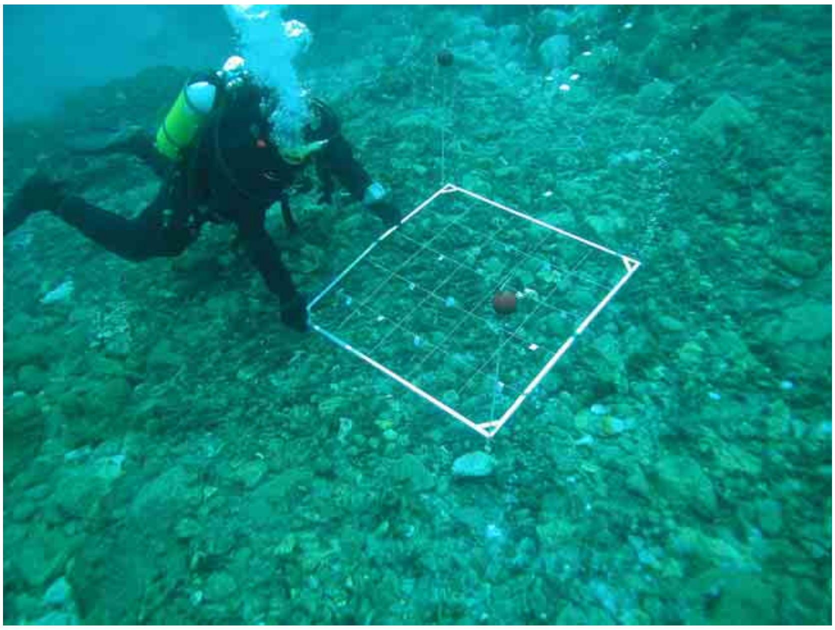
- Underwater sampling of fluids (water and gas), solid deposits and biological material
- Gaschromathographic analysis of the gases
- Development of underwater fluid samplers and techniques (i.e. gas and water sampling, gas flow measurement, biological monitoring)
- Measurements with ADCP current meter, CTD (hydrography), and *in situ* pH-sensor
- Video and photographic documentation





pH measured during dive between strong vents.

G. Caramanna, U. of Rome.



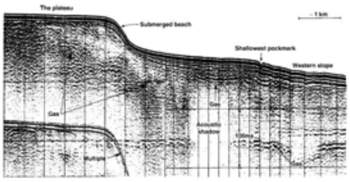
Literature survey of monitoring techniques

🟧	Sediments	🟩	Primary use
🟩	Seafloor	🟨	Secondary use
🟦	Water column		
🟨	Applicable for two or more locations		

Technique			**Liquid phase**	**Gas phase**	**Dis-solved**
Electromagnetic		Seabottom EM	🟩	🟩	
Acoustic imaging		Sparker/boomer	🟩	🟩	
		High resolution imaging	🟩	🟩	
Sonar bathymetry		Sidescan sonar	🟩	🟩	
		Multi-beam echo sounding	🟩	🟩	
Sonar		Active sonar	🟩	🟩	
		Passive sonar	🟩	🟩	
Geo-chemical	Seawater chemistry	Electrochemical			🟩
		Optochemical			🟩
		IR/NIR spectroscopy			🟩
		Raman spectroscopy	🟩		🟨
		Gas flux in water	🟩	🟩	
	Soil chemistry	Gas flux in soil	🟨	🟩	
		Gas concentration	🟨	🟩	
Ecosystem		Ecosystem studies	🟨	🟨	🟩
		Biological sensors	🟨	🟨	🟩
Other		Tracers	🟨	🟨	🟩
		Isotope	🟨	🟨	🟩
		Visual inspection	🟨	🟩	
		Well monitoring	🟩	🟩	🟩

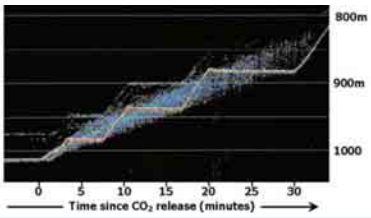
Jon Hellevang, CMR

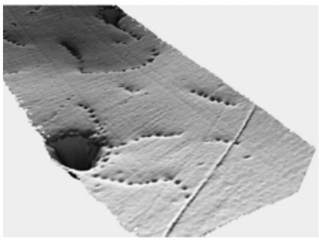
Some examples



Above: Shallow seismic (sparker) profile across the Gullfaks field. Courtesy of M. Hovland, Statoil

Below: CO_2 Experiment conducted by Brewer et al. (2006). (Geophysical Research Letters). Courtesy of P.G. Brewer, MBARI





Above: Model from high resolution multibeam echo sounder. (Vertical axis exaggerated five times). Haltenbanken pipeline down to the right. Courtesy of M. Hovland, Statoil

Below: Collection structure for shallow gas (CH_4) monitoring at Troll. Courtesy of NGI and IFE

Capabilities and limitations

Technique			Capability	Limitation
Electromagnetic		Seabottom EM	Used for HC identification	
Acoustic imaging		Sparker/boomer	1m resolution. Several hundred meters depths.	2D profile
		High resolution imaging	Better than 1m resolution. To about 100m depths.	2D profile
Sonar bathymetry		Sidescan sonar	Resolution down to 10cm.	Survey
		Multi-beam echo sounding	Greater coverage in short time. High resolution.	Survey
Sonar		Active sonar	Very high sensitivity. 100 Sm3/day @ 100m	Limited detection range. (freq. dep.)
		Passive sonar	50 Sm3/day @Δp=5bar, 25m	Need pressure drop
Geo-chemical	Seawater chemistry	Electrochemical	pH ~0.1-0.01% of Full scale	Depending on system
		Optochemical	pCO2 ~1-2uAtm	Depending on system
		IR/NIR spectroscopy	pCO2 ~1-2uAtm Accuracy < ~0.004pH	Depending on system
		Raman spectroscopy	~15mAtm dissolved	Complex. Best suited for fluids.
		Gas flux in water	Very sensitive	Collective structure
	Soil chemistry	Gas flux in soil	0.04g/m2 day 14.6t/km2 year	Point measurement
		Gas concentration	± 1-2ppm	Point measurement
Ecosystem		Ecosystem studies	Not known	Complex.
		Biological sensors	Not known	Complex.
Other		Tracers	Parts per 10^12 possible. CO2 resolution depends.	Complex subsea
		Isotopes	Very sensitive lab systems	Complex subsea
		Visual inspection	Depending on visibility. Could be combined with dye	Survey, bio fouling. Best with background structure.
		Well monitoring	Depending on system	Point monitoring

Technology status CO_2 monitoring in water

🟩	Industrialised
🟨	Demonstrated
🟥	Research phase

Technique			Status	Adaptability to CO2 from exising solution
Electromagnetic		Seabottom EM		Good
Acoustic imaging		Sparker/boomer		Good
		High resolution imaging		Good
Sonar bathymetry		Sidescan sonar		Good
		Multi-beam echo sounding		Good
Sonar		Active sonar	🟨	Good
		Passive sonar		Not known
Geo-chemical	Seawater chemistry	Electrochemical	🟩	
		Optochemical	🟩	
		IR/NIR spectroscopy	🟨	
		Raman spectroscopy	🟥	
		Gas flux in water		Good
	Soil chemistry	Gas flux in soil		Not known
		Gas concentration		Not known
Ecosystem		Ecosystem studies	🟥	Complex
		Biological sensors		Complex
Other		Tracers		Not known
		Isotope		Not known
		Visual inspection	🟨	Good
		Well monitoring		Good

Future: How to assess the mitigation of global warming by carbon capture and ocean/geological storage

Motivation:

- What may be gained from CCS and how do we quantify the benefits of leaky reservoirs/temporary storage?

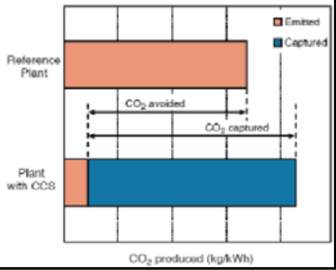
Approach:

- Generic climate model study
- Choose reference scenario and sequestration cases
- Generate results and compare different metrics

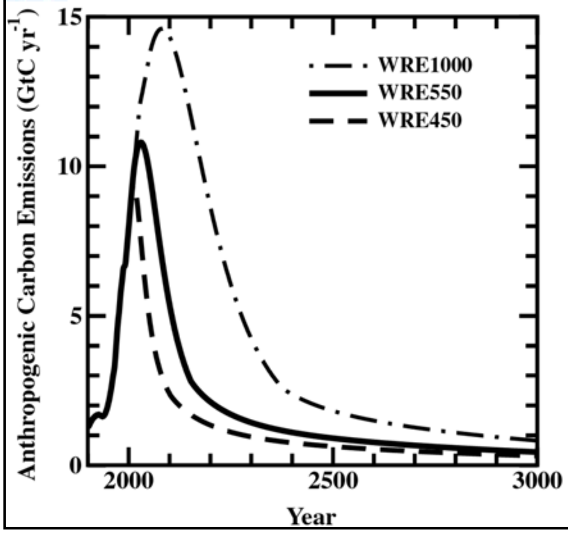
Peter M. Haugan and Fortunat Joos 2004. Metrics to assess the mitigation of global warming by carbon capture and storage in the ocean and in geological reservoirs. *Geophysical Research Letters* 31, L18202, doi:10.1029/2004GL020295.

Approach

- Use reduced form carbon cycle climate model in millennium time scale runs: HIgh Latitude Diffusion-Advection (HILDA) ocean model coupled to a 4-box biosphere model and an energy balance model
- Choose stabilization reference scenarios: WRE 550, 450 and 1000
- Capture and store 30 % of emissions after a ramp-up period 2010-2035 => CCS comes in addition to stabilization, not instead.
- Investigate effects of
  - Perfect storage *PS* (no leakage)
  - Geological storage with 0.01 annual leakage
  - Geological storage with 0.001 annual leakage
  - Storage in the ocean at 800m (dissolved)
  - Storage in the ocean at 3000m (dissolved)
- Include energy penalty of 20% and 5%



Deduce emissions corresponding to the reference (stabilization) scenarios with no carbon storage



Anthropogenic carbon emissions for the WRE450, WRE550, and WRE1000 stabilization scenarios.

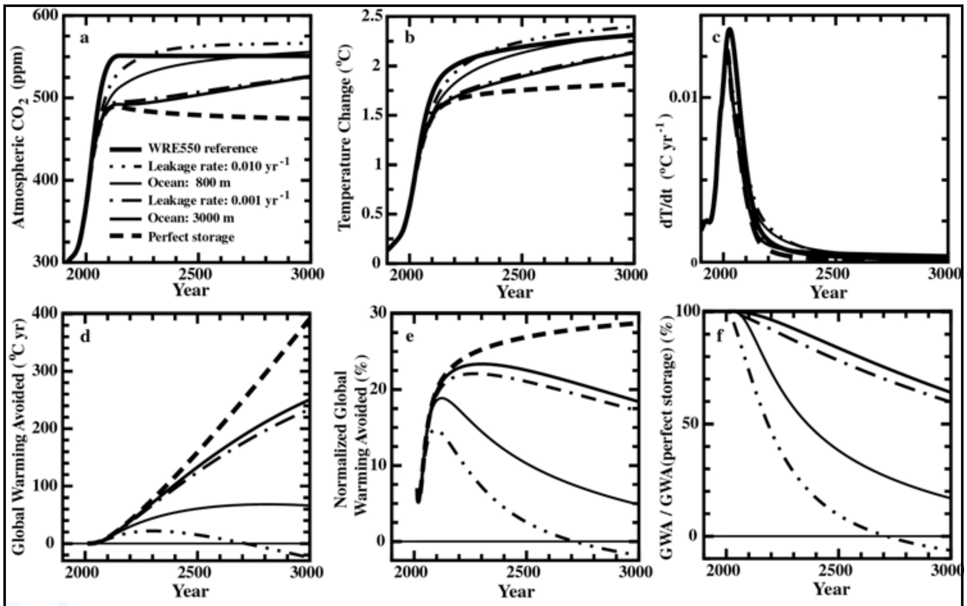
Use model to investigate effects of capture and storage of 30 % of these emissions

Output parameters to look at for storage cases (*S*):

- Atmospheric CO_2
- Surface air temperature *T*
- Rate of change of surface air temperature
- Global Warming Avoided (GWA):

$$GWA(t) = \int_{t_0}^{t} (T_{ref} - T_s)\,dt \qquad GWA_{Norm}(t) = \frac{\int_{t_0}^{t} (T_{ref} - T_s)\,dt}{\int_{t_0}^{t} (T_{ref} - T_0)\,dt}$$

Storage effectiveness $EFF(t) = GWA(t) / GWA_{PS}(t)$



(a) atmospheric CO_2, (b) global average surface temperature change, (c) rate of global average surface temperature change, and GWA (d) in °C year, (e) in percent of the cumulative warming of the reference case, and (f) relative to the perfect storage case for WRE550.

Impact of geological vs. ocean storage on climate

Maximum rates of change of temperature are not much affected by any of these carbon storage cases, not even the perfect.

Geological storage with 0.01 annual leakage fraction is less effective than shallow ocean storage (800m). Its effectiveness[1] for storing 30% of emissions peaks at 15 % and GWA gets negative after 6-700 years.

Geological storage with 0.001 annual leakage fraction has similar performance to deep ocean storage.[2]

Normalized GWAs for a given storage case tend to collapse to similar values for different reference scenarios.

Reducing energy penalty from 20 to 5 % has limited effect.

[1] Storage effectiveness EFF(t) is defined here to be the fraction of the GWA obtained relative to that obtained by perfect storage.

[2] Deep ocean storage in lakes on the seafloor would perform better than directly dissolved because of delayed mixing into the water column.

Some recommendations for this community

- Address the question of carbon credits for CCS in particular when reservoirs are leaky
- Address ocean acidification from leakages

- Subseabed fluid flow is intriguing and interesting – link up with natural seepage studies for basic and very applied research

- Try to understand and engage in public perception and its variation across cultures and conditions
- Get involved in science -policy interaction; try to explain the need for the scientific method!

[Environmental impact assessment: are tradeoffs between different components allowed? E.g. is lex specialis = NIMBY = Not In My Back Yard an acceptable principle when different conventions come in conflict?]