NTNU – Trondheim
Norwegian University of
Science and Technology

CO_2 capture and storage

April 17, 2015

Masaryk University

Brno

NTNU – Trondheim
Norwegian University of
Science and Technology

Olav Bolland

Head of Department
of Energy and Process
Engineering, NTNU

Professor of Thermal Power
Generation

Worked with research and
education within CCS since 1989

www.ntnu.edu/employees/olav.bolland

Czech Republic:

Population 10.5 mill
GDP per capita (PPP): $ 26,300
Area: 78,866 km^2

Norway:

Population 5.2 mill
GDP per capita (PPP): $ 55,400
Area: 323,772 + 61,000 km^2

Keywords Norway:

Skiing, Football,
Oil & gas,
Salmon, Hiking,
Marine, Fjords, Skiing

NTNU

Norwegian University of Science and Technology

www.ntnu.no

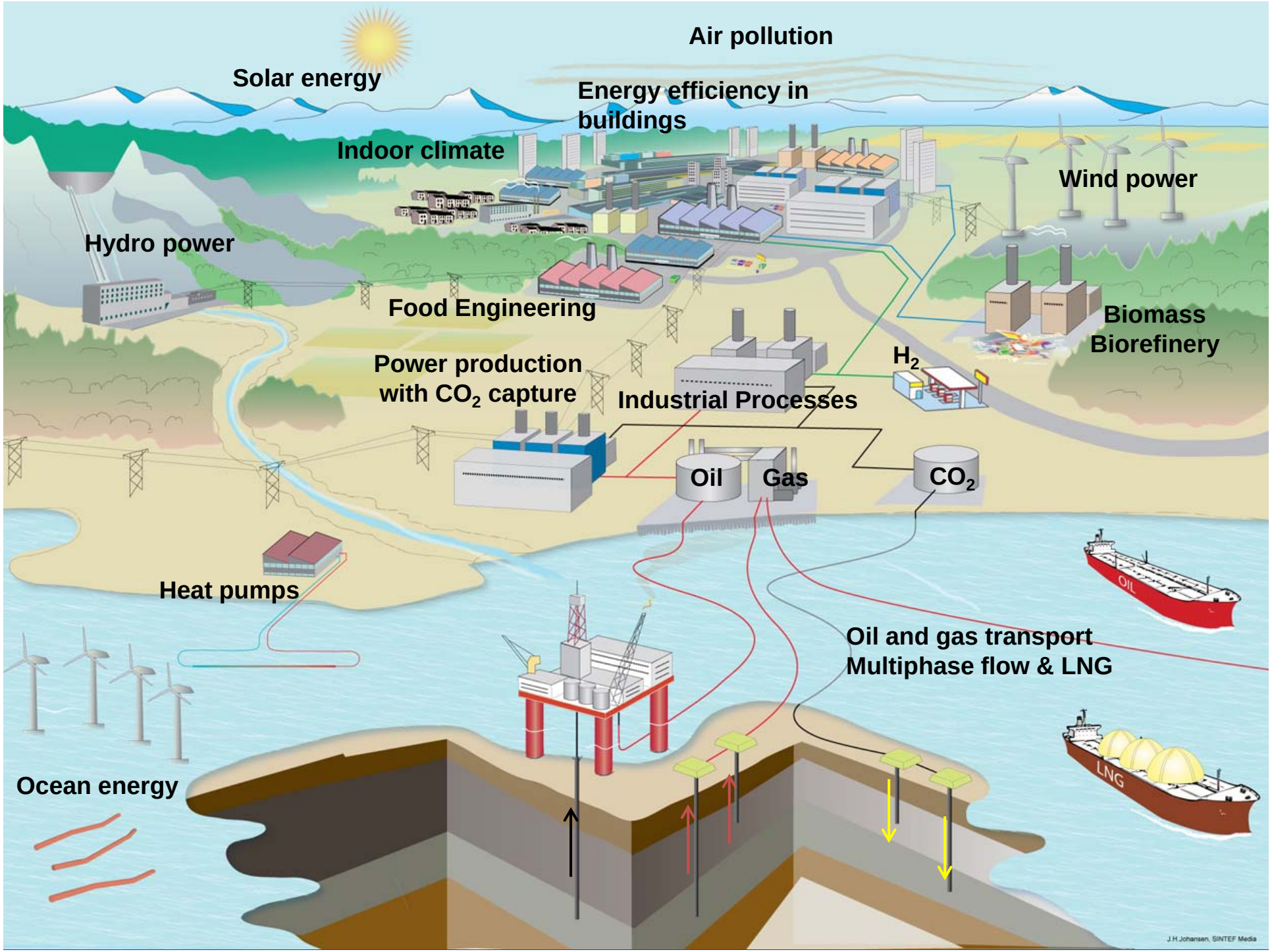
NTNU – Trondheim
Norwegian University of
Science and Technology

NTNU and SINTEF campus
in Trondheim

23 000 students

<u>Focus areas</u>:
Oil and Gas
Maritime engineering
Materials
Renewable energy
CCS

Close cooperation with
research institute
SINTEF

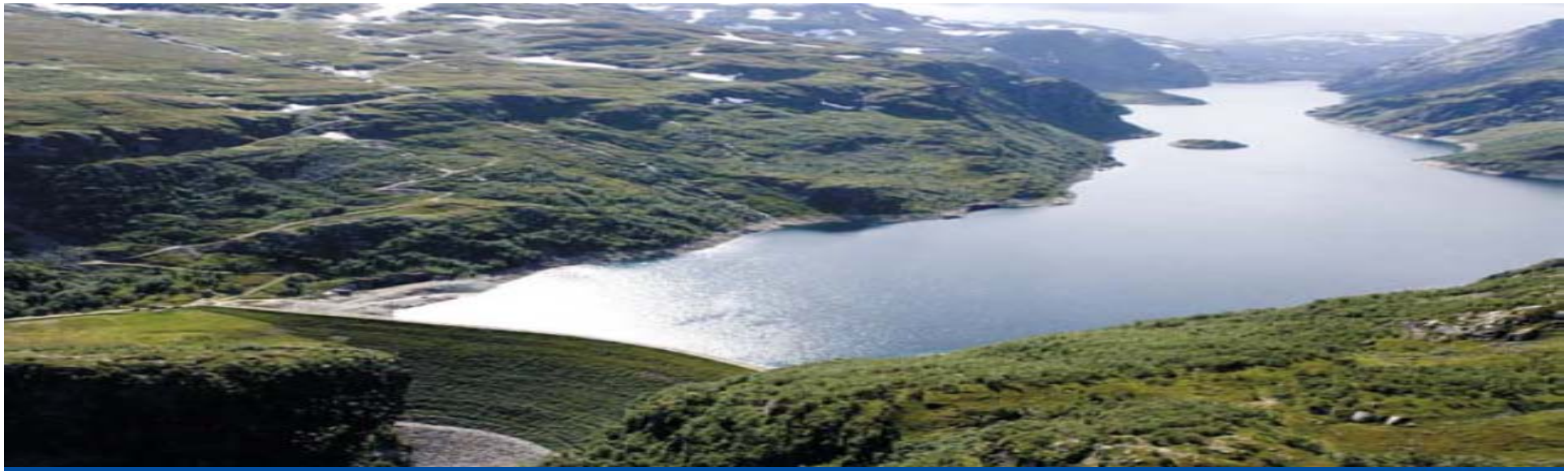

Air pollution
Solar energy
Energy efficiency in buildings
Indoor climate
Wind power
Hydro power
Food Engineering
Biomass Biorefinery
H_2
Power production with CO_2 capture
Industrial Processes
Oil
Gas
CO_2
Heat pumps
Oil and gas transport
Multiphase flow & LNG
Ocean energy
OIL
LNG
J.H.Johansen, SINTEF Media

Focus on laboratories

Energy in Norway - History

1st: Hydro Power Year 1882

- First plant in Norway and Europe in 1882 for industrial purposes (6.5 kW)
- Engineers educated abroad saw potential and bought rights to waterfall with foreign money
- New legislation in 1906 with nickname “Panic Acts”
  - Foreign investors needed permission
  - Licensing became cornerstone in hydro power politics



2nd: Petroleum Year 1969

- Oil found in North-Sea in December 1969
- Much debate in Europe if government should own and develop the resources or just charge taxes
- Denmark gave it to private company and surely regrets
- Our Prime-minister understood importance of state owned company
- Norway made strong actions to keep control (Statoil!)

Norwegian oil & gas

Northern Areas
Artic conditions

Barents Sea
Snøhvit +++

Norwegian Sea
Deep waters

(Mature)

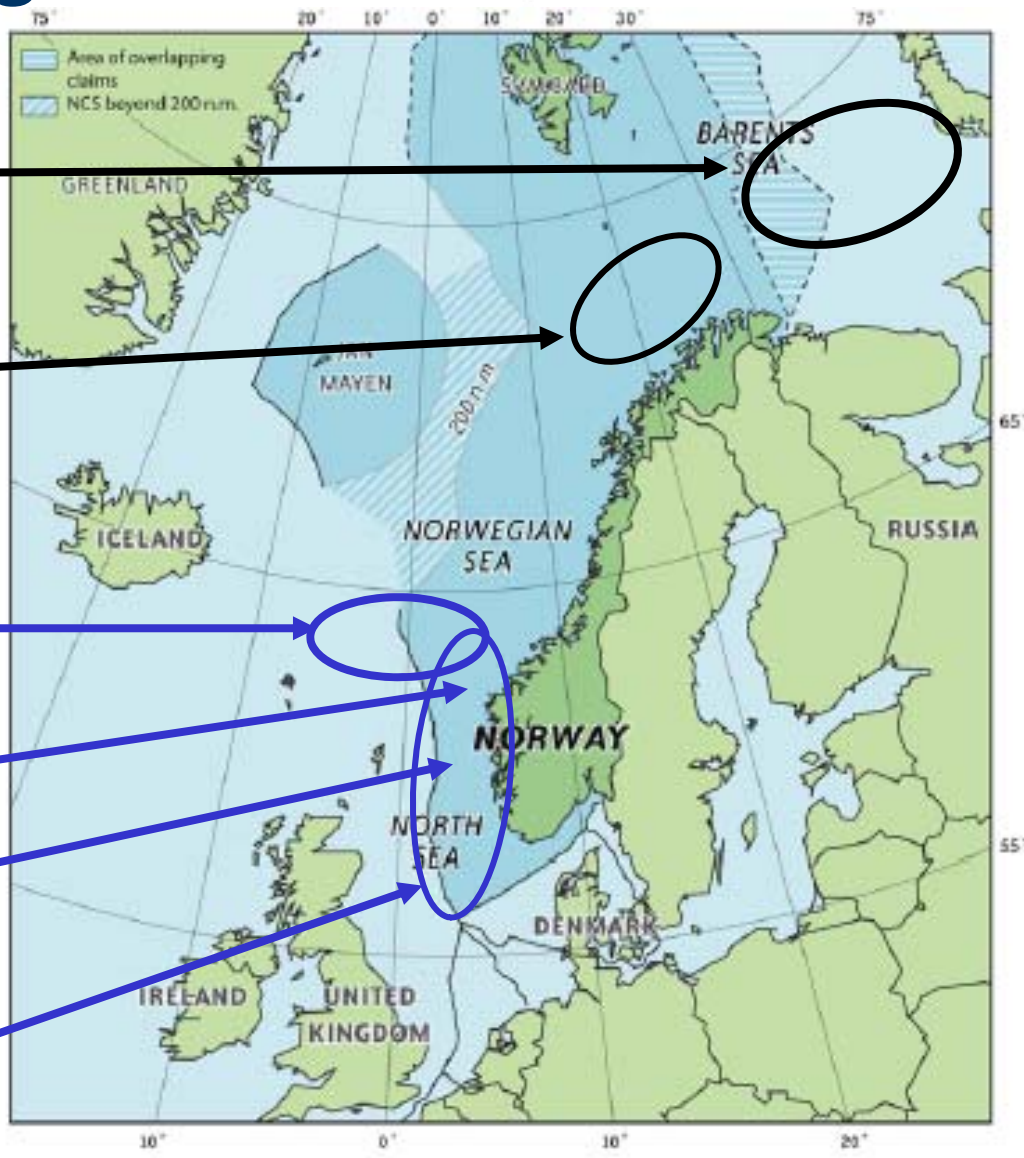
Haltenbanken

(Mature)

Northern North Sea
Tampen Oseberg +++

(Mature)

Southern North Sea
Ekofisk Valhall +++



Norwegian Natural Gas Pipeline System

Norway

11th larges oil producer
5th largest oil exporter

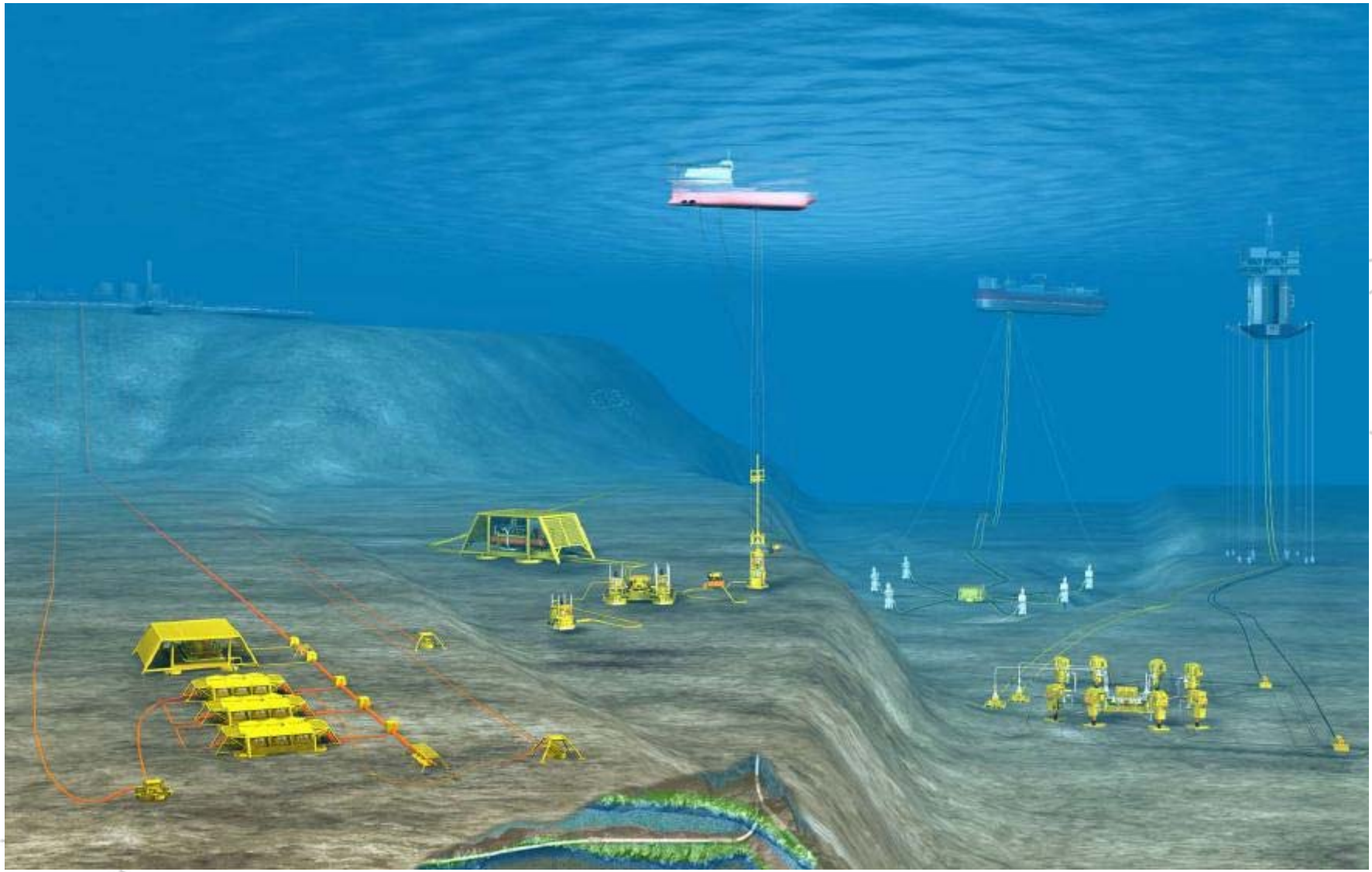
3rd largest natural gas exporter
5th largest natural gas producer

27% of Norwegian CO_2 emissions from oil and gas production

Troll platform

New oil & gas production last 10 years

Subsea technology



3rd: New Renewable Energy Year 2001

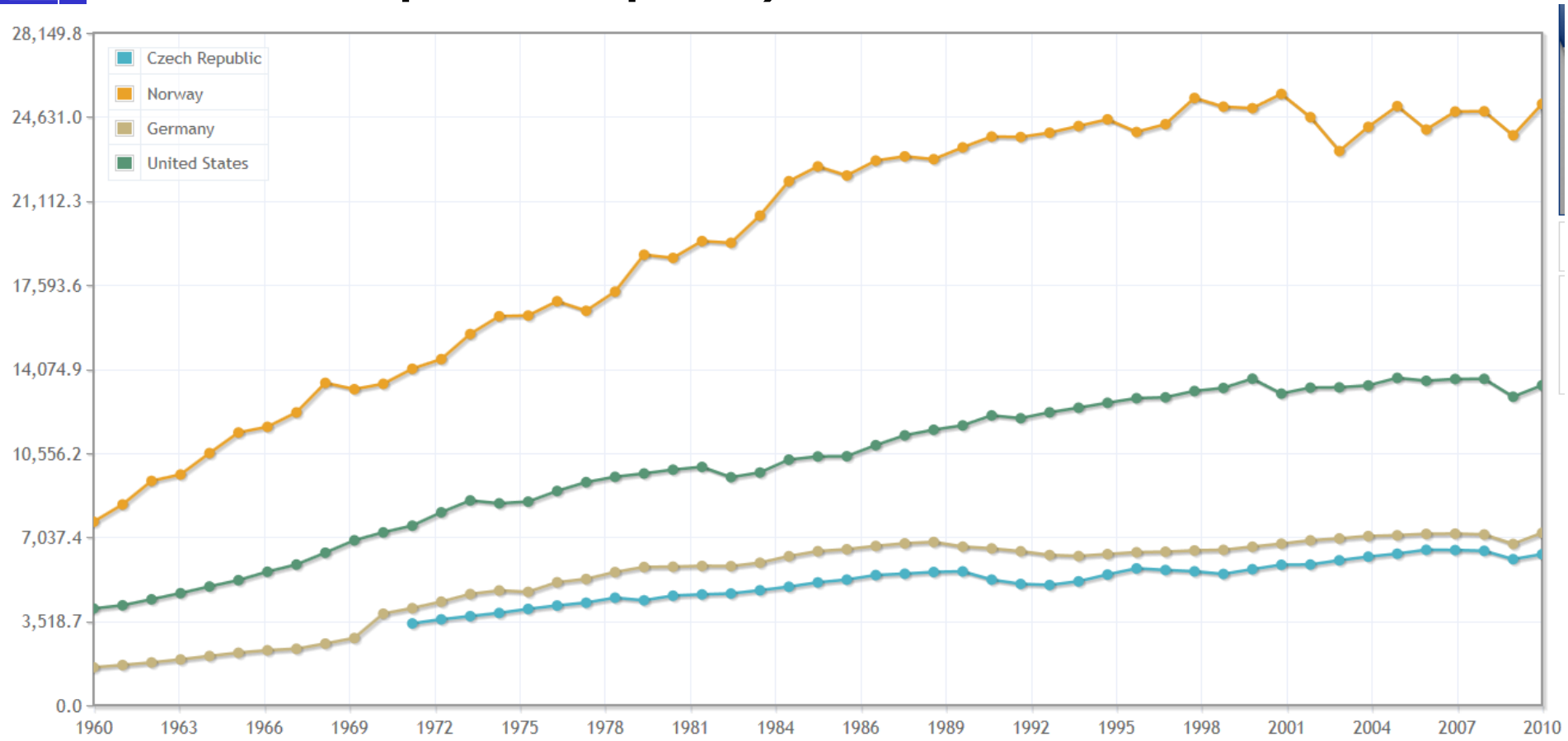
- Government decided on an effort for wind power in 2001
- A long coast line, a large ocean area, a large mountain area; wind power resources very good!
- PV: Producer of high-purity silicon for PV wafers

Power production in Norway

- National grid: ≈98% hydropower
  - 28000 MW - 120 TWh/a
  - 800 MW wind power (2.2 TWh/a)
  - Per capita: 5.6 kW - 24000 kWh/a
- Offshore oil/gas: mechanical power and local grids
  - 3000 MW gas turbine power - 10 TWh/a
- Future:
  - Wind power: Large resources (especially offshore)
  - More hydropower: potential YES, acceptance NO
  - Natural gas power: potential YES, problem is CO_2
  - CO_2 is a hot issue!!
  - Surplus of electric power in Nordic area

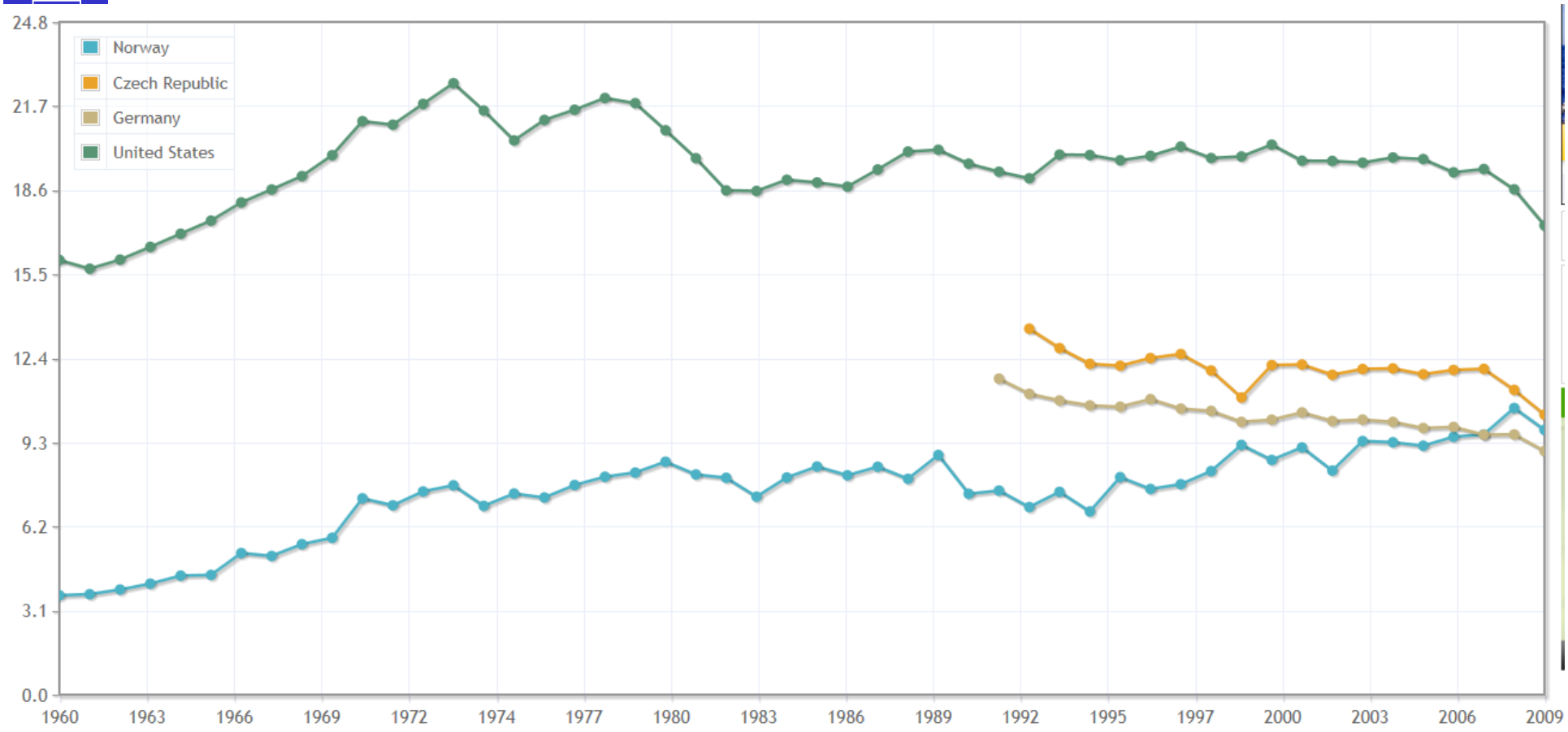
The Czech Republic vs. Norway

Electric power consumption kWh per capita)



www.indexmundi.com/facts/indicators

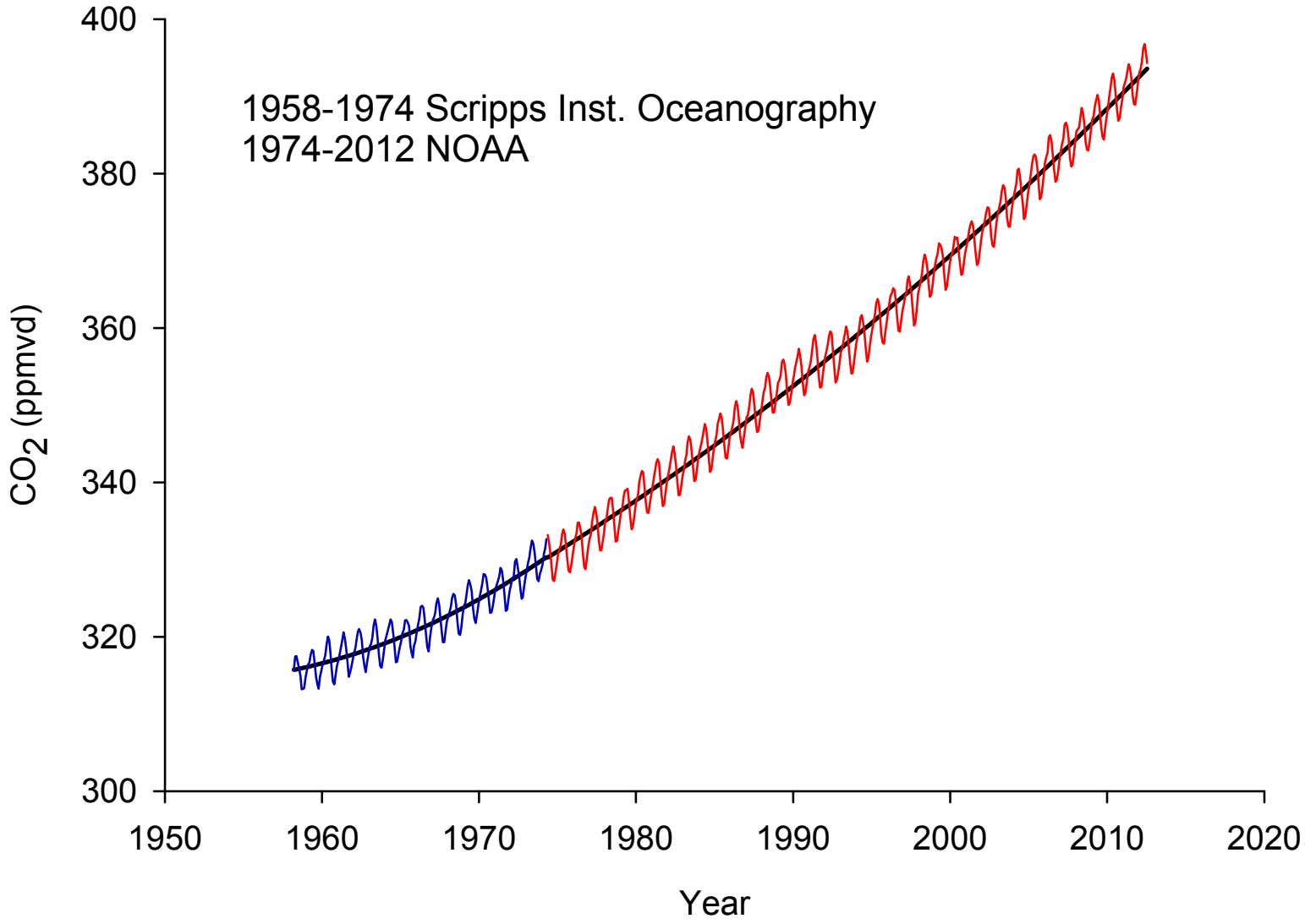
CO_2 emissions
metric tons per capita



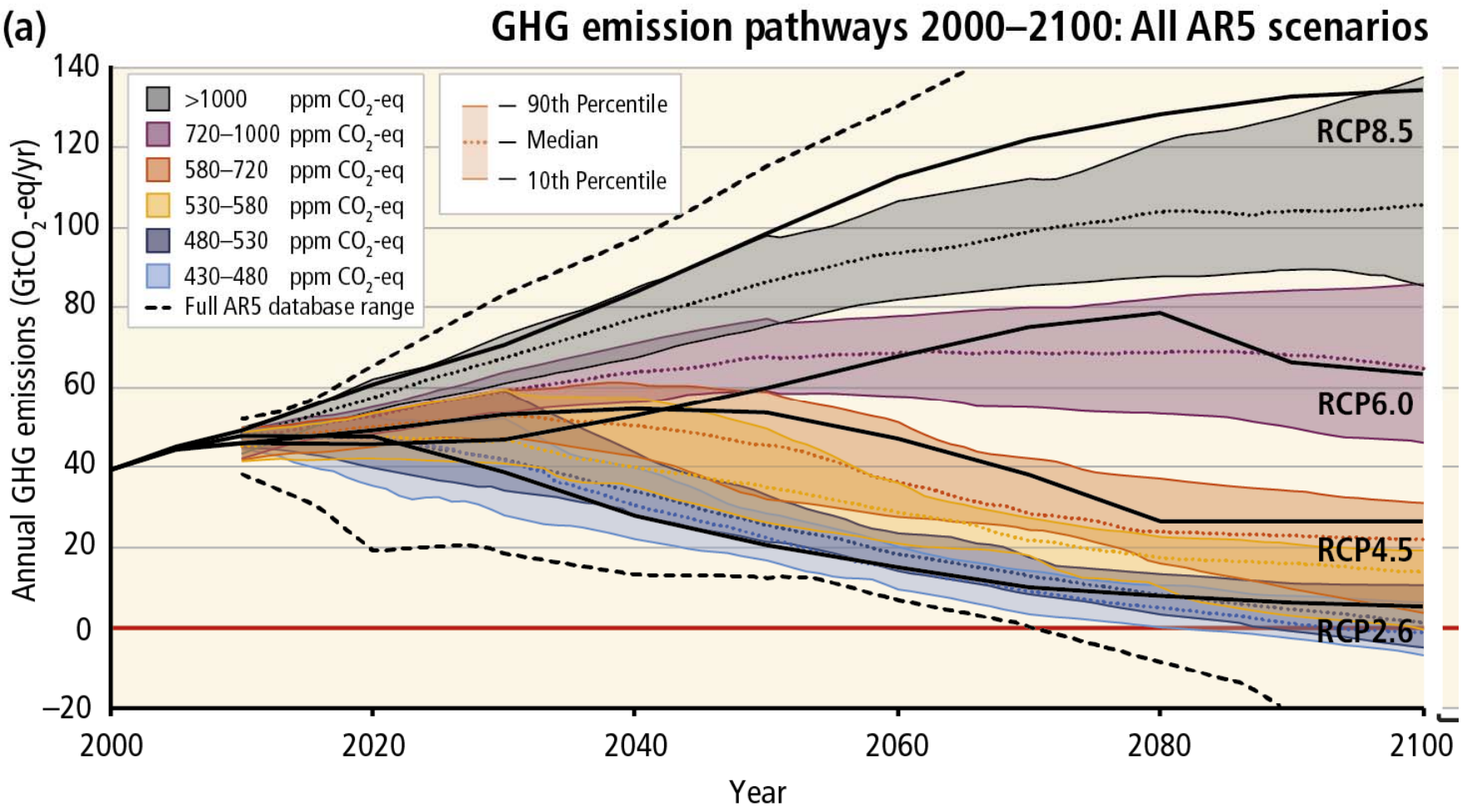
www.indexmundi.com/facts/indicators

Climate – the challenge

Monthly mean atmospheric CO_2 at Mauna Loa Observatory, Hawaii

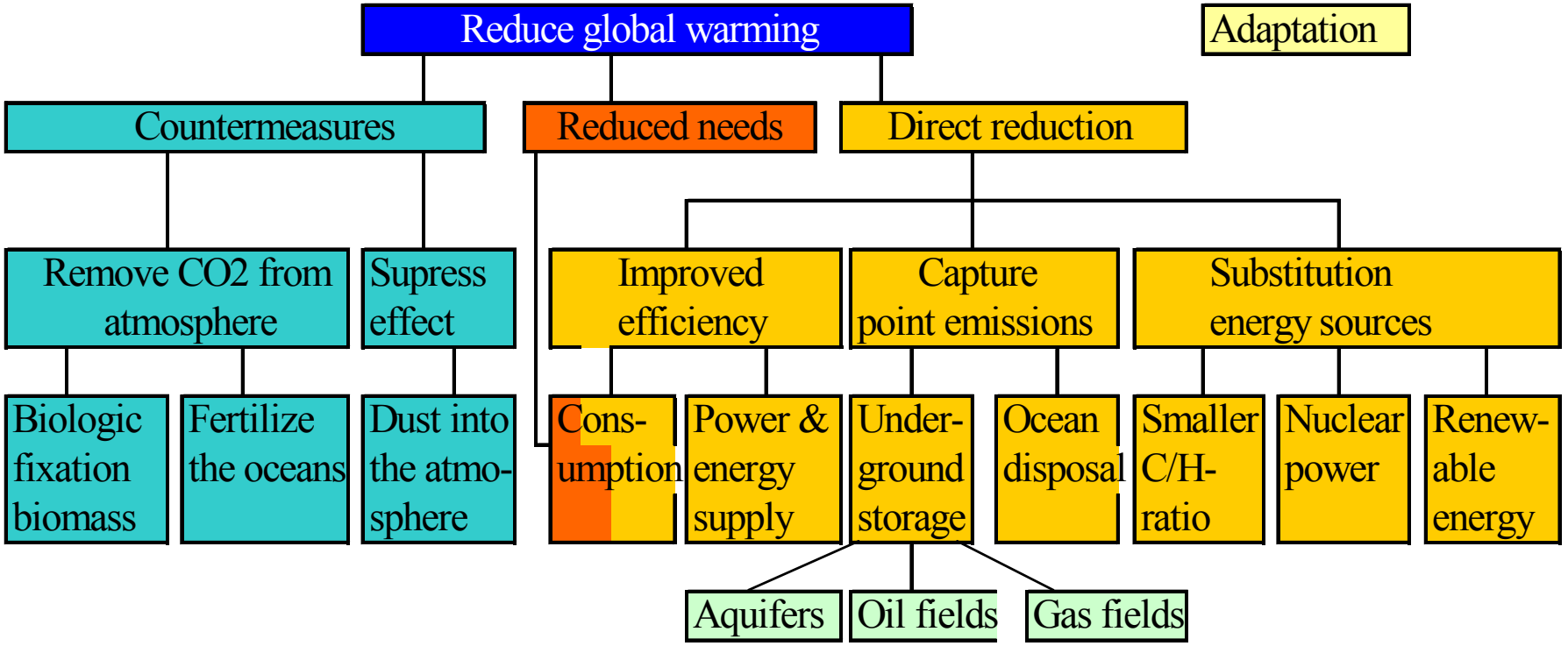


GHG emission pathways (IPCC)



IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp. www.ipcc.ch/pdf/assessment-report/ar5/syr/AR5_SYR_FINAL_SPM.pdf

How to relate to the possible man-made global warming ?

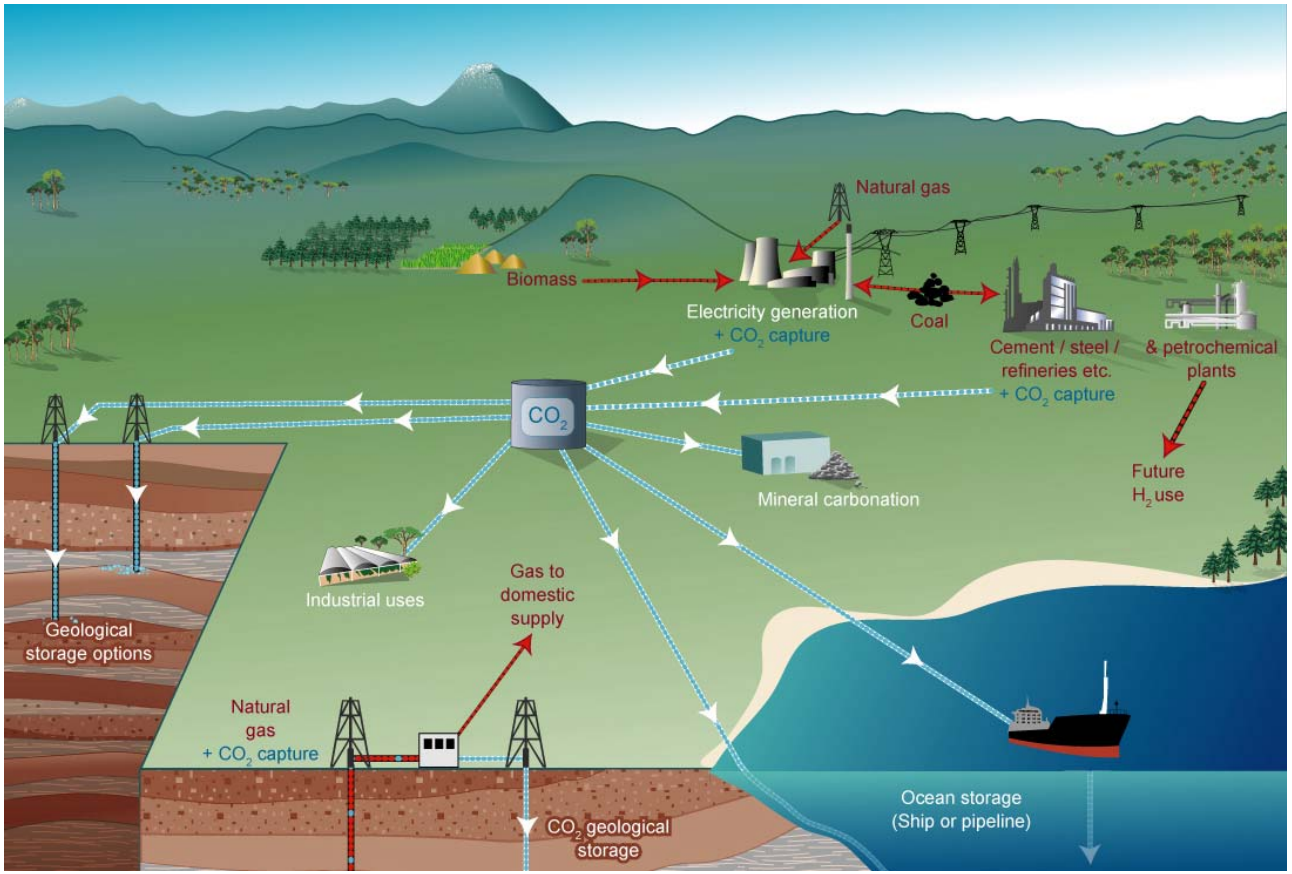


CCS

Carbon Capture and Storage

Carbon dioxide Capture and Storage

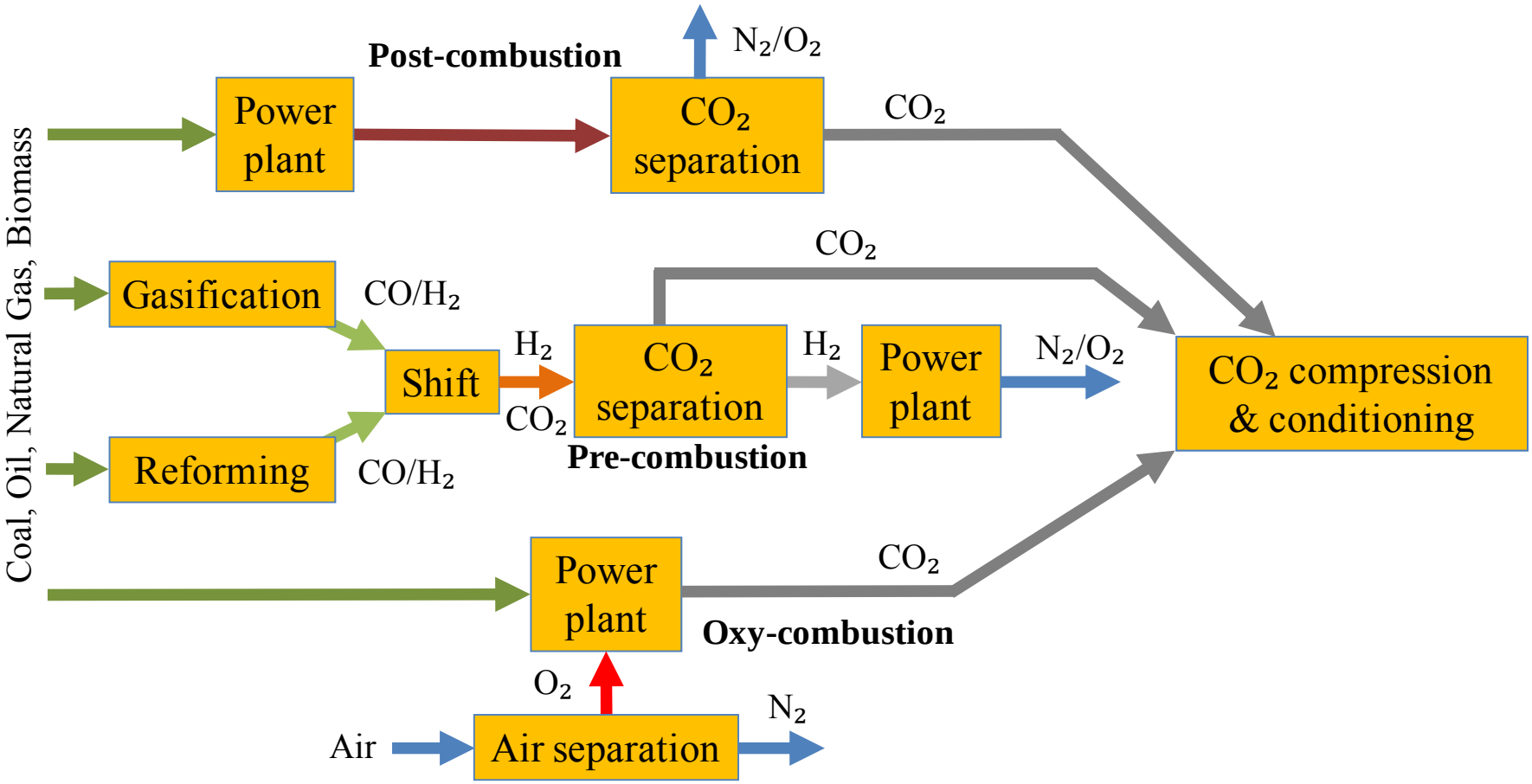
CO_2 Capture and Storage - CCS



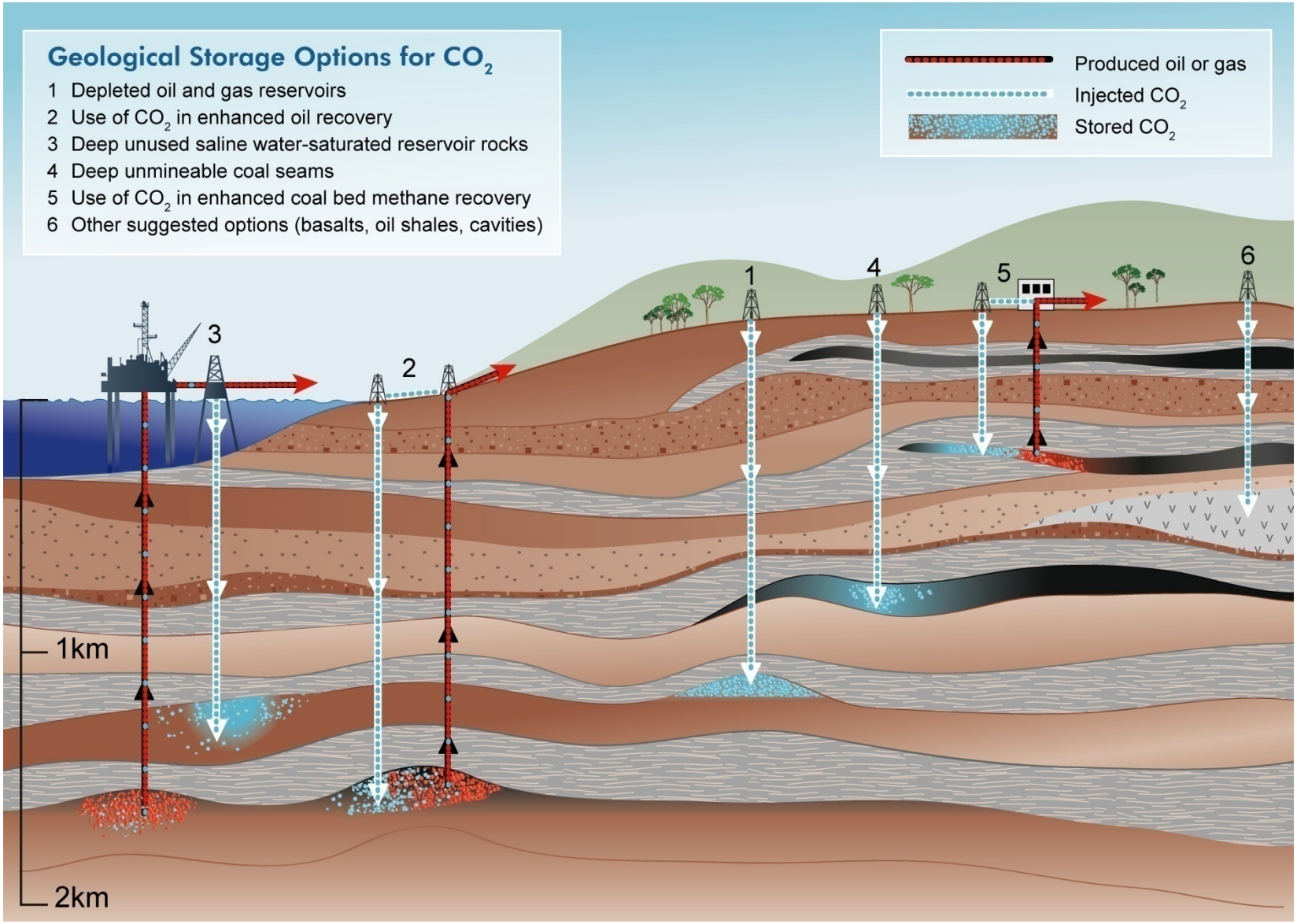
Definition:

"Carbon dioxide (CO_2) capture and storage" (CCS) or "carbon sequestration" is a family of methods for capturing and permanently isolating CO_2 that otherwise would be emitted to the atmosphere and could contribute to global climate change.

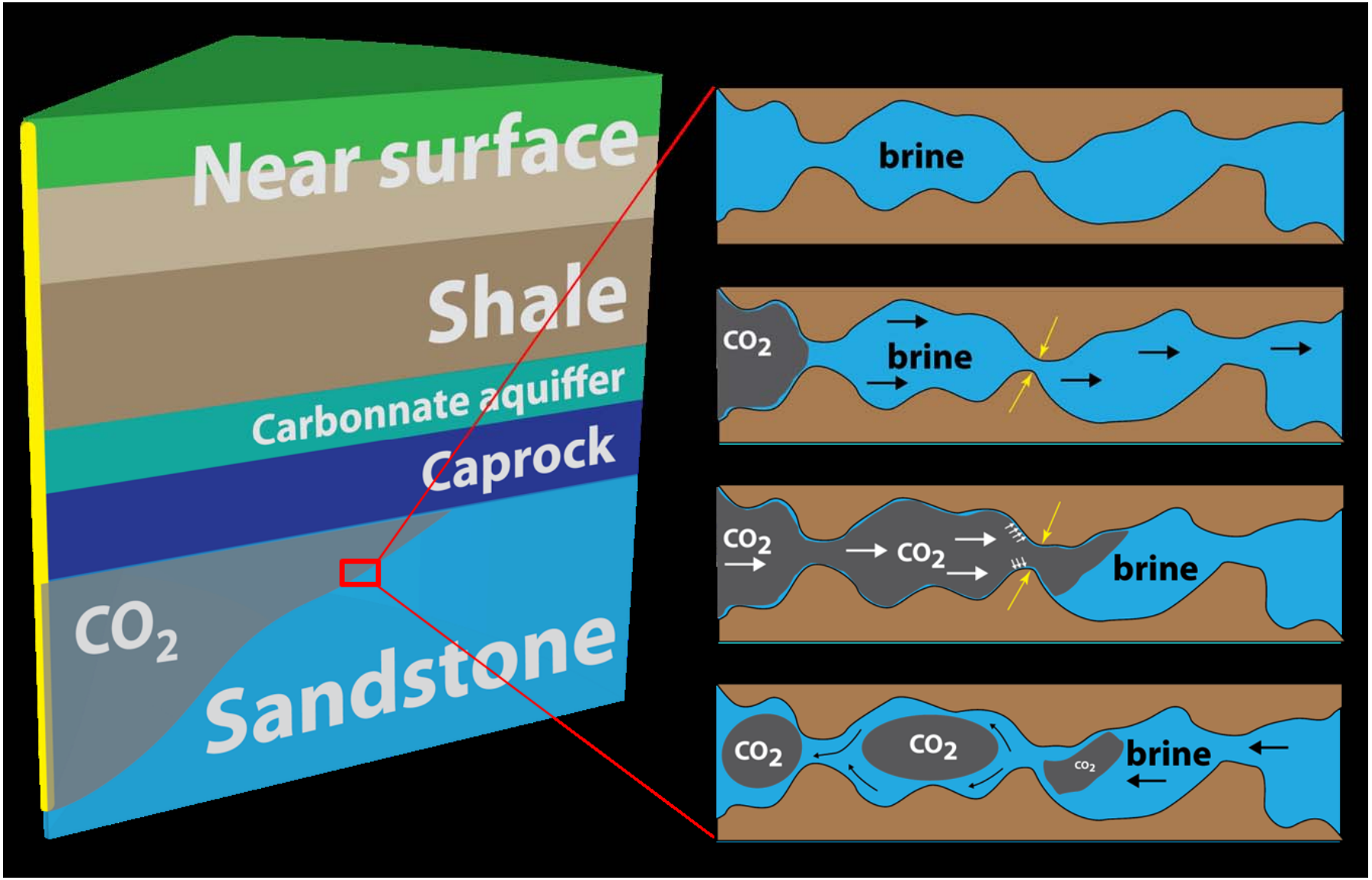
Methods for CO_2 capture from power plants



Storage of CO_2

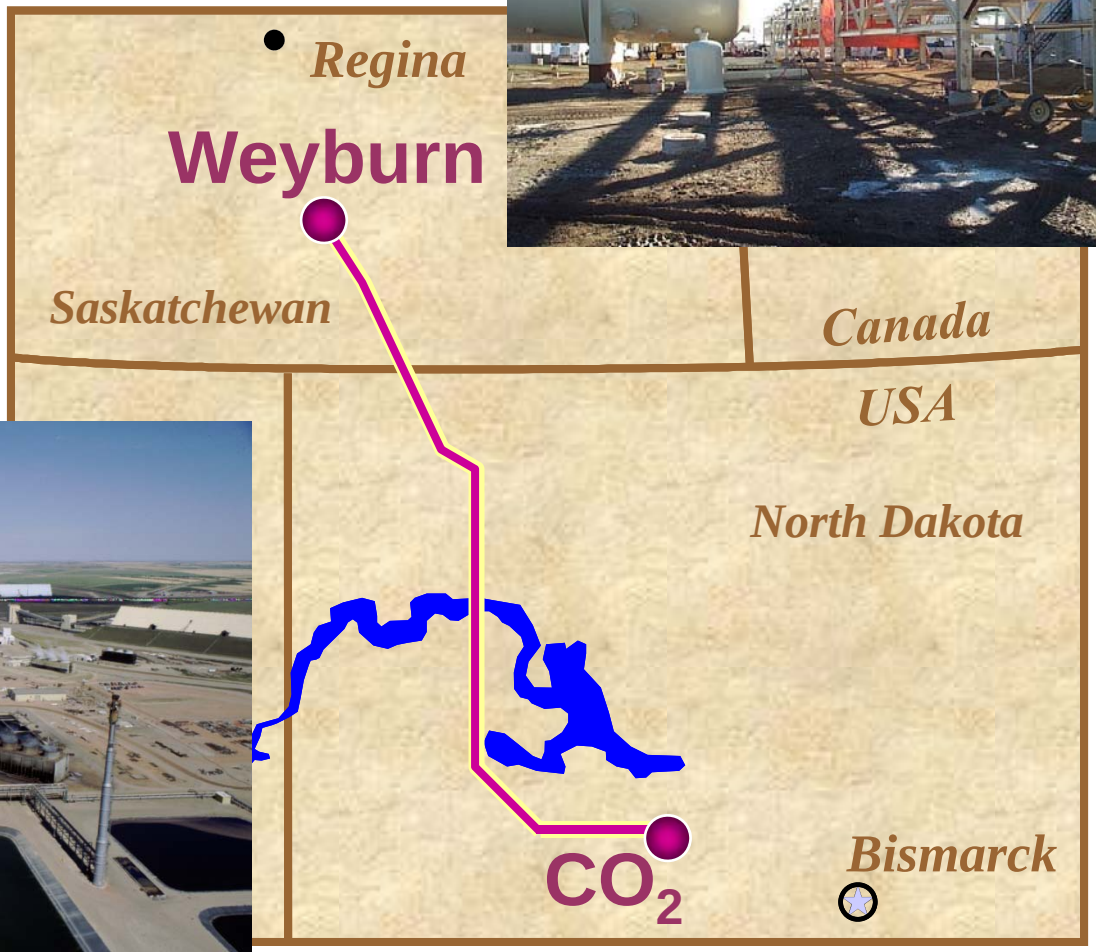


Storage of CO_2

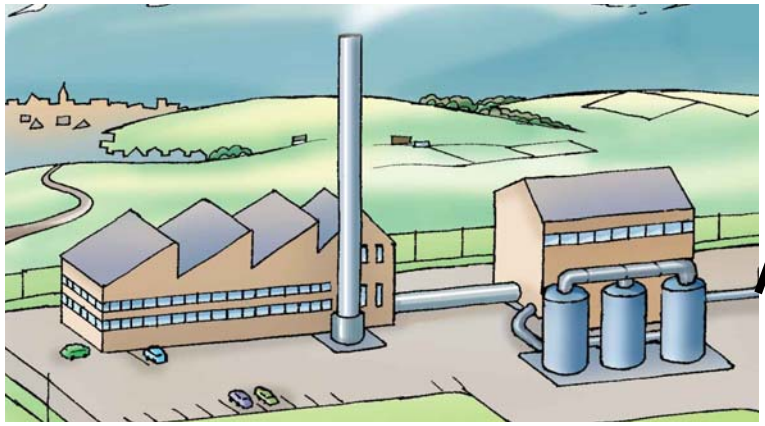


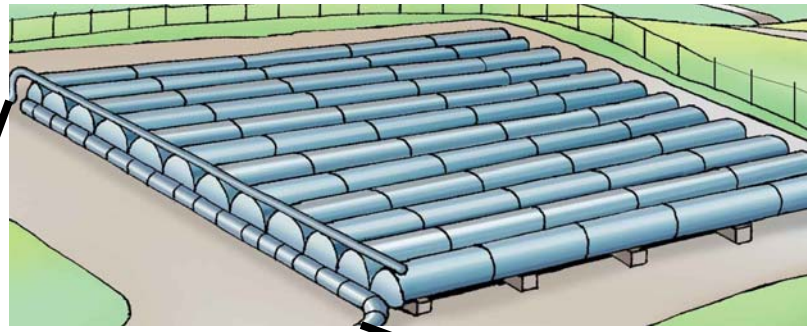
Enhanced Oil Recovery with CO_2 -
≈ 67 projects in Northern America + 10 in Trinidad
≈ 35 Mt CO_2/year
of which 9 Mt CO_2/year from anthropogenic sources
>3500 km CO2 pipelines

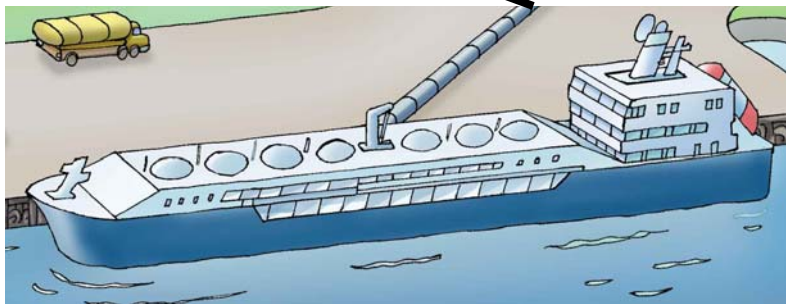
Weyburn

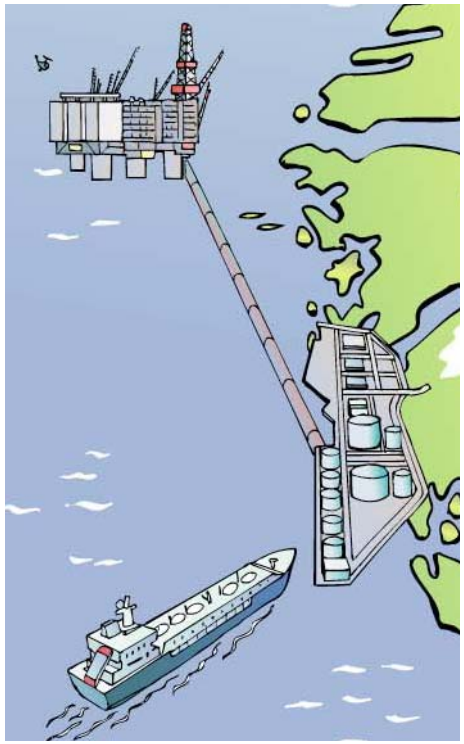

Regina
Weyburn
Saskatchewan
Canada
USA
North Dakota
CO_2
Bismarck

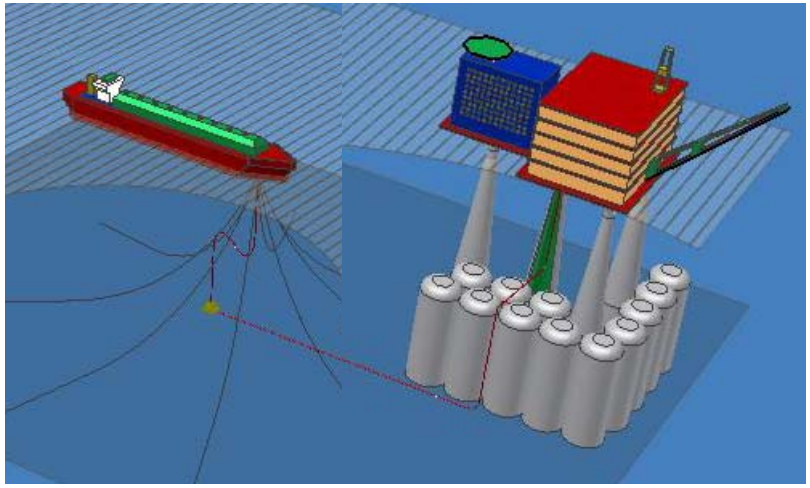
Ship transport of CO_2 ?











Source: Orkla Engineering

Yara CO_2-tankers, 1500 m^3 capacity

Example of ship carrying liquid CO_2 for Yara International

Yara CO2-tankers, 1500 m3 capacity

Loading CO_2 at Sluiskil fertilizer plant, the Netherlands

Yara Industrial's CO_2 terminal at Teesside

Example of 900 m^3 tank delivered as one piece

How and why is CO_2 generated?

How and why is CO_2 formed – 1
Combustion of Carbon

$$C + O_2 \Leftrightarrow CO_2$$

$$Q + H_r = H_p$$

$$Q + \sum_r n_i \bar{h}_i = \sum_p n_e \bar{h}_e$$

h is enthalpy

Assuming that both reactants and products are each at a total pressure of 1 bar and 25 ^{o}C, and that we assign the value of zero of all elements at the 1 bar and 25 ^{o}C,

$$Q = H_p = -\ 393.5\ \text{MJ/kmol}\ CO_2$$

This is the enthalpy of formation of CO_2

How and why is CO_2 formed – 2
Combustion of Methane

$$CH_4 + 2O_2 \Rightarrow CO_2 + 2H_2O$$

$$Q + \sum_r n_i \bar{h}_i = \sum_p n_e \bar{h}_e$$

$$\sum_r n_i \bar{h}_i = -74873 + 2 \cdot 0$$

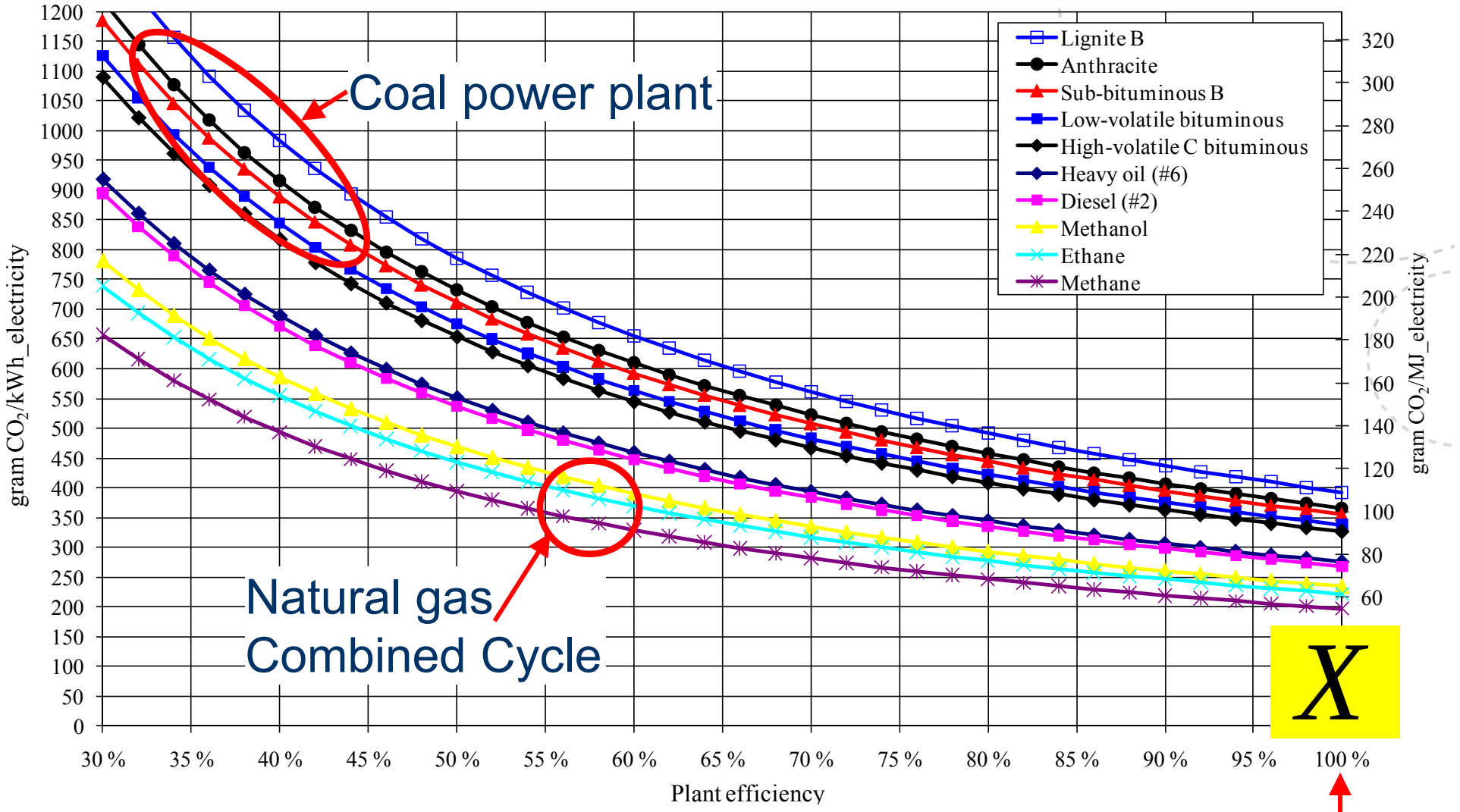
$$\sum_p n_e \bar{h}_e = -393522 + 2 \cdot -241826_{gas} = -877174$$

$$Q = -877174 + 74873 = 802301\,\text{kJ/kmol}\,CH_4$$

$$Q = 802301\,\text{kJ/kmol}\,CH_4 = 50009\,\text{kJ/kg}\,CH_4$$

Q is here the Lower Heating Value of CH_4

Emission of CO_2 from fossil fuels



$$X_{\text{COAL}} = 91\text{-}109 \qquad X_{\text{NATURAL GAS}} = 55 - 63 \qquad \left[\frac{\text{gram CO}_2}{\text{MJ}_{\text{LHV}}}\right]$$

Per fuel lower heating value

Why is the partial pressure of CO_2 in exhaust gas so low

Excess air

Air

Reactants $$C_mH_n + \Phi\left(m + \frac{n}{4}\right)(O_2 + 3.77N_2) \Rightarrow$$

Products $$mCO_2 + \frac{n}{2}H_2O + (\Phi - 1)\left(m + \frac{n}{4}\right)O_2 + \Phi\left(m + \frac{n}{4}\right)3.77N_2$$

Gas turbine fired with natural gas:

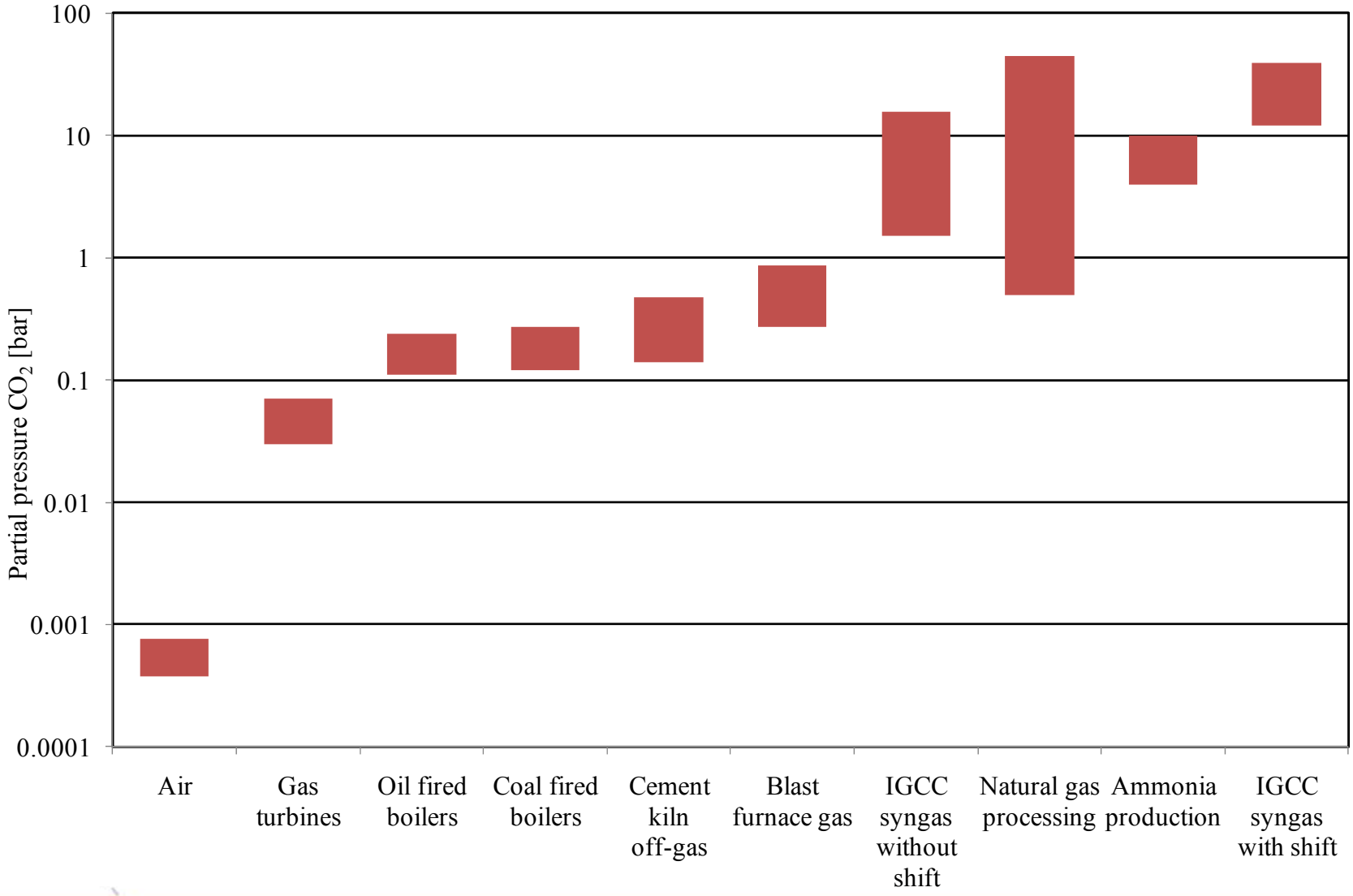
- Φ=2.2-3
- Exhaust: 3.2-4.2 volume-% CO_2

Coal-fired plant:

- $\Phi \approx 1.2$
- Exhaust: 12-14 volume-% CO_2

Gases has to be separated

Partial pressure of CO_2 from various sources



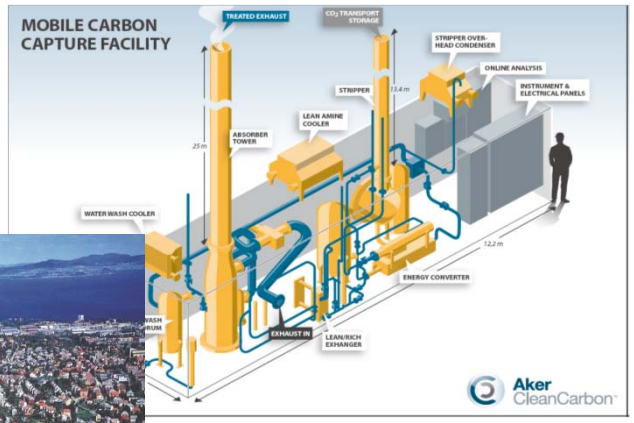
History of CCS - 1

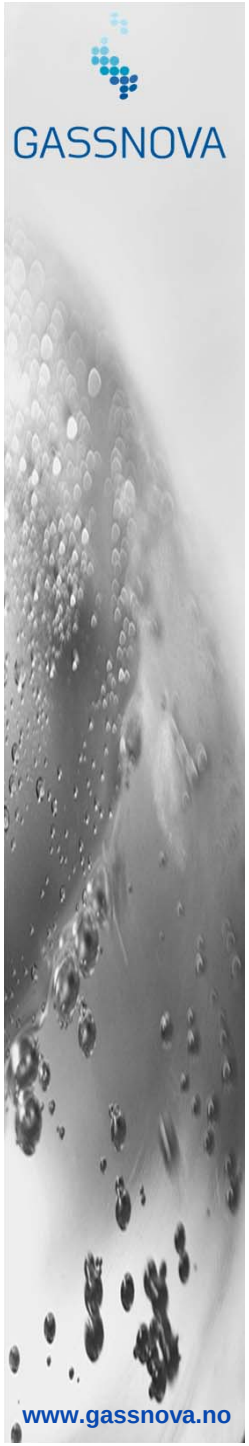
- One of the first to suggest CCS was **Cesare Marchetti in** 1977
  - He gave references to several methods for CO_2 capture from power plants and blast furnaces
  - proposed to store CO_2 in the ocean
  - Marchetti worked for The International Institute for Applied Systems Analysis (IIASA) in Austria
- In 1980 **Anthony Albanese** and **Meyer Steinberg** published a paper with a very detailed discussion on capture technologies and energy consumption as well as storage
- During the 1980s **Steinberg** published a number of reports and papers dealing with CCS - Father of CCS (?)
- US in the 1980s: Many projects with CO_2 injection for enhanced oil recovery (EOR)
- The Norwegians **Erik Lindeberg** and **Torleif Holt** did a lot of work on CCS in the late 1980s, and were the initiators for CCS in Norway
- Oak Ridge National Laboratory (ORNL), Electric Power Research Institute (EPRI), and Argonne National Laboratory were active within CCS R&D during 1980s

History of CCS - 2

- From late 1980s the Japanese were very active, RITE and others, focussing on CO_2 fixation, utilisation and ocean storage
- Intergovernmental Panel of Climate Change (**IPCC**) established by **the United Nations Environment Programme (UNEP)** and the **World Meteorological Organization (WMO);** UN General Assembly Resolution 43/53 of 6 December 1988
- IPCC First Assessment Report 1990 (FAR)
- **IEA Greenhouse Gas R&D Programme** (IEA GHG) was established 1991
  - By 2015: 16 member countries, the European Commission, OPEC and 17 multi-national industrial sponsors
- Norway: Statoil decided 1991 on the **Sleipner** CO_2 injection project!
- Turkenburg, Blok and Hendriks organised the First International Conference on Carbon Dioxide Removal (ICCDR) in Amsterdam March 1992 – CCS R&D took off
- The Netherlands, USA, Japan, Norway early movers throughout 1990s

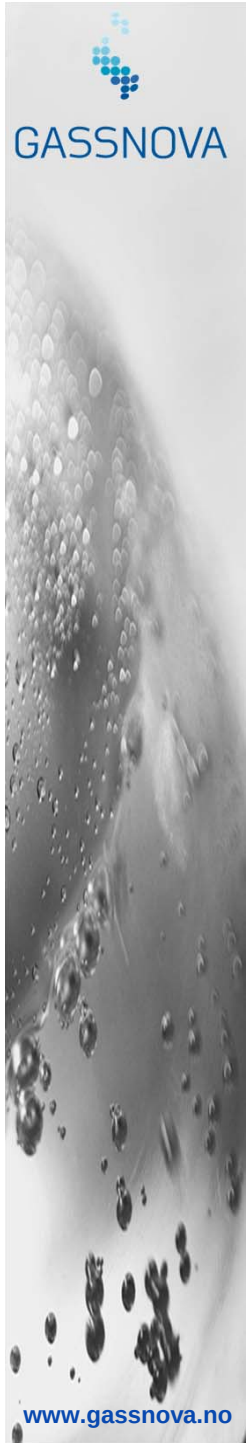
Norway and CCS





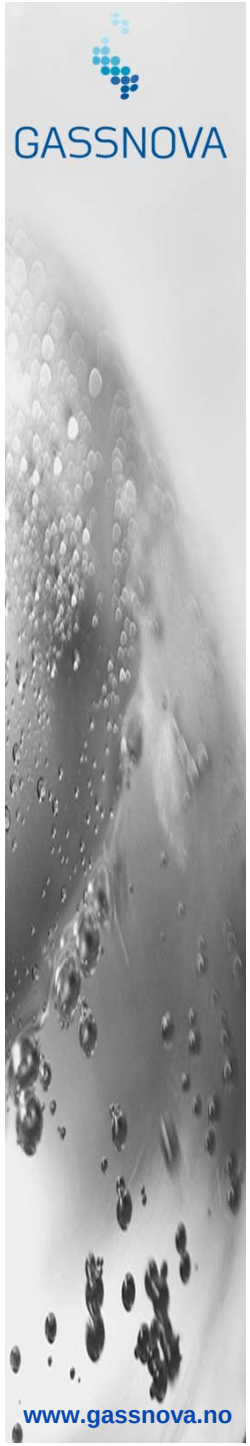
CO_2 history in Norway

- CCS research began ≈1986
- CO_2 tax offshore oil/gas 1991, 50 USD/t CO_2
- Storage: Sleipner 1 Mt CO_2/yr, 1996
- R&D 1997->: Klimatek and CLIMIT (Research Council of Norway)
- Kyoto Target 1997: + 1% (1990-basis)
- Govt resignation, fossil emissions, 2000
- Govt.declaration: CCS reqd. on fossil power plants
- Gassnova SF: State CCS company, 2005/2008



GASSNOVA

The Norwegian state enterprise
for carbon capture and storage



Gassnova SF:

The Norwegian state enterprise for carbon capture and storage

- *Gassnova was established in January 2008 to manage the State's interests in the area of Carbon Capture & Storage (CCS)*
- *This includes representing the State's interests in the development and construction of CCS facilities*
- *Providing support to technology development*
  - *CO_2-capture*
  - *CO_2 transport*
  - *Injection and storage of CO_2*
- *Acting as an advisor for the authorities*

CLIMIT programme – Research Council of Norway (RCS)

CLIMIT is the national programme for research, development, piloting and demonstration of CO_2 capture and storage (CCS) technologies for power generation and other industrial sources.

http://www.climit.no/en

http://www.climit.no/en/Documents/Programme%20plan_eng.pdf

Carbon tax in Norway

Table 1. Norwegian CO_2 taxes and emissions in 2006. NOK/tonne CO_2 and million tonne CO_2

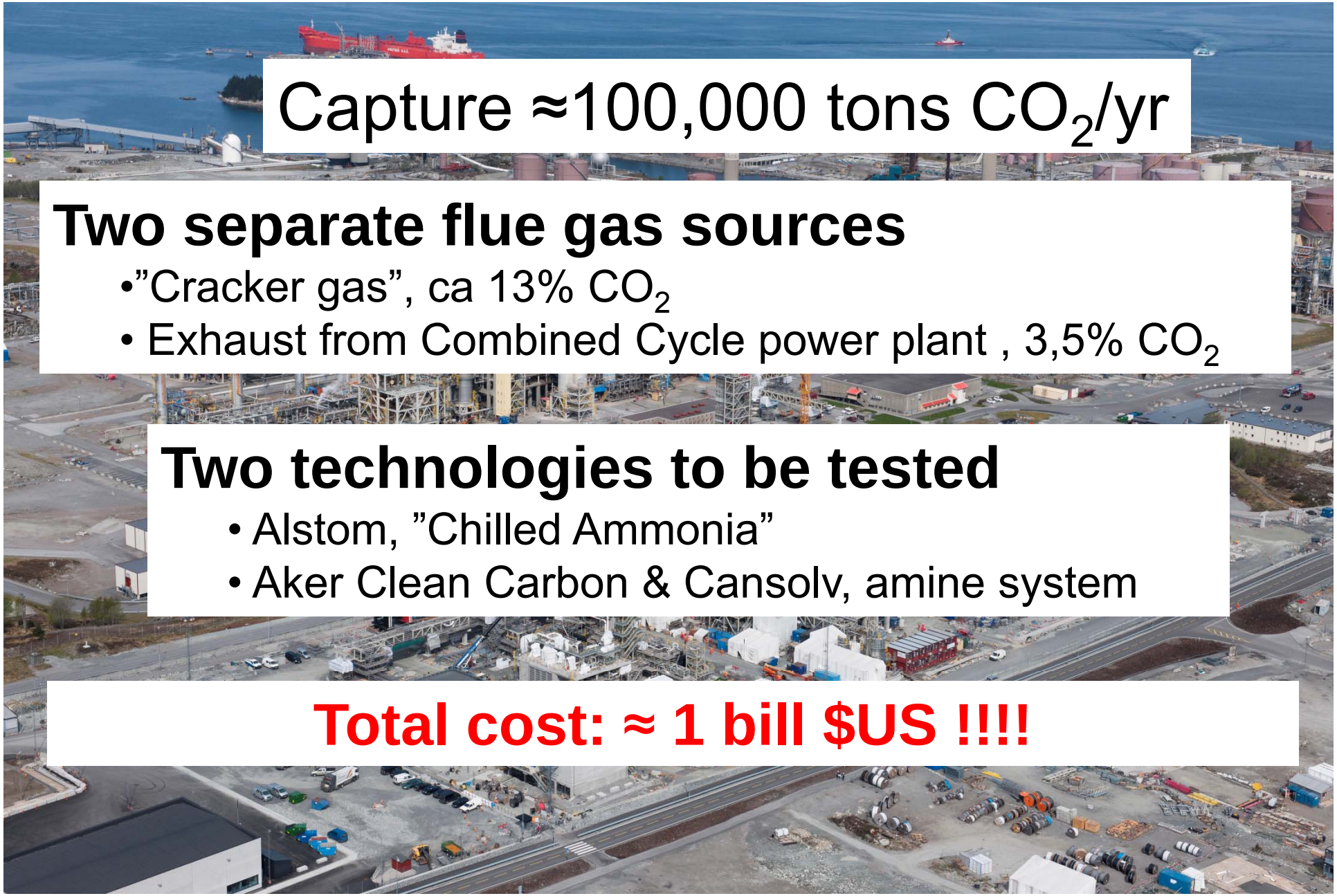
Sector	Energy source	Stationary combustion, NOK/tonne CO_2	Mobile combustion, NOK/tonne CO_2	Process emissions, NOK/tonne CO_2	Emissions mill. tonne CO_2
Extraction of crude oil/natural gas and pipe transport	Natural gas	338	-	-	10.5
	Light mineral oil: middle distillates	297	297	-	0.4
	Unspecified	-	-	0	0.9
Private households	Petrol	-	341	-	3.7
	Light mineral oils: paraffin	208	-	-	0.3
	Light mineral oils: middle distillates	199	199	-	1.1
	Light mineral oils: special distillates	190	-	-	0.0
	LPG/Natural gas	0	0	-	0.0
	Coal and coke	0	-	-	0.0
	Unspecified	0	-	0	0.1
Inland transport by road, domestic shipping (e.g. fishing) and domestic air service	Petrol	-	341	-	0.1
	Light mineral oils: paraffin		208		0.9
	Light mineral oils: middle distillates	-	199	-	5.7
	Light mineral oils: special distillates	-	190	-	0.2
	Heavy mineral oils	-	169	-	0.3
	LPG/Natural gas	-	0	-	0.0
	Unspecified	-	-	0	0.0
Other process emissions	Unspecified	-	-	0	7.3
Other stationary combustion		0 - 208*	-	-	7.6
Other mobile combustion		-	0 - 341**	-	4.2
Total emissions		19.1	16.5	7.6	43.3

Carbon tax in Norway

http://www.ssb.no/a/english/publikasjoner/pdf/doc_200916_en/doc_200916_en.pdf

http://en.wikipedia.org/wiki/Carbon_tax

Technology Center Mongstad (TCM)



Capture ≈100,000 tons CO_2/yr

Two separate flue gas sources

- ”Cracker gas”, ca 13% CO_2
- Exhaust from Combined Cycle power plant , 3,5% CO_2

Two technologies to be tested

- Alstom, ”Chilled Ammonia”
- Aker Clean Carbon & Cansolv, amine system

Total cost: ≈ 1 bill $US !!!!

Alstom Chilled Ammonia
In operation until end of 2014

Aker Clean Carbon
In operation March 2012 till mid 2013

Cansolv/Shell 2014-2015

Full-scale CO_2 capture plant Mongstad

Trondheim- World centre CCS R&D

R&D: ≈20 million Euro/yr (NTNU and SINTEF)

3 important CCS-players in Trondheim:

- NTNU
- SINTEF
- STATOIL R&D Centre

ECCSEL

BIGCCS International CCS Research Centre

nordiccs Nordic CCS Competence Centre CO_2

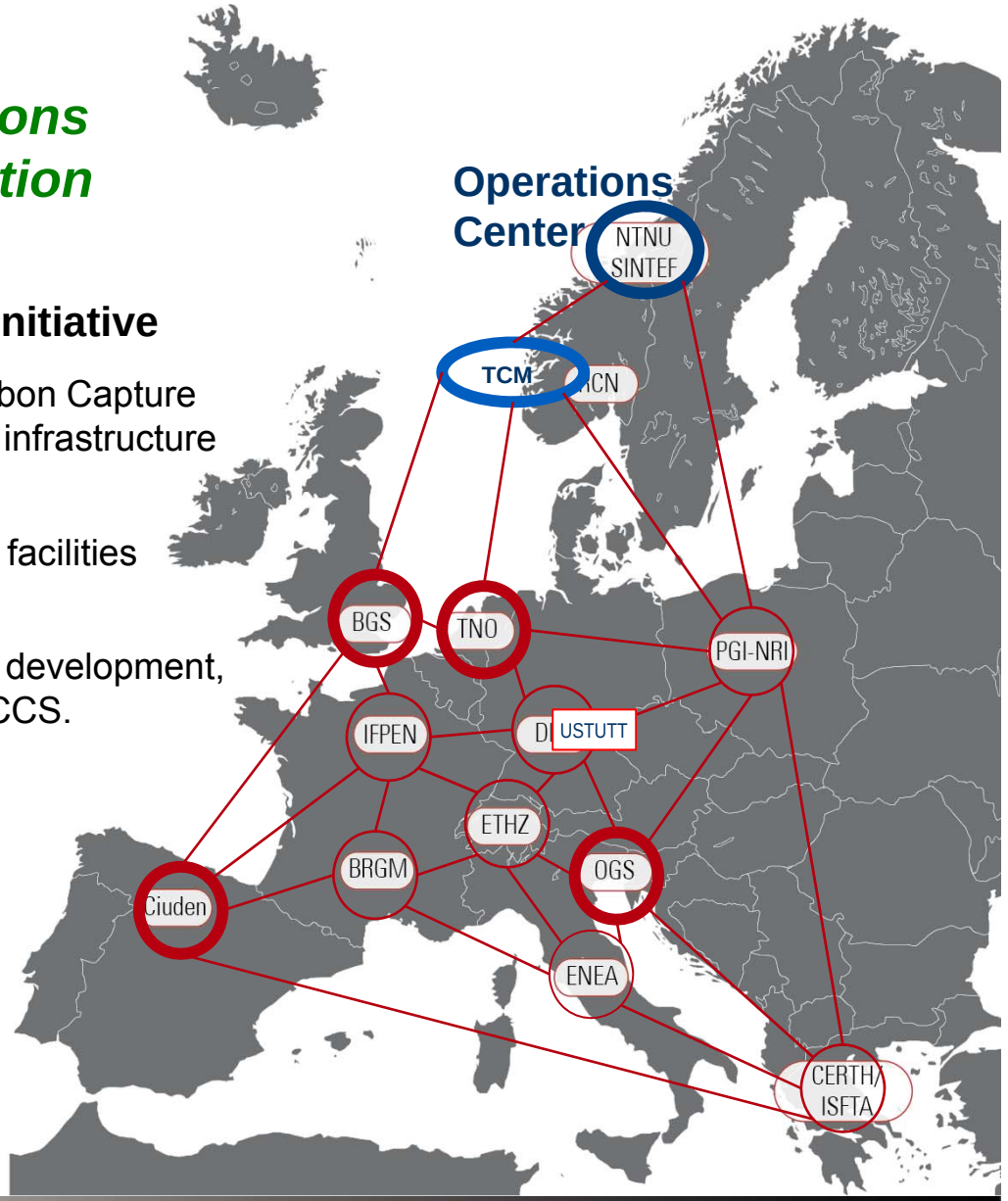
European Carbon Dioxide Capture and StoragE Laboratory Infrastructure

www.eccsel.org

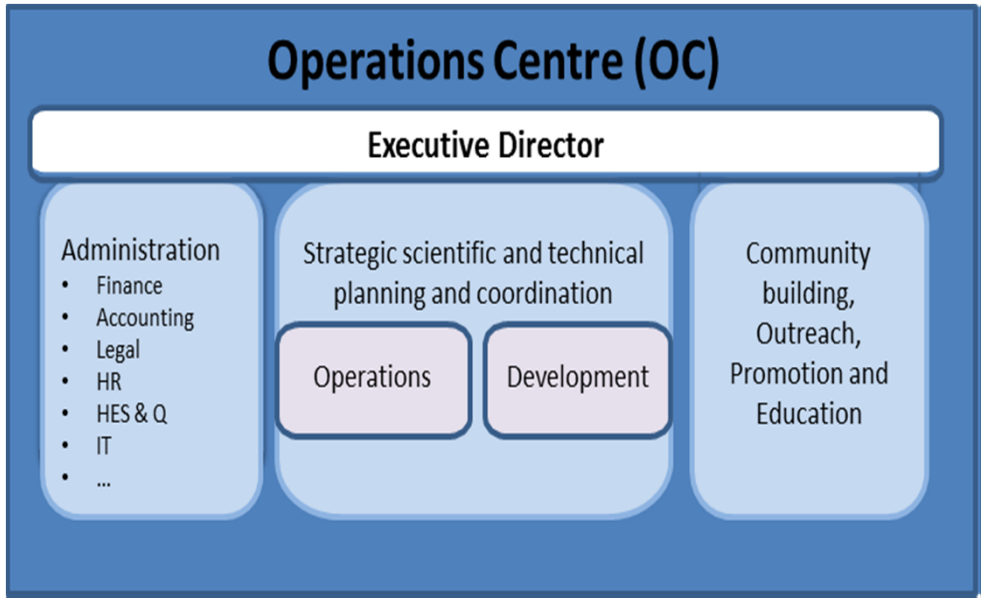
ECCSEL vision:

Enabling low to zero CO_2 emissions from industry and power generation

- **The main objectives of the ECCSEL initiative**
  - Establish and operate a world class Carbon Capture and Storage (CCS) distributed research infrastructure in Europe
  - Integrate and upgrade existing research facilities and supplement with new ones
  - Enhance European science, technology development, innovation and education in the field of CCS.
- **Societal impact**
  - Enable spin-off activities and generation of new business
  - Secure new employment
  - Contribute with spill-over effects for the society and communities involved



ECCSEL Operations Centre, Trondheim



Lean organization:

- 4-6 employees
- Annual budget ≈ 1 MEUR
- Legal form: ERIC
  - European Research Infrastructure Consortium

Location:
NTNU/SINTEF Campus
Trondheim, Norway

CENTRE FOR ENVIRONMENT-FRIENDLY ENERGY RESEARCH

BIGCCS
International research centre

Facts and status

BIGCCS – key information

- **Duration**: 8 years
- **Scientific staff**: 60
- **PhDs**: 30
- **Budget**: 512 MNOK (1.5 bill CZK)

Achievements

- Industrial **success stories** (Snøhvit, TCM, EOR, …)
- **Laboratory infrastructure** established (ECCSEL, CO_2 FieldLab, CO_2/Tiller Lab …)
- 31 new R&D projects initiated based on BIGCO2/BIGCCS activity:
  - 9 CLIMIT KPN projects – added to BIGCCS – Premium projects
  - 22 Offspring projects
- Significant **scientific achievements**
- 327 publications
- **Commercial project opportunities** identified

BIGCCS Industry partners

Statoil

GDF SUEZ

TOTAL

GASSCO

BIGCCS Research partners

SINTEF

NTNU

UiO : University of Oslo

British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

CICERO

DLR

GEUS

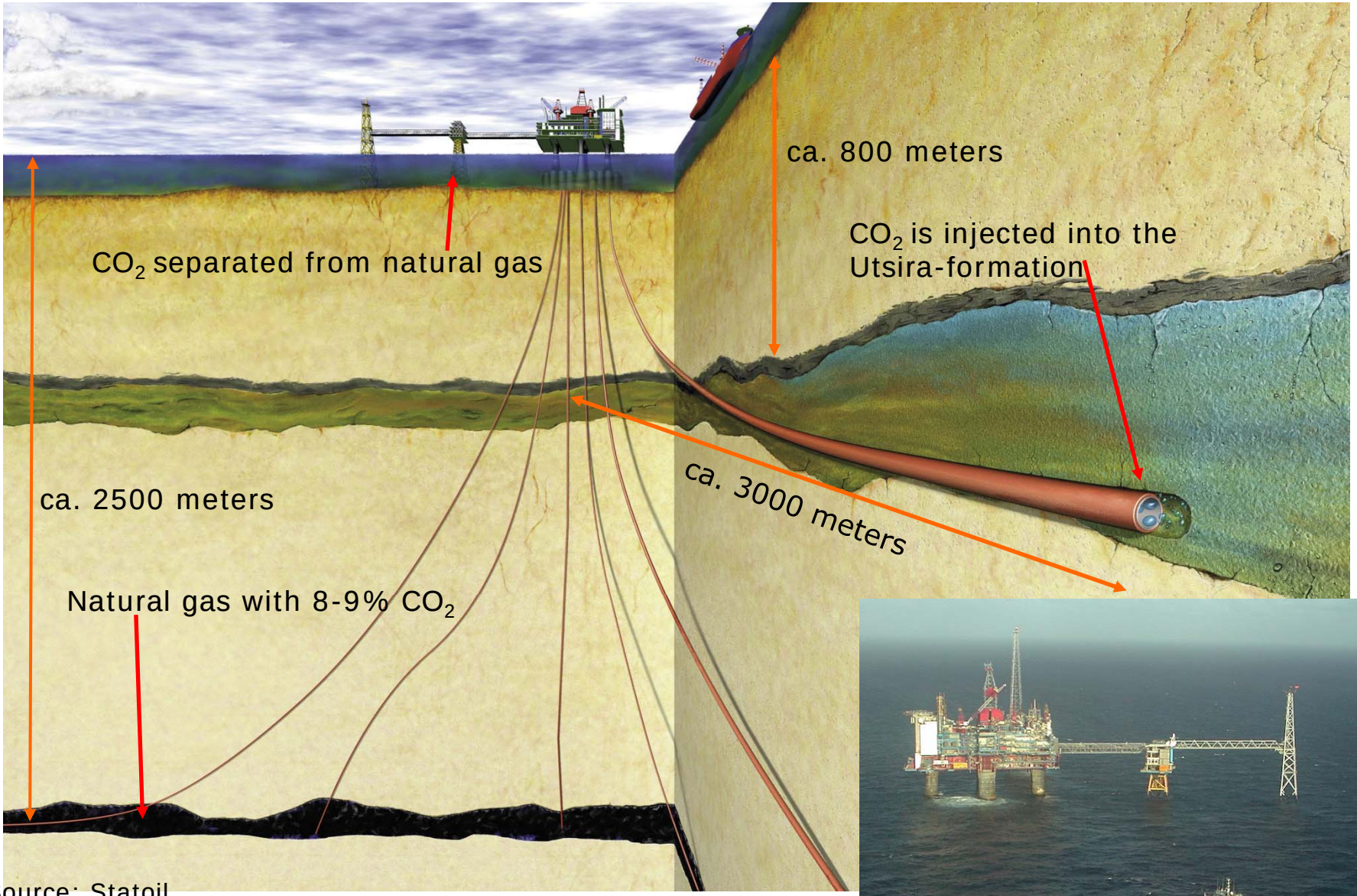
TUM

Sandia National Laboratories

RESOURCES FOR THE FUTURE

Sleipner gas field – CO_2 storage

≈1 million tonnes CO_2 annually since 1996



Source: Statoil

Sleipner and Snøhvit cases in short:

Sleipner:

Removes 1 mill. tonnes/year from Natural gas

Conditions: 100 bar, 9% CO_2 down to <2.5% CO_2

Uses an amine system, MDEA

Stores the CO_2 in the Utsira formation(aquifer)

In operation since 1996

Snøhvit:

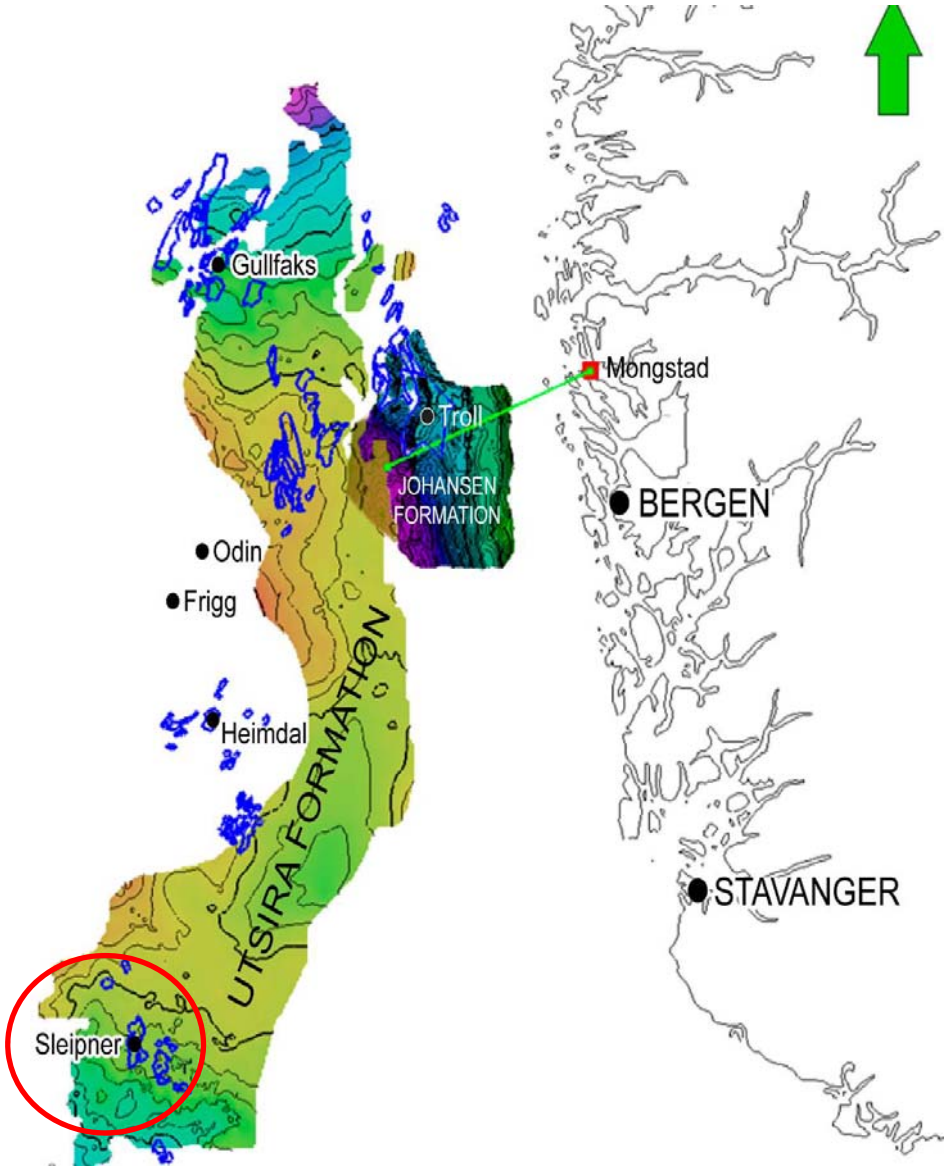
Removes 0.7 mill. tonnes/year from natural gas (LNG plant)

Conditions: 65 bar, 5% CO_2 down to 50 ppm

Uses: BASF aMDEA amine system

Stores the CO_2 in a saline aquifer

In operation since end of 2007



CCS – where are we? - 1

- Still few large-scale CCS plants, but
  - Boundary Dam (power), April 2014, 1 mill. ton CO_2/yr
  - Port Arthur (refinery), Sept 2015, 1 mill. ton CO_2/yr
  - Quest (oil sand), 2015(?), 1.1 mill. ton CO_2/yr
- Despite clear signals from climate research and IEA projections emphasising the need for CCS, construction of large plants coming along very slow
- Significant increase in international R&D efforts since about 2005

CCS – where are we? - 2

- Norway stands out internationally!
  - Sleipner CO_2 injection (since 1996)
  - Snøhvit CO_2 storage (since 2008)
  - Technology Centre Mongstad (TCM)
  - Extensive R&D activities

- R&D has led to reduced CCS energy consumption
- Post-combustion (amine technology) technologies commercially ready
- Costs are still too high and very uncertain

CCS – where are we? - 3

- The economical framework for CCS (emissions trading or cap-and-trade) not sufficient for CCS to start to move
- Acceptance for CO_2 transport and storage in populated areas is a potential show stopper

Thank you!