Institute for
Thermal Turbomaschinery
and Machine Dynamics

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Carbon Capture and Storage

Lecture at the
Department of Aerospace Engineering
Middle East Technical University
Ankara, April 2008

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Graz University of Technology
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>> MIDDLE EAST TECHNICAL UNIVERSITY

Motivation

How do you want your egg(s)? - Sunny side up?

But do not have it burned!

Global Warming

Posted on Fri, Jan. 16, 2004

Star-Telegram

Global warming evidence is mounting

By Seth Borenstein
Knight Ridder News Service

WASHINGTON - It's cold comfort to people shivering in much of the United States right now, but 2003 tied for the world's second-hottest year, according to federal government data released Thursday.

Germany unlikely to meet CO2 reduction targets - DIW

GERMANY: February 21, 2003

FRANKFURT - Germany is unlikely to deliver on its pledges to curb emissions of carbon dioxide (CO2), despite a further reduction last year, the Berlin-based German Institute for Economic Research DIW said.

Global warming 'threatens 1 million species'

Global warming could wipe out a quarter of all species of plants and animals by 2050 in one of the biggest mass extinctions since the dinosaurs, according to an international study.

Tuesday, 10 September, 2002, 11:54 GMT 12:54 UK

Carbon burial experiment works

It could become standard practice in the North Sea

By Jonathan Amos
BBC News Online science staff in Leicester

UK geologists say efforts to bury the carbon dioxide byproduct from gas exploration in the North Sea have been hugely successful.

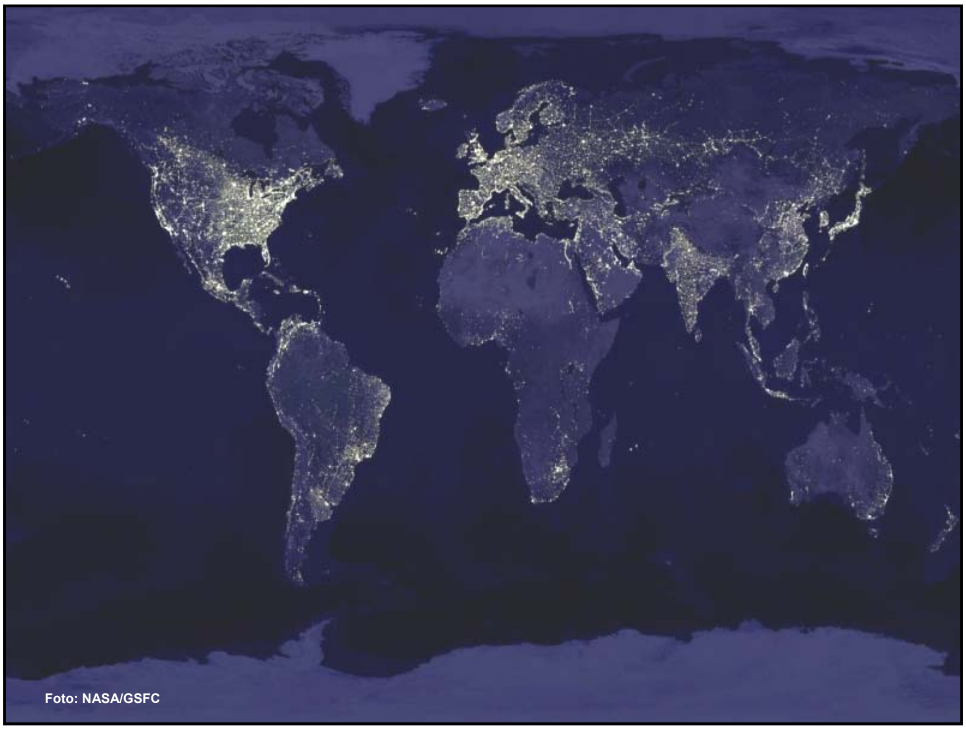
An experiment has been running in the Sleipner Field since 1996, in which waste CO2 that comes up with the extracted methane is separated off and then pumped back under ground. It would normally be vented into the atmosphere.

GLOBAL WARMING

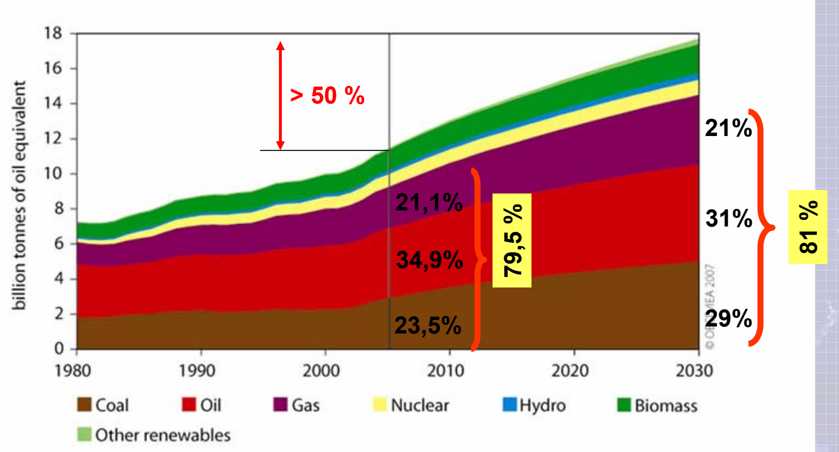
"I think it is fair to say that the record of the Bush Administration on environmental matters is fatally flawed."
Gov. Howard Dean, M.D.

Content

- **World energy situation**
- **CO2 emissions and climate change**
- **CO2 transport and storage**
- **CO2 capture**
  - **Post combustion technologies**
  - **Pre combustion technologies**
  - **Oxyfuel technologies**
- **Summary and conclusions**

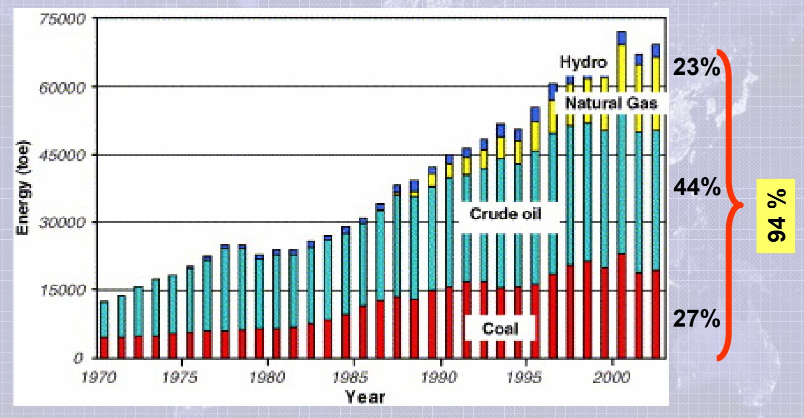


World Primary Energy Demand in the Reference Scenario



Source: World Energy Outlook 2007

Energy demand in Turkey



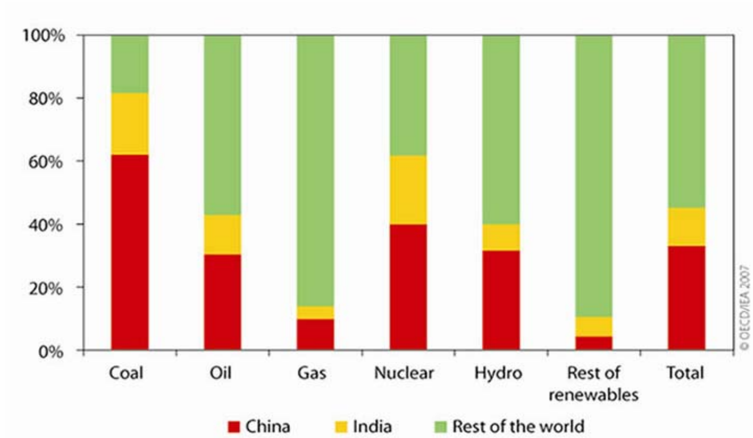
Including Renewables: Share of fossil fuels is 87%

In 2000: Turkey: 81 Mtoe (Austria: 28 Mtoe, USA: 2300 Mtoe)

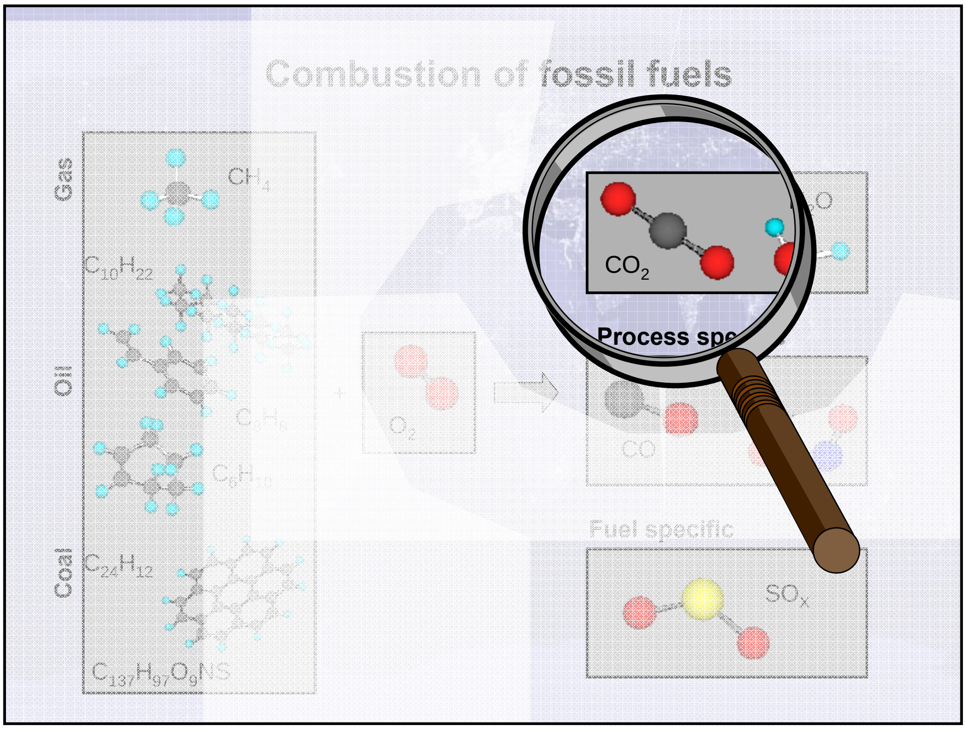
Increase to 180 Mtoe till 2015

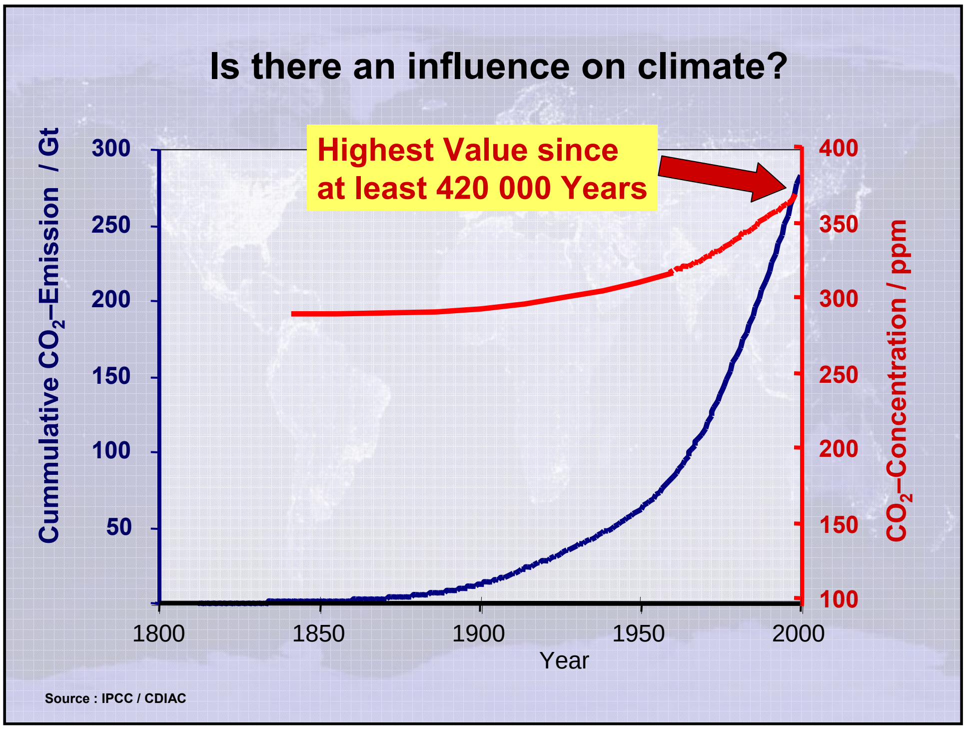
Source: Say and Yücel, Engery Policy 2006

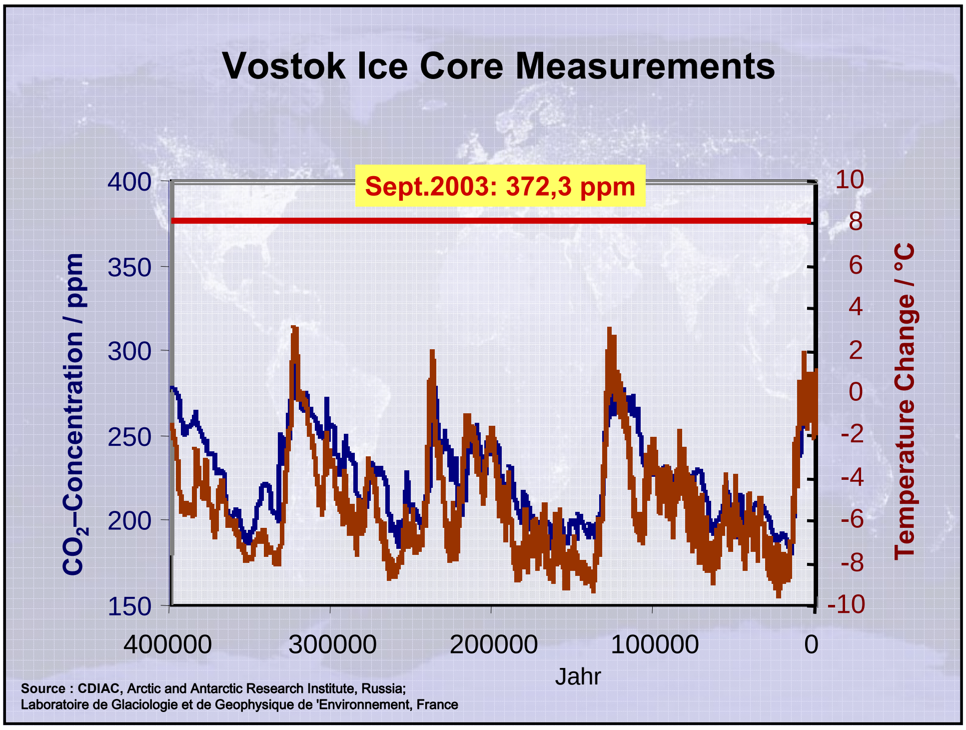
Increase in World Primary Energy Demand in the Reference Scenario, 2005-2030

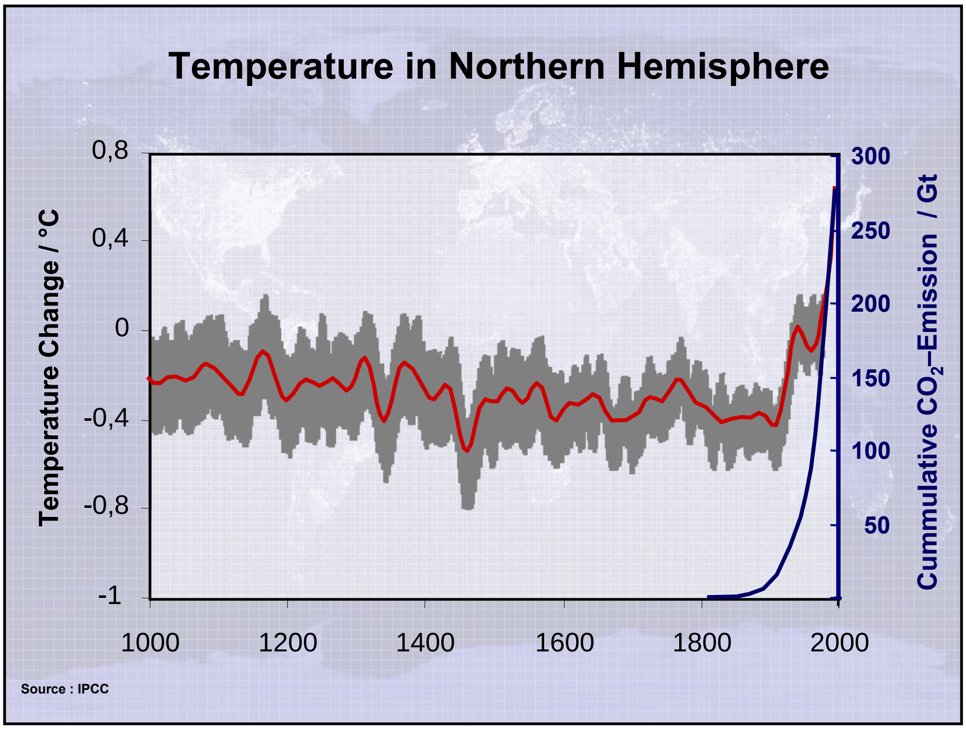


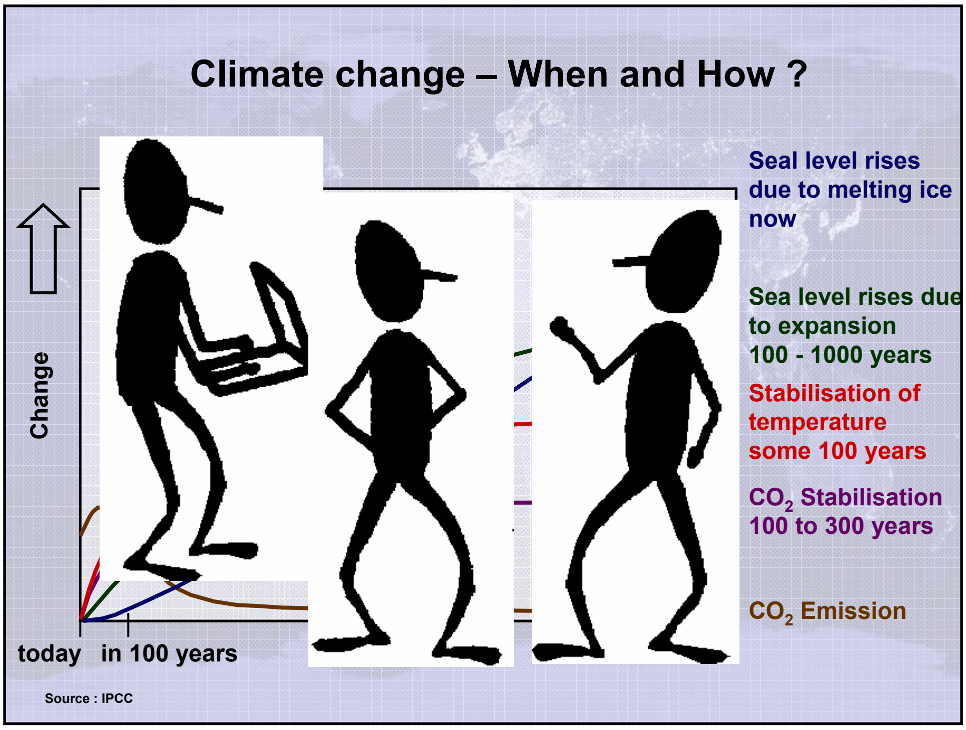
Source: World Energy Outlook 2007

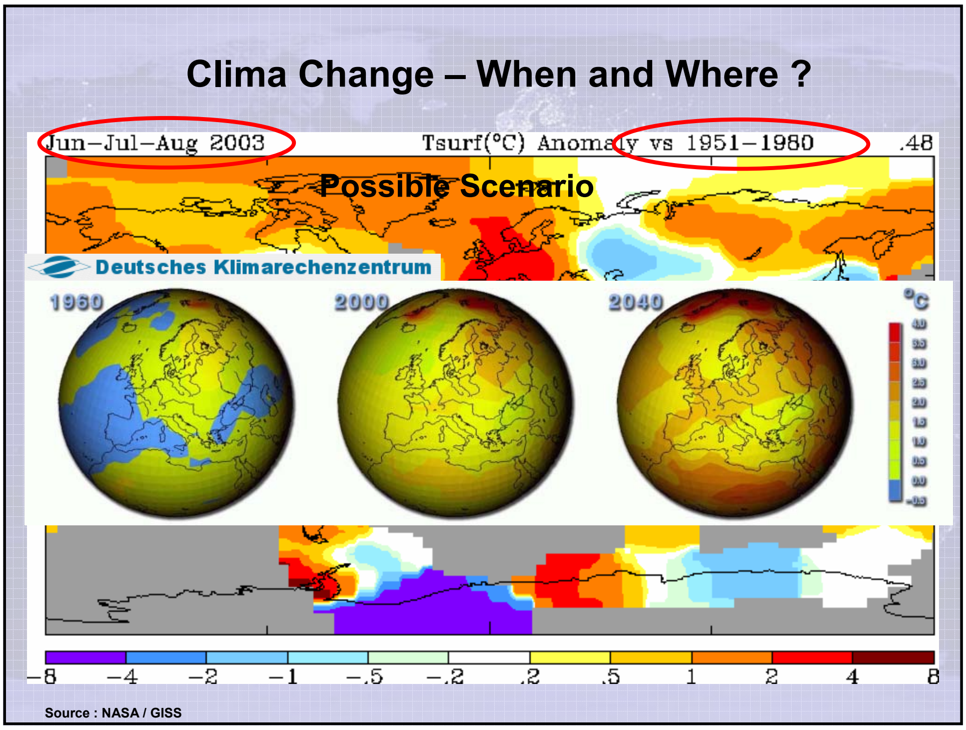

Combustion of fossil fuels
Gas
Oil
Coal
CH_4
$C_{10}H_{22}$
C_8H_8
C_6H_{10}
$C_{24}H_{12}$
$C_{137}H_{97}O_9NS$
O_2
CO_2
Process spe
CO
Fuel specific
SO_x


Is there an influence on climate?
Highest Value since
at least 420 000 Years
Cummulative CO_2–Emission / Gt
CO_2–Concentration / ppm
300
250
200
150
100
50
400
350
300
250
200
150
100
1800
1850
1900
1950
2000
Year
Source : IPCC / CDIAC

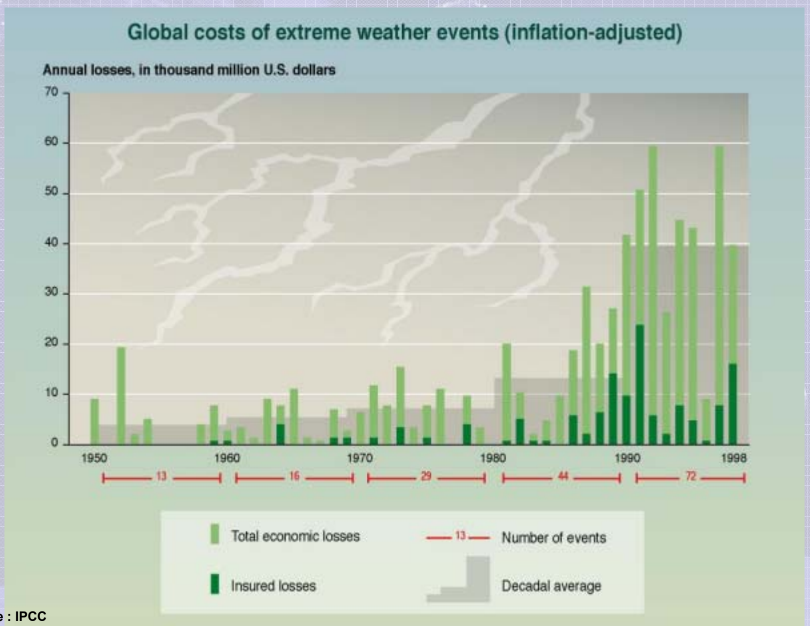

Vostok Ice Core Measurements
Sept.2003: 372,3 ppm
400
350
300
250
200
150
10
8
6
4
2
0
-2
-4
-6
-8
-10
CO2–Concentration / ppm
Temperature Change / °C
400000
300000
200000
100000
0
Jahr
Source : CDIAC, Arctic and Antarctic Research Institute, Russia;
Laboratoire de Glaciologie et de Geophysique de 'Environnement, France


Temperature in Northern Hemisphere
0,8
0,4
0
-0,4
-0,8
-1
300
250
200
150
100
50
Temperature Change / °C
Cummulative CO2–Emission / Gt
1000
1200
1400
1600
1800
2000
Source : IPCC

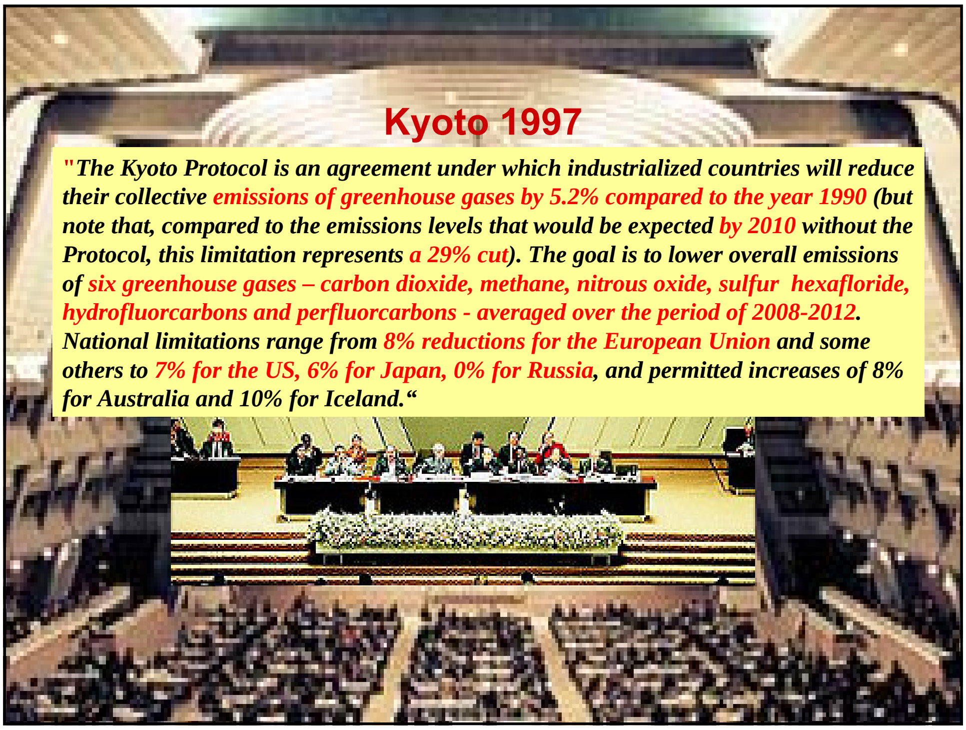

Climate change – When and How ?
Change
Seal level rises due to melting ice now
Sea level rises due to expansion 100 - 1000 years
Stabilisation of temperature some 100 years
CO_2 Stabilisation 100 to 300 years
CO_2 Emission
today
in 100 years
Source : IPCC


Clima Change – When and Where ?
Jun–Jul–Aug 2003
Tsurf(°C) Anomaly vs 1951–1980
.48
Possible Scenario
Deutsches Klimarechenzentrum
1960
2000
2040
°C
–8 –4 –2 –1 –.5 –.2 .2 .5 1 2 4 8
Source : NASA / GISS

Costs of Climate Change

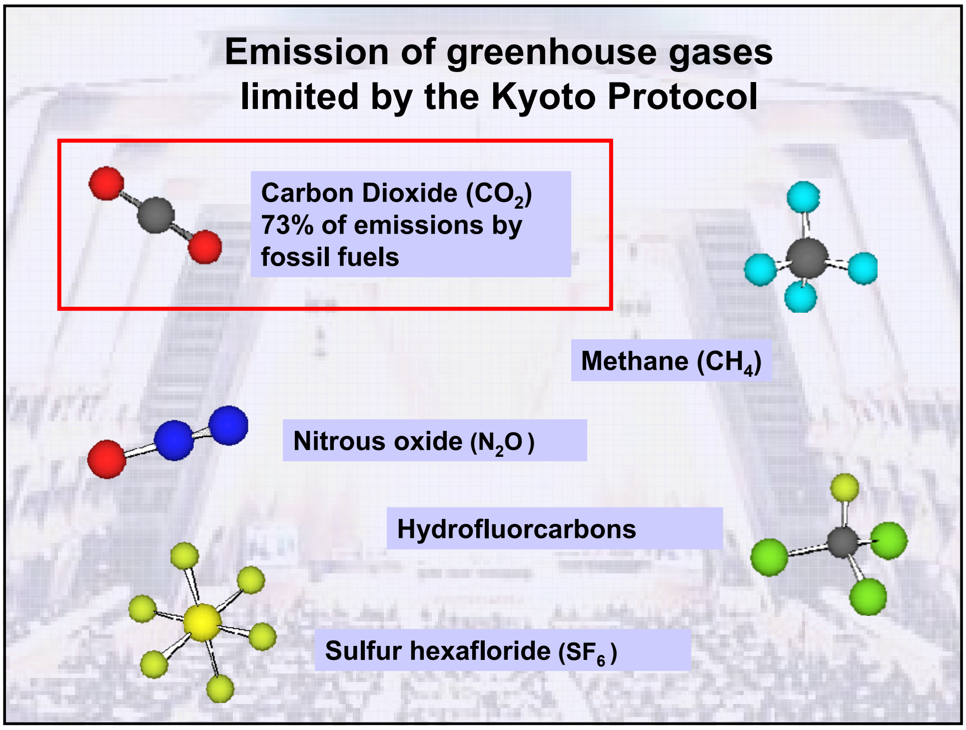


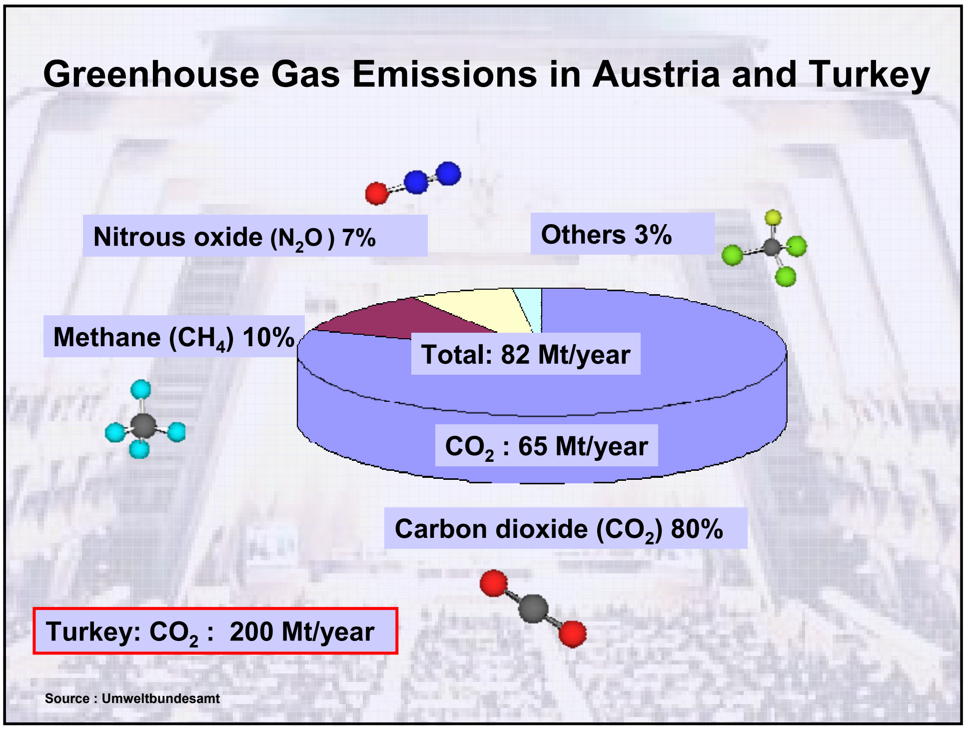
Source : IPCC

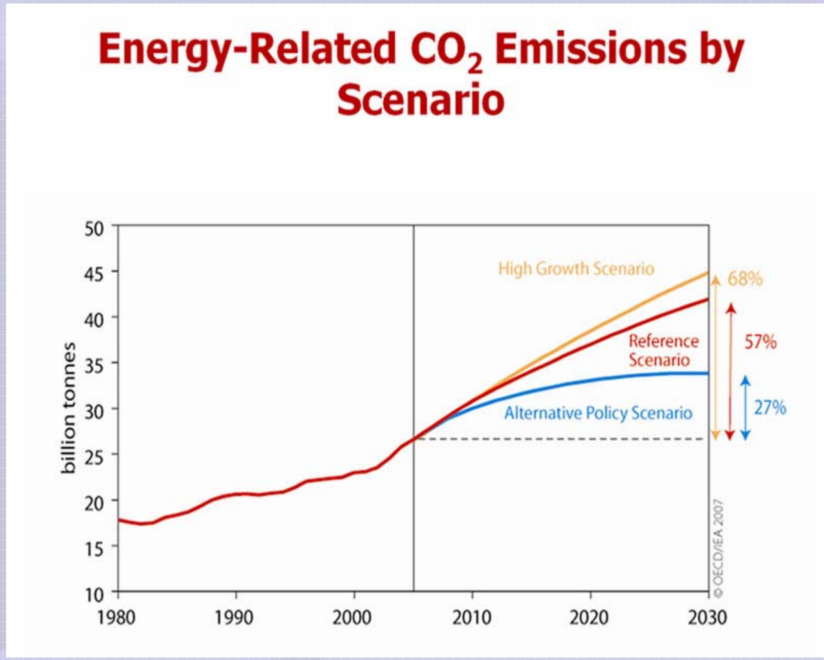


Kyoto 1997

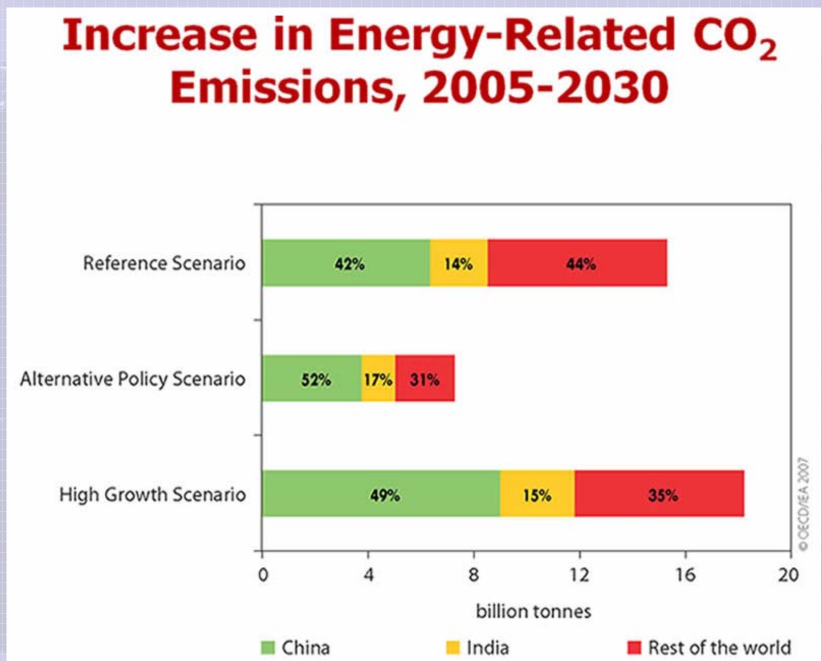
"The Kyoto Protocol is an agreement under which industrialized countries will reduce their collective emissions of greenhouse gases by 5.2% compared to the year 1990 (but note that, compared to the emissions levels that would be expected by 2010 without the Protocol, this limitation represents a 29% cut). The goal is to lower overall emissions of six greenhouse gases – carbon dioxide, methane, nitrous oxide, sulfur hexafloride, hydrofluorcarbons and perfluorcarbons - averaged over the period of 2008-2012. National limitations range from 8% reductions for the European Union and some others to 7% for the US, 6% for Japan, 0% for Russia, and permitted increases of 8% for Australia and 10% for Iceland."


Emission of greenhouse gases
limited by the Kyoto Protocol
Carbon Dioxide (CO_2)
73% of emissions by
fossil fuels
Methane (CH_4)
Nitrous oxide (N_2O)
Hydrofluorcarbons
Sulfur hexafloride (SF_6)

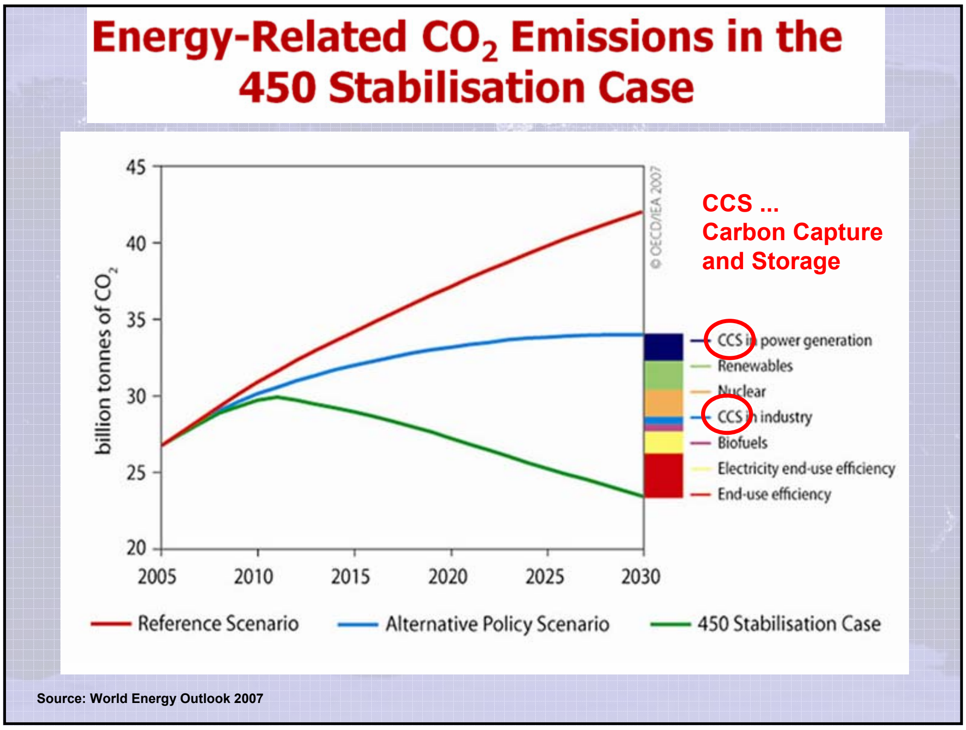

Greenhouse Gas Emissions in Austria and Turkey
Nitrous oxide (N_2O) 7%
Others 3%
Methane (CH_4) 10%
Total: 82 Mt/year
CO_2 : 65 Mt/year
Carbon dioxide (CO_2) 80%
Turkey: CO_2 : 200 Mt/year
Source : Umweltbundesamt

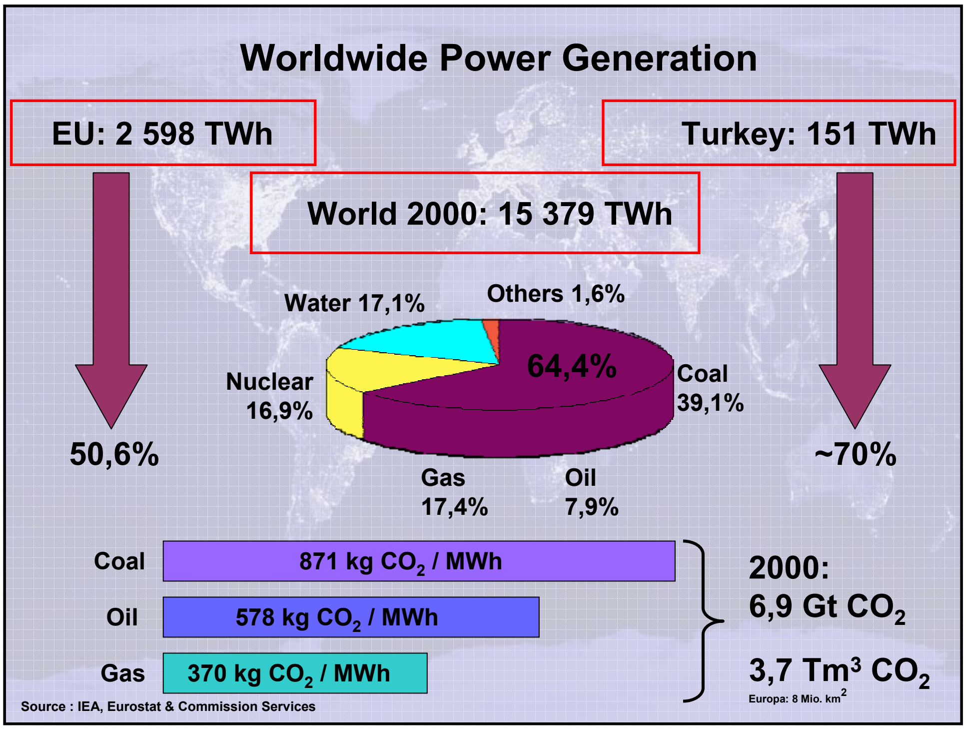


Source: World Energy Outlook 2007



Source: World Energy Outlook 2007


Energy-Related CO_2 Emissions in the 450 Stabilisation Case
45
40
35
30
25
20
billion tonnes of CO_2
2005
2010
2015
2020
2025
2030
© OECD/IEA 2007
CCS ...
Carbon Capture
and Storage
CCS in power generation
Renewables
Nuclear
CCS in industry
Biofuels
Electricity end-use efficiency
End-use efficiency
Reference Scenario
Alternative Policy Scenario
450 Stabilisation Case
Source: World Energy Outlook 2007


Worldwide Power Generation
EU: 2 598 TWh
Turkey: 151 TWh
World 2000: 15 379 TWh
50,6%
~70%
Water 17,1%
Others 1,6%
Nuclear 16,9%
64,4%
Coal 39,1%
Gas 17,4%
Oil 7,9%
Coal
871 kg CO_2 / MWh
Oil
578 kg CO_2 / MWh
Gas
370 kg CO_2 / MWh
2000:
6,9 Gt CO_2
3,7 Tm^3 CO_2
Europa: 8 Mio. km^2
Source : IEA, Eurostat & Commission Services

Number of large CO2 Sources

Table SPM.1. Profile by process or industrial activity of worldwide large stationary CO_2 sources with emissions of more than 0.1 million tonnes of CO_2 ($MtCO_2$) per year.

Process	Number of sources	Emissions ($MtCO_2$ yr^{-1})
Fossil fuels		
Power	4,942	10,539
Cement production	1,175	932
Refineries	638	798
Iron and steel industry	269	646
Petrochemical industry	470	379
Oil and gas processing	Not available	50
Other sources	90	33
Biomass		
Bioethanol and bioenergy	303	91
Total	**7,887**	**13,466**

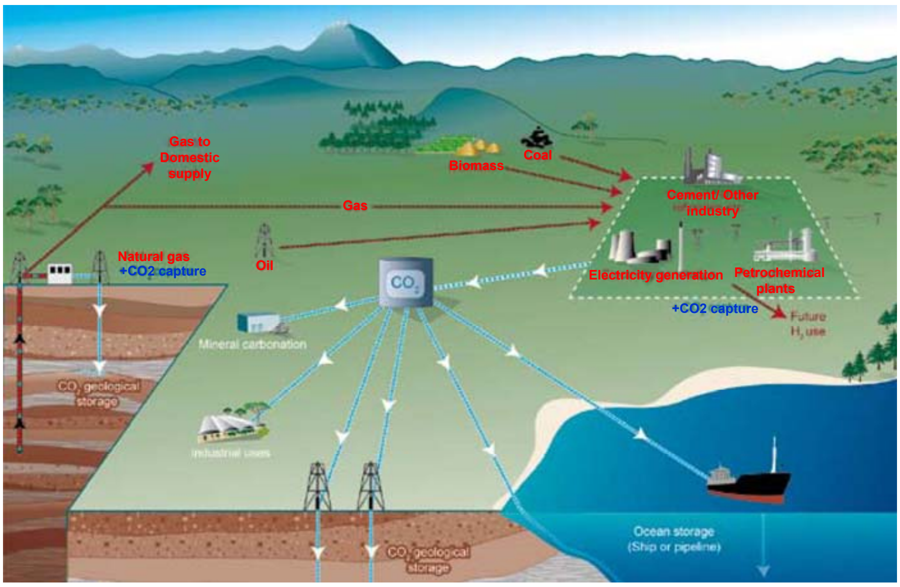
EU Emission Trading Scheme:

In January 2005 the European Union Greenhouse Gas Emission Trading Scheme (EU ETS) commenced operation as the largest multi-country, multi-sector Greenhouse Gas emission trading scheme world-wide.

→ **CO2 emissions generate costs**

Source: IPCC Special Report on CCS (2005)

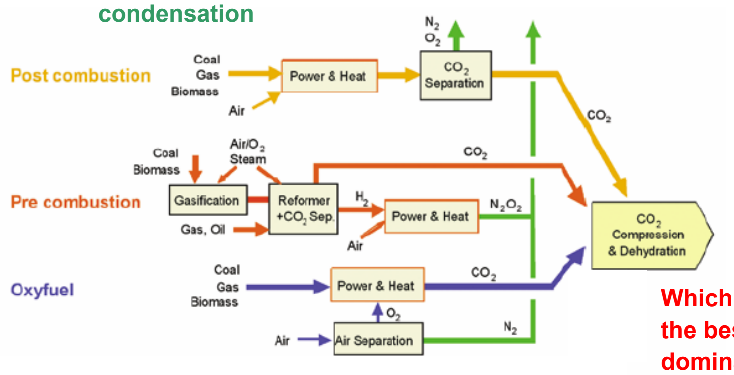
CCS – Carbon Capture and Storage



Source: IPCC Special Report on CCS (2005)

CCS Technologies

- **Post-combustion:** CO2-Capture from exhaust gas (chemical absorbtion, membranes, …)
- **Pre-combustion:** Decarbonization of fossil fuel to produce pure hydrogen for power cycle (e.g. steam reforming of methane, …)
- **Oxy-fuel power generation:** Internal combustion with pure oxygen and CO2/H2O as working fluid enabling CO2 separation by condensation



Which technology has the best chances to dominate future power generation ?

Source: IPCC Special Report on CCS (2005)

CO2 Transport

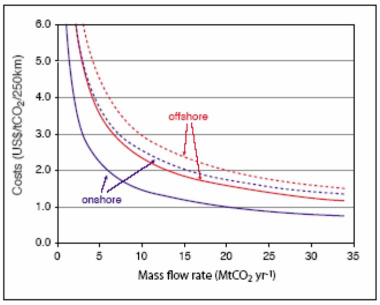


Figure TS.5. Transport costs for onshore pipelines and offshore pipelines, in US$ per tCO_2 per 250 km as a function of the CO_2 mass flow rate. The graph shows high estimates (dotted lines) and low estimates (solid lines).

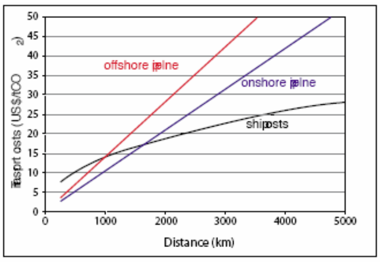


Figure TS.6. Costs, plotted as US$/$tCO_2$ transported against distance, for onshore pipelines, offshore pipelines and ship transport. Pipeline costs are given for a mass flow of 6 $MtCO_2\ yr^{-1}$. Ship costs include intermediate storage facilities, harbour fees, fuel costs, and loading and unloading activities. Costs include also additional costs for liquefaction compared to compression.

Source: IPCC Special Report on CCS (2005)

CO2 Storage

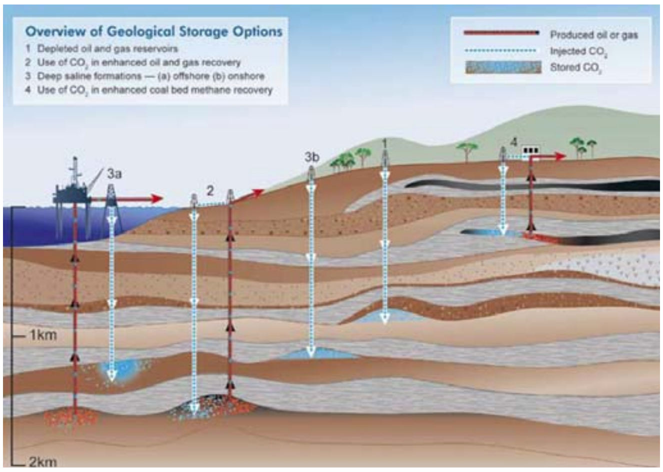


Table TS.6. Storage capacity for several geological storage options. The storage capacity includes storage options that are not economical.

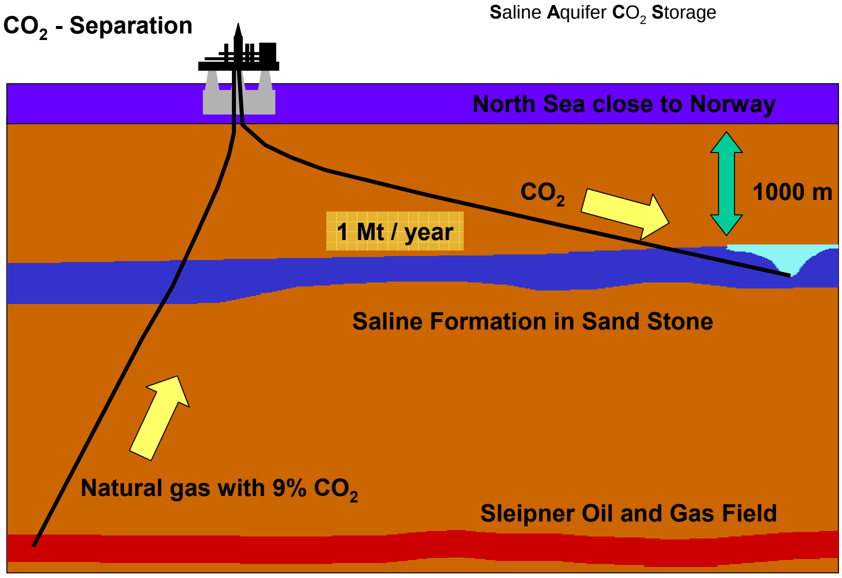
Reservoir type	Lower estimate of storage capacity ($GtCO_2$)	Upper estimate of storage capacity ($GtCO_2$)
Oil and gas fields	675[a]	900[a]
Unminable coal seams (ECBM)	3-15	200
Deep saline formations	1,000	Uncertain, but possibly 10^4

Source: IPCC Special Report on CCS (2005)

CO_2 Storage

SACS Project (since 1996)

Saline **A**quifer **C**O_2 **S**torage



SACS

Ocean Storage

Source: IPCC Special Report on CCS (2005)

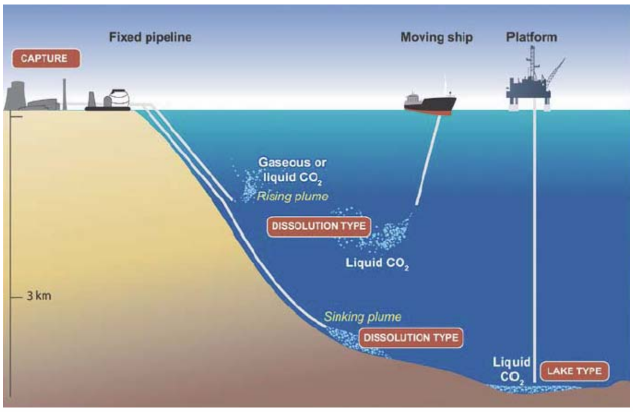
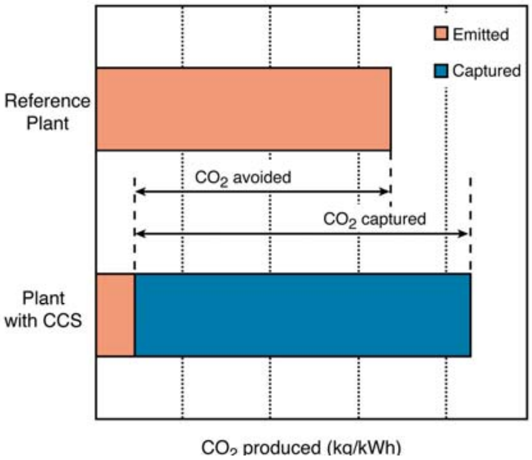


Table TS.7. Fraction of CO_2 retained for ocean storage as simulated by seven ocean models for 100 years of continuous injection at three different depths starting in the year 2000.

	Injection depth		
Year	**800 m**	**1500 m**	**3000 m**
2100	0.78 ± 0.06	0.91 ± 0.05	0.99 ± 0.01
2200	0.50 ± 0.06	0.74 ± 0.07	0.94 ± 0.06
2300	0.36 ± 0.06	0.60 ± 0.08	0.87 ± 0.10
2400	0.28 ± 0.07	0.49 ± 0.09	0.79 ± 0.12
2500	0.23 ± 0.07	0.42 ± 0.09	0.71 ± 0.14

CO2 Mitigation Costs



Source: IPCC Special Report on CCS (2005)

CCS – Costs

Table TS.11. Mitigation cost ranges for different combinations of reference and CCS plants based on current technology for new power plants. Currently, in many regions, common practice would be either a PC plant or an NGCC plant[14]. EOR benefits are based on oil prices of 15 - 20 US$ per barrel. Gas prices are assumed to be 2.8 -4.4 US$/GJ^{-1}, coal prices 1-1.5 US$/GJ^{-1} (based on Table 8.3a).

CCS plant type	NGCC reference plant US$/t$CO_2$ avoided (US$/tC avoided)	PC reference plant US$/t$CO_2$ avoided (US$/tC avoided)
Power plant with capture and geological storage		
NGCC	40 - 90 (140 - 330)	20 - 60 (80 - 220)
PC	70 - 270 (260 - 980)	30 - 70 (110 - 260)
IGCC	40 - 220 (150 - 790)	20 - 70 (80 - 260)
Power plant with capture and EOR		
NGCC	20 - 70 (70 - 250)	0 - 30 (0 - 120)
PC	50 - 240 (180 - 890)	10 - 40 (30 - 160)
IGCC	20 - 190 (80 - 710)	0 - 40 (0 - 160)

NGCC Natural Gas Combined Cycle
PC Pulverized Coal
IGCC Integrated Gasification Combined Cycle
EOR Enhanced Oil Recovery

Source: IPCC Special Report on CCS (2005)

Post Combustion Technology

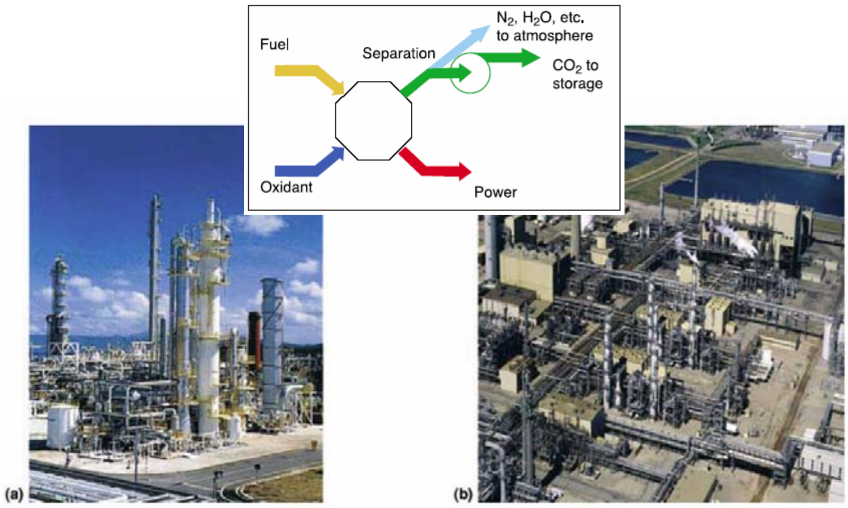


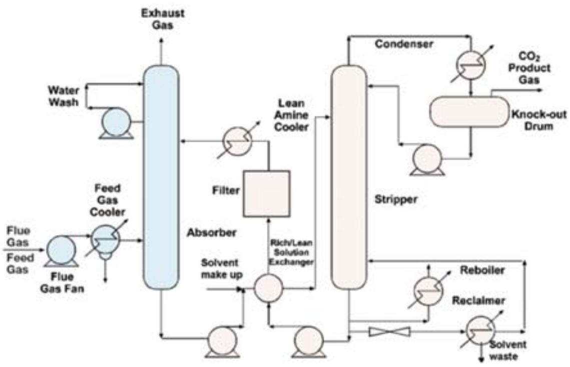
Figure TS.4. (a) CO_2 post-combustion capture at a plant in Malaysia. This plant employs a chemical absorption process to separate 0.2 $MtCO_2$ per year from the flue gas stream of a gas-fired power plant for urea production (Courtesy of Mitsubishi Heavy Industries). (b) CO_2 pre-combustion capture at a coal gasification plant in North Dakota, USA. This plant employs a physical solvent process to separate 3.3 $MtCO_2$ per year from a gas stream to produce synthetic natural gas. Part of the captured CO_2 is used for an EOR project in Canada.

Source: IPCC Special Report on CCS (2005)

membranes

Chemical Absorption

- CO2 concentration in flue gas: NGCC: 4 vol-%, coal steam cycle: 13 vol-%
- Use of reversible chemical reaction of an aqueous alkaline solvent, usually an amine, with an acid or sour gas.
- In absorber (40 – 60°C) CO2 is bound by the chemical solvent
- In stripper regeneration of chemical solvent (100 – 140°C)
- Necessary heat (reboiler) leads to a thermalenergy penalty



Source: IPCC Special Report on CCS (2005)

Physical Solvent Absorption

- Needs less energy (only for compression)
- Works only for higher CO2 content

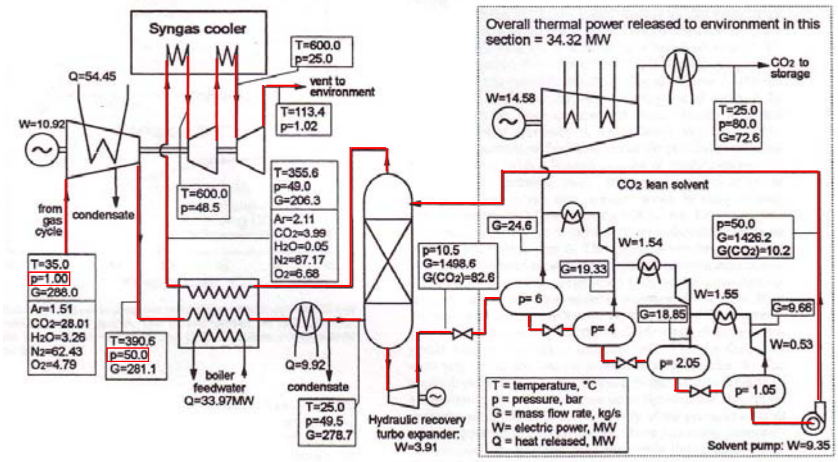
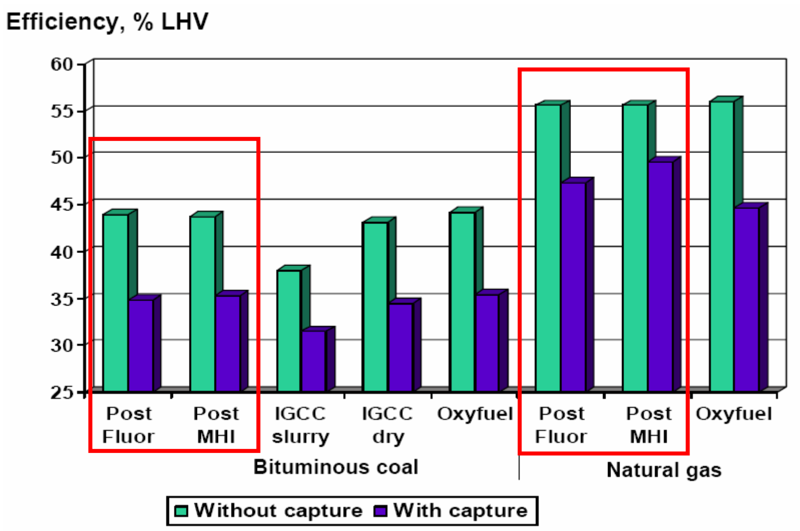


Fig. 3 Energy and mass balance of the carbon-dioxide physical separation process, including the compression/liquefaction train, for a cycle pressure ratio of 15 and a thermal input of 900 MW (LHV). Gas compositions in mass percentage fraction.

Source: Chiese and Lozza, ASME (1999)

Efficiency Penalty

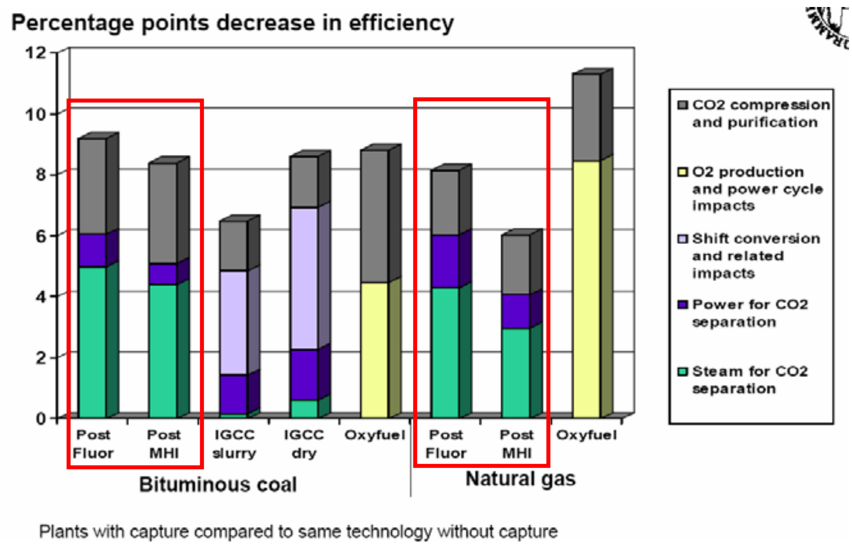


Fluor: Mono-Ethanolamine (MEA)

MHI: sterically hindered amine

Source: Davison, IEA (2005)

Efficiency Penalty

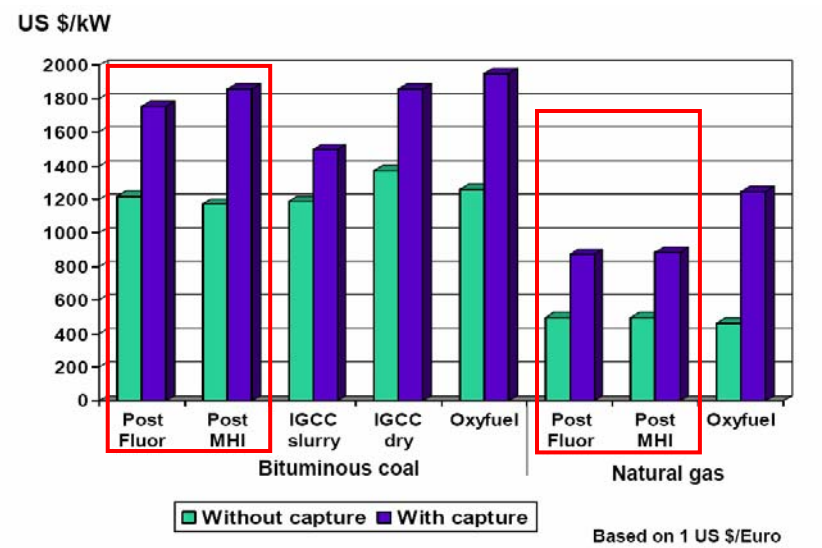


Fluor: Mono-Ethanolamine (MEA)

MHI: sterically hindered amine

Source: Davison, IEA (2005)

Capital Costs

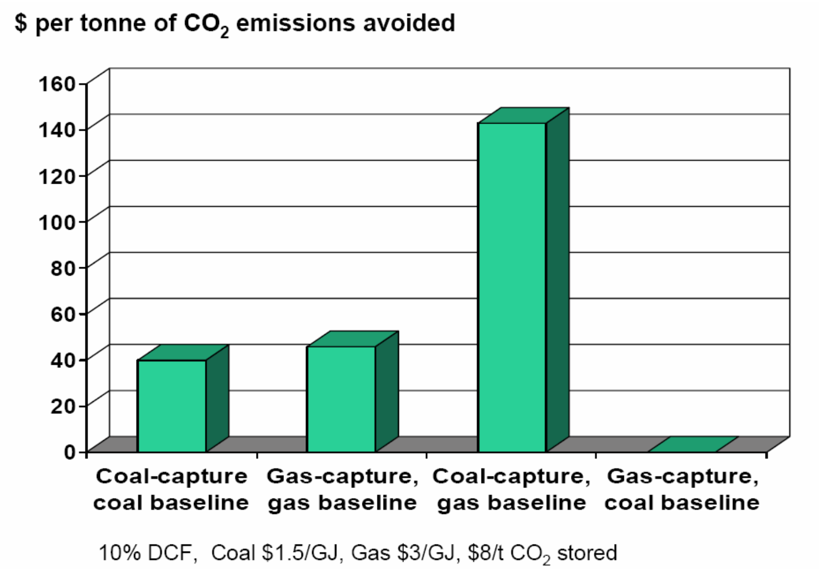


Fluor: Mono-Ethanolamine (MEA)

MHI: sterically hindered amine

Source: Davison, IEA (2005)

Costs per ton of CO2



Source: Davison, IEA (2005)

Pre-combustion technology

- Production of a mixture of hydrogen and carbon monoxide (syngas) from a primary fuel (coal, natural gas, biomass, ...):

  a) steam reforming: $C_xH_y + xH_2O \leftrightarrow xCO + (x+y/2)H_2$ ΔH +ve

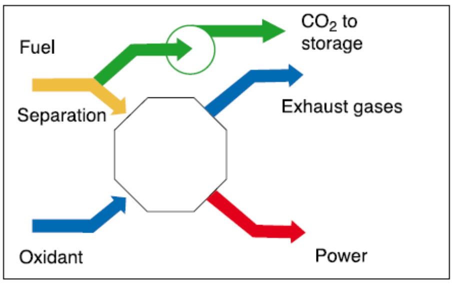
  b) partial oxidation: $C_xH_y + x/2O_2 \leftrightarrow xCO + (y/2)H_2$ ΔH –ve

- Water Gas Shift Reaction to convert CO to CO2 by the addition of steam

  $CO + H2O \leftrightarrow CO2 + H2$ ΔH - 41 kJ/mol

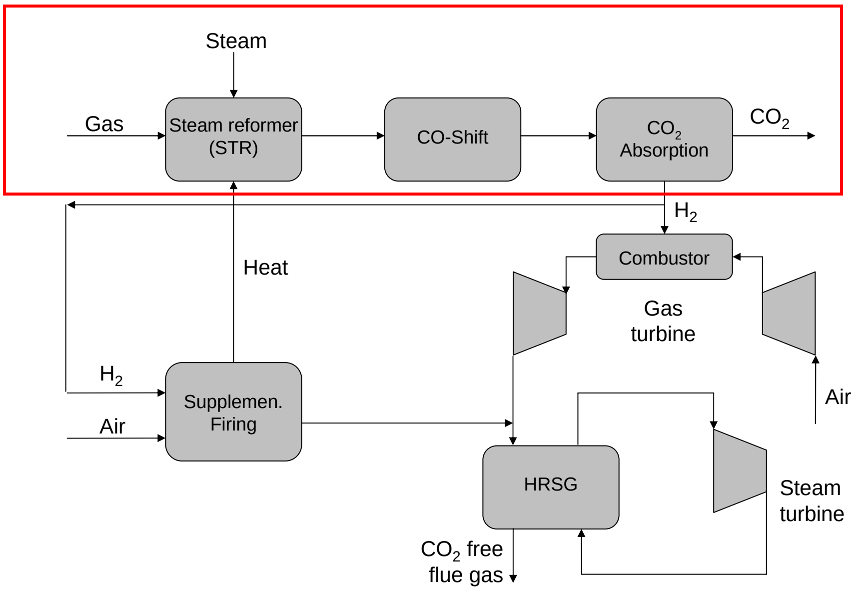
- CO2 is removed from the CO_2/H_2 mixture by e.g. physical absorption (CO_2 content 15-60%)

- Hydrogen is used as fuel for power generation



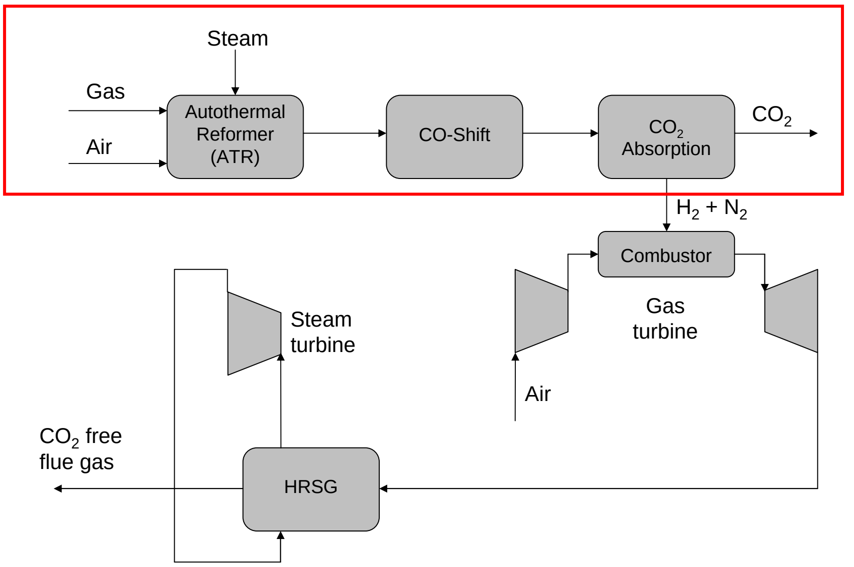
Source: IPCC Special Report on CCS (2005)

Steam Reformer



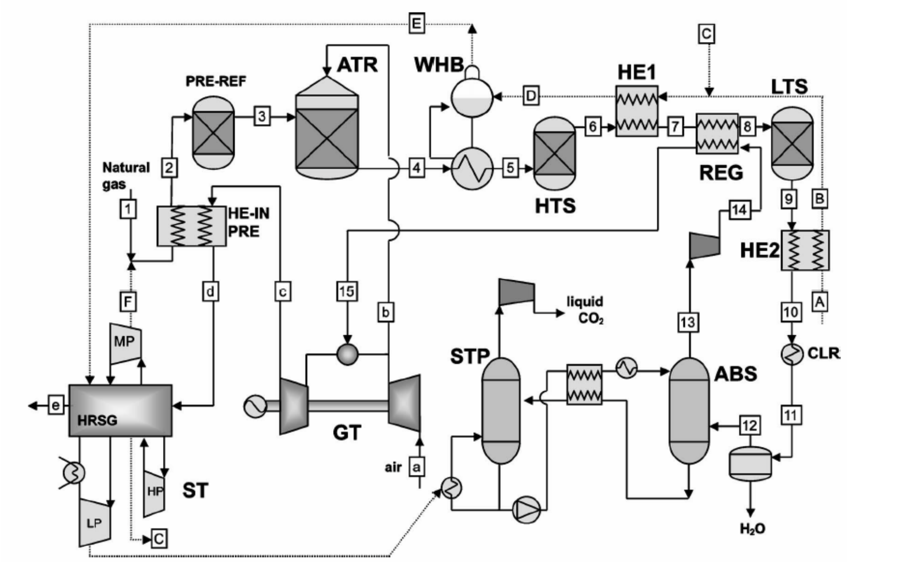
Source: Heegemann, 2008

Autothermal Reformer



Source: Heegemann, 2008

Autothermal Reformer (ATR)



Source: Corradetti and Desideri, ASME (2005)

PRE-REF: Pre-Reformer, WHB: waste heat boiler, HTS: High temp. Shift, LTS: Low temp. Shift, HE: heat exchanger, REG: Regenerator CLR: Cooler, ABS: Absorber, STP: stripper

Autothermal Reformer

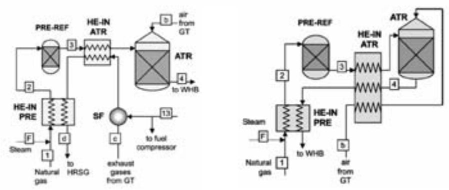
Table 7 Overall performances of the various plants

Operating temperature of ATR	Reference 850°C	Reference 950°C	SF 850°C	SF 950°C	Gas Gas 850°C	Gas Gas 950°C
GT net power [MW]	256.27	256.21	256.34	256.30	256.23	256.14
Steam cycle net power [MW]	141.35	158.27	148.79	166.11	122.97	136.97
Fuel compressor [MW]	6.51	7.33	5.90	6.80	5.81	6.61
Solvent pump power [MW]	0.77	0.80	0.78	0.82	0.72	0.75
CO_2 compressor [MW]	12.97	13.64	13.24	13.93	11.84	12.76
Plant net power [MW]	377.37	392.71	385.21	400.87	360.82	372.98
Natural gas LHV input [MW]	797	838	813	855	751	783
Net efficiency [%]	47.37	46.87	47.36	46.88	48.06	47.62
CO_2 emissions [kg/s]	4.38	4.61	4.48	4.70	4.13	4.27
CO_2 specific emissions [g/kWh]	41.8	42.2	41.8	42.2	41.2	41.2
Actual CO_2 reduction [%]	88.3	88.1	88.3	88.2	88.4	88.4

Reference Plant: NG-CC

Efficiency: 56%

SF … Supplementary Firing



Source: Corradetti and Desideri, ASME (2005)

IGCC (Integrated Gasification CC)

TU Graz
Graz University of Technology

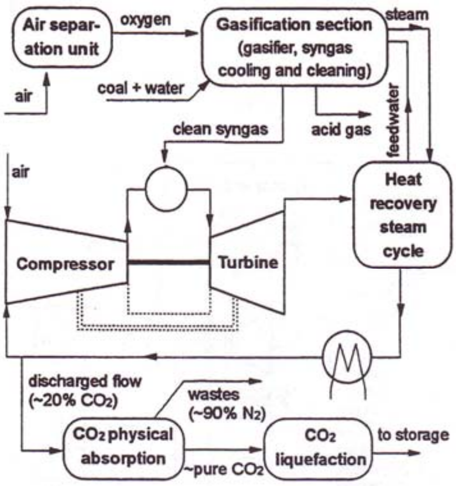


Fig. 1 Conceptual overview of the air-blown semiclosed cycles here analyzed, with physical absorption of CO_2

Source: Chiesa and Lozza, ASME (1999)

IGCC (Integrated Gasification CC) - Details

TU Graz
Graz University of Technology

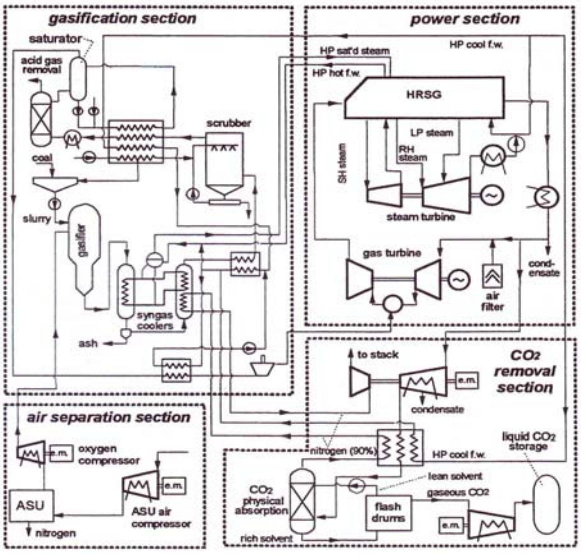


Fig. 2 Plant configuration of the semiclosed cycle with air-blow combustion (scheme B)

Source: Chiesa and Lozza, ASME (1999)

IGCC - Efficiency

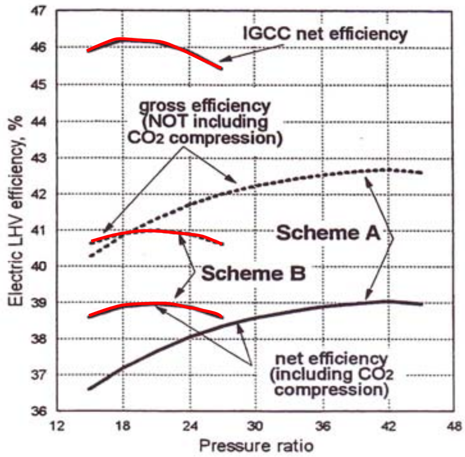
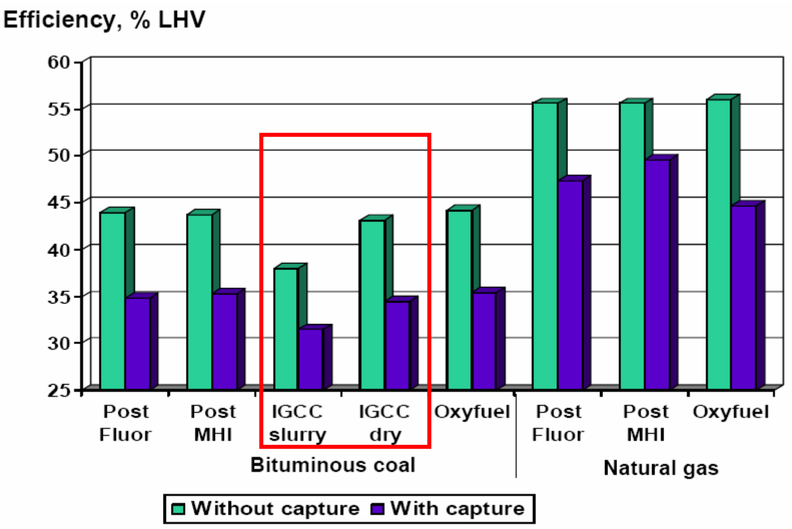


Fig. 4 Influence of the cycle pressure ratio on the efficiency of IGCC and of semiclosed cycles A and B. The dotted curves do not take into account the power consumption of the carbon dioxide compression/ liquefaction train.

Source: Chiesa and Lozza, ASME (1999)

Efficiency Penalty

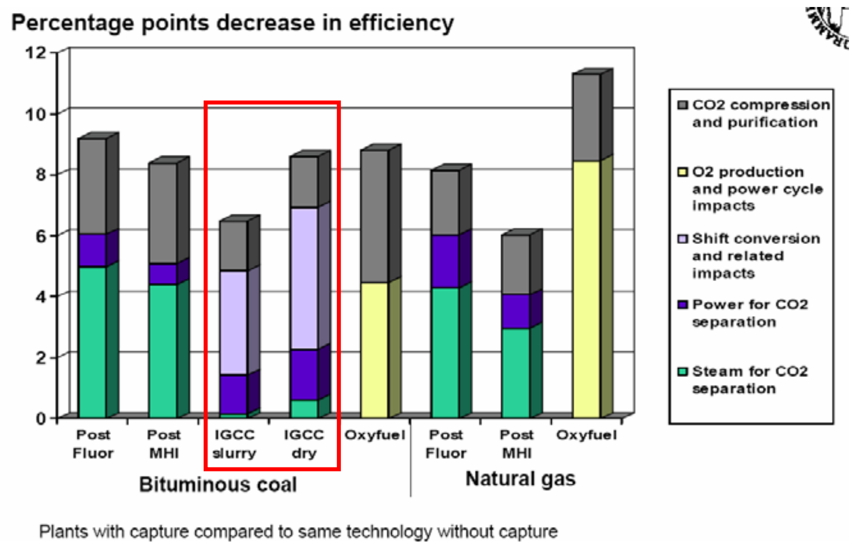


Fluor: Mono-Ethanolamine (MEA)

MHI: sterically hindered amine

Source: Davison, IEA (2005)

Efficiency Penalty

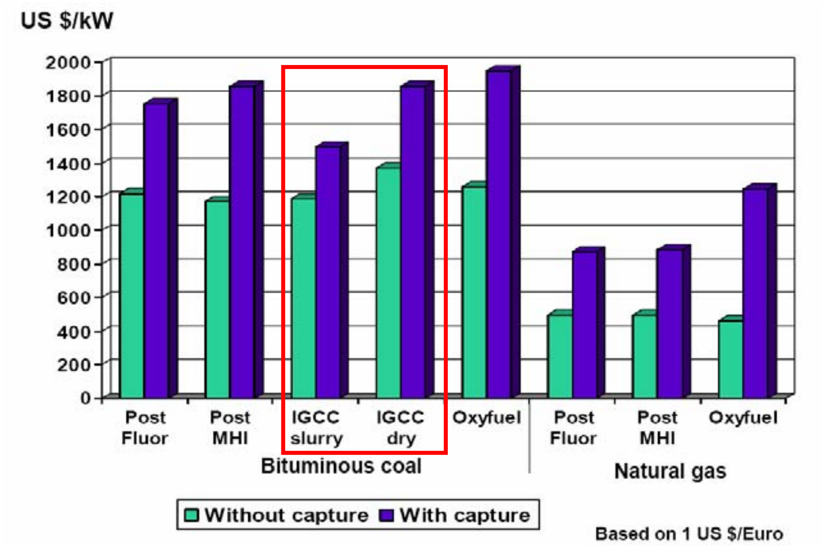


Fluor: Mono-Ethanolamine (MEA)

MHI: sterically hindered amine

Source: Davison, IEA (2005)

Capital Costs

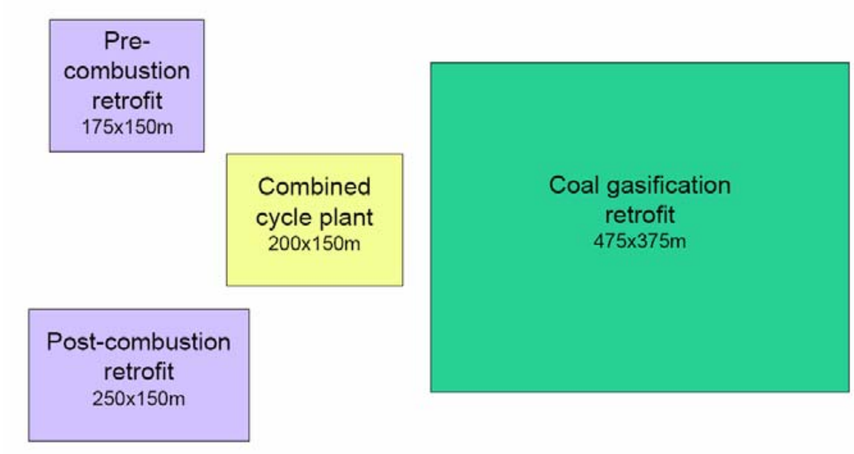


Fluor: Mono-Ethanolamine (MEA)

MHI: sterically hindered amine

Source: Davison, IEA (2005)

Plant Area Requirement



Source: Davison, IEA (2005)

Oxy-Fuel Cycles

- **Combustion with nearly pure oxygen leads to an exhaust gas consisting largely of CO_2 and H_2O**

+ **CO2 can be easily separated by condensation from working fluid consisting of CO2 and H2O**

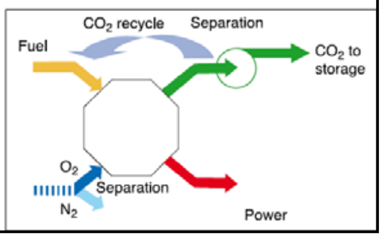
+ **Very low NOx generation (fuel bound N2)**

+ **Flexibility regarding fuel: natural gas, syngas from coal, biomass or refinery residue gasification**

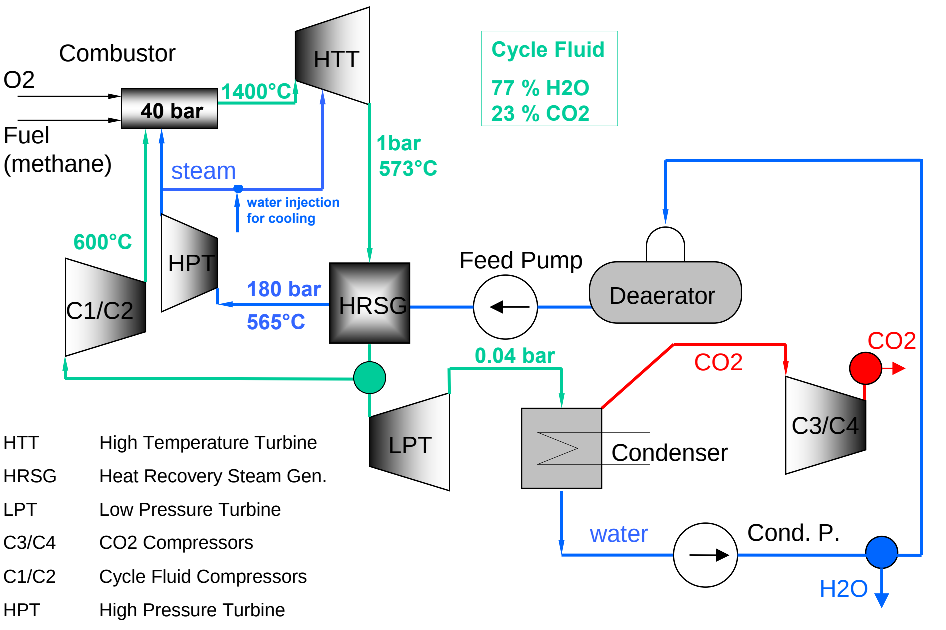
\- **New equipment required**

\- **Additional high costs of oxygen production**

+ **These new cycles show higher efficiencies than current air-based combined cycles (Graz Cycle, Matiant cycle, Water cycle,...)**



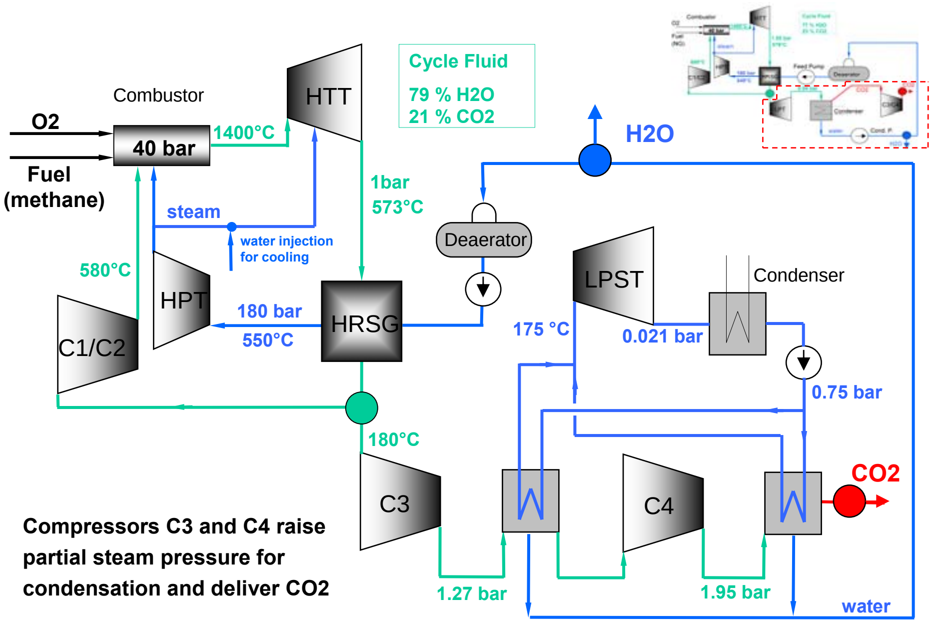
Graz Cycle Basic Configuration (ASME 04/05)



Power Balance ASME 2005

- **Electrical cycle efficiency for methane firing:**
  Efficiency: 64.6 % (same for syngas firing)
- **Oxygen production (0.15 - 0.3): 0.25 kWh/kg**
  Oxygen compression (2.38 to 40 bar, inter-cooled): 325 kJ/kg
  Efficiency: 54.8 %
- **Compression of separated CO2 for liquefaction (1 to 100 bar, inter-cooled): 270 kJ/kg (3.7 MW)**
  Efficiency: 52.7 %

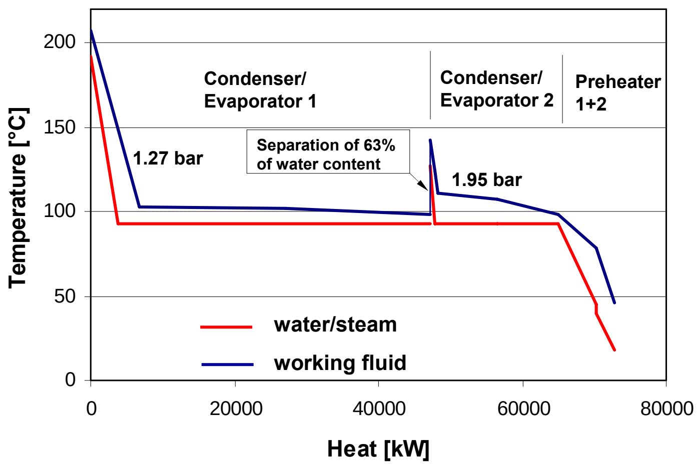
Condensation/Re-Vaporization at around 1 bar



Compressors C3 and C4 raise partial steam pressure for condensation and deliver CO2

Heat Transfer in Condenser/Evaporator

- Constant re-evaporation pressure of 0.75 bar for the bottoming steam cycle
- LPST inlet temperature of 175 °C; expansion line crosses Wilson line at last blade inlet, thus low humidity losses



S-Graz Cycle Power Balance for 400 MW net power

	Basic Layout	New Layout
HTT power [MW]	635	638
Total turbine power [MW]	753	739
Total compression power [MW]	249	235
Net shaft power [MW]	**504**	**505**
Total heat input [MW]	759	759
Thermal cycle efficiency [%]	**66.5**	**66.5**
Electrical cycle efficiency [%]	**64.6**	**64.6**

Additional Losses and Expenses

- **Oxygen production: 0.25 kWh/kg = 900 kJ/kg Oxygen compression (2.38 to 42 bar, inter-cooled): 325 kJ/kg**

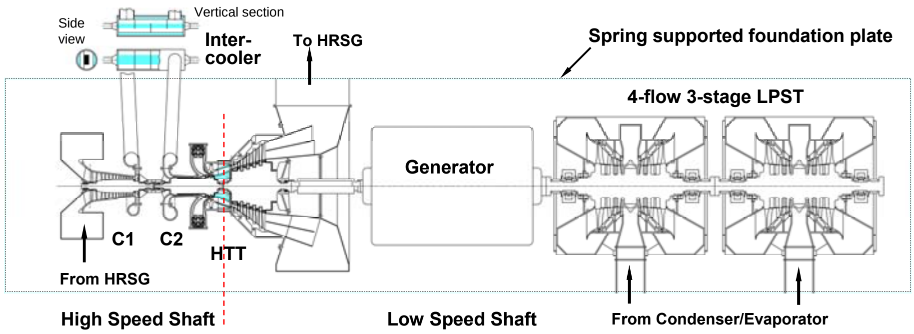
  Efficiency: 54.8 %

- **Compression of separated CO2 for liquefaction (1.9 to 100 bar): 13 MW (1 to 100 bar: 15.6 MW)**

  Efficiency: 53.1 % **(compared to 52.7 %)**

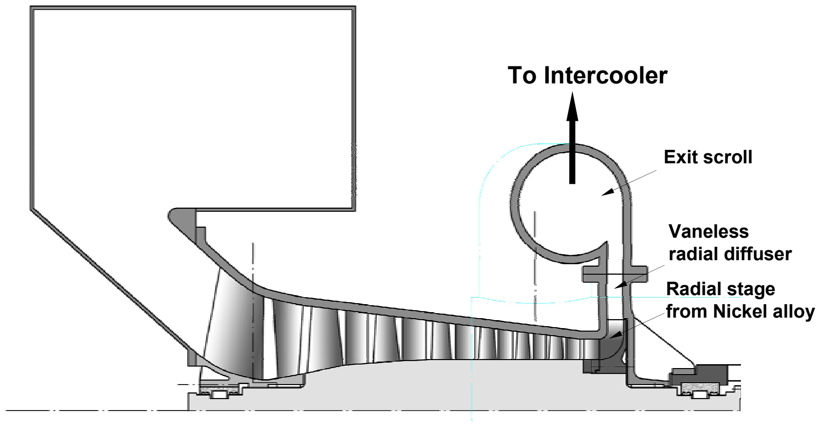
490 MW Turbo Shaft Configuration

- Main gas turbine components on two shafts
- Compression shaft of 8500 rpm: cycle compressors C1 and C2, driven by first part of HTT, the compressor turbine HTTC
- Power shaft of 3000/3600 rpm: power turbine HTTP as second part of HTT drives the generator
  Four-flow LPST at the opposite side of the generator
- Shafts on same spring foundation
  Intercooler between C1 and C2 on fixed foundation connected to HRSG



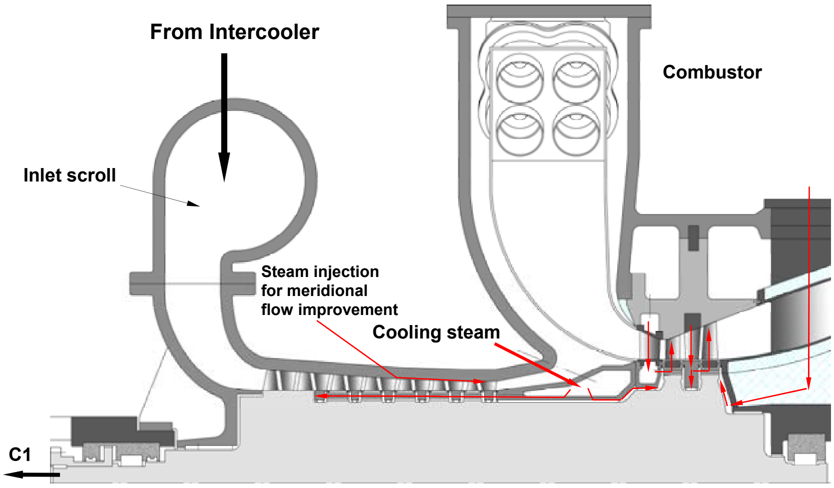
Working Fluid Compressor C1

- Compression 1 -> 13 bar, 106° -> 442°C
- Speed of 8500 rpm leads to inlet tip Mach number of 1.3
- 7 axial and 1 radial stage
- Uncooled drum rotor of ferritic steel (high temperature 9 %-chrome steel)



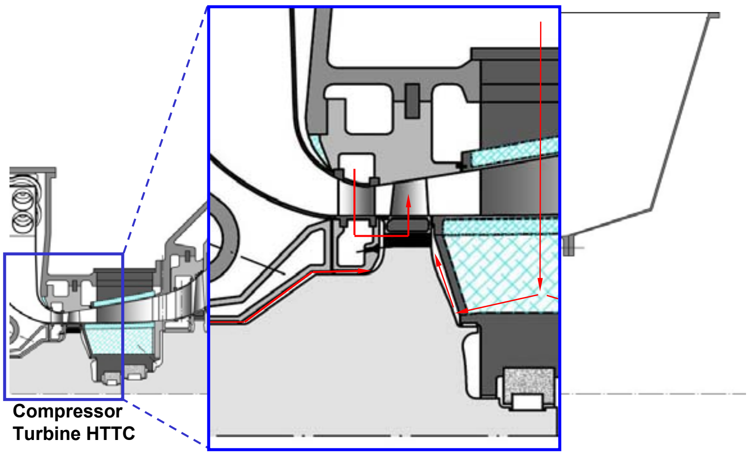
Working Fluid Compressor C2

- Compression 13 -> 40 bar, 380° -> 580°C , 7 stages
- Cooled drum rotor of ferritic steel with counterflow of cooling steam
- Blade length of 90 to 40 mm, small radial tip clearances



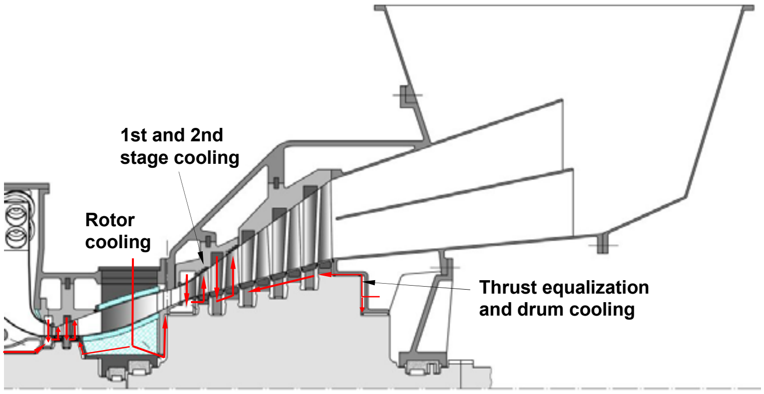
Compressor Turbine HTTC for 50 Hz

- Alternative HTTC expansion with one transonic stage
- Blade length of 120 mm at higher radius and loading
- Application of innovative cooling design developed for transonic flows using underexpanded jets from slots (ASME 2004)



Power Turbine HTTP for 50 Hz

- 5 stages with strong change of inner radius
- Last blade length of 750 mm at 1300 mm inner radius
- Insulation of intermediate bearing casing, design similar to HP steam turbine presented at ASME 1988, Amsterdam
- Necessary thrust equalization and drum surface cooling on the exhaust side by steam



Economic Analysis S-GC - I

Investment costs

Component	Scale parameter		Specific costs
Reference Plant [13]			
Investment costs	Electric power	$\$/kW_{el}$	414
S-Graz Cycle Plant			
Investment costs	Electric power	$\$/kW_{el}$	414
Air separation unit [14]	O_2 mass flow	$\$/(kg\ O_2/s)$	1 500 000
Other costs (Piping, CO_2-Recirc.) [14]	CO_2 mass flow	$\$/(kg\ CO_2/s)$	100 000
CO_2-Compression system [14]	CO_2 mass flow	$\$/(kg\ CO_2/s)$	450 000

- yearly operating hours: 8500 hrs/yr
- capital charge rate: 12%/yr
- natural gas is supplied at 1.3 ¢/kWh_{th}

Comparison of Component Size

	Conventional CC Plant 400 MW	Graz Cycle Plant 400 MW
turbine of "gas turbine"/ HTT	667 MW	618 MW
compressor of "gas turbine"/ C1+C2+C3+C4	400 MW	232 MW
steam turbine/ HPT+LSPT	133 MW	120 MW
HRSG	380 MW	360 MW
Generator	400 MW	490 MW

- Turbine power of same size
- Compressor power smaller
- Generator power higher

Economical Analysis S-GC - II

COE ...

Cost of Electricity

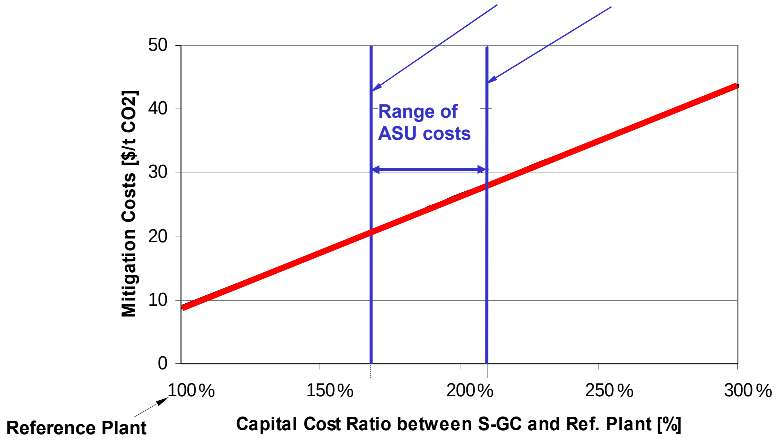
	Reference plant [23]	S-GC base version
Plant capital costs [$/kW$_{el}$]	414	414
Addit. capital costs [$/kW$_{el}$]		288
CO_2 emitted [kg/kWh$_{el}$]	0.342	0.0
Net plant efficiency [%]	58.0	53.1
COE for plant amort. [¢/kWh$_{el}$]	0.58	0.99
COE due to fuel [¢/kWh$_{el}$]	2.24	2.45
COE due to O&M [¢/kWh$_{el}$]	0.7	0.8
Total COE [¢/kWh$_{el}$]	3.52	4.24
Comparison		
Differential COE [¢/kWh$_{el}$]		0.72 (+ 20 %)
Mitigation costs [$/ton CO_2 capt.]		21.0

Influence of Capital Costs S-GC

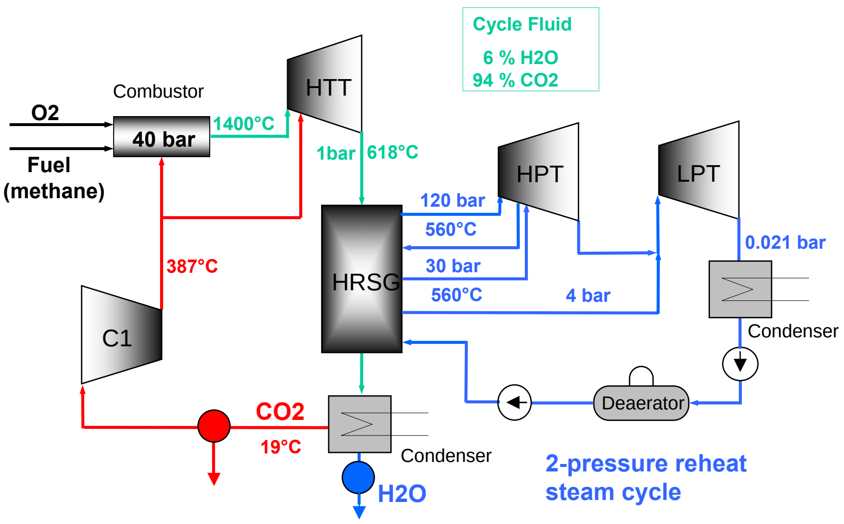
Favorable assumption of Göttlicher (VDI): 70 % additional capital costs for air supply and CO2 compression

But large uncertainty in cost estimation:

e.g.: ASU: cost estimates differ between 230 and 400 $/kW_el



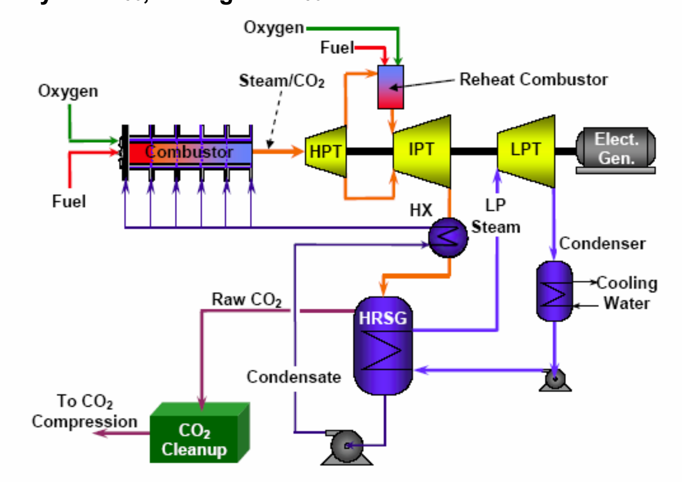
Semi Closed Oxy-Fuel Combustion CC



- Less new components
- Smaller efficiency (- 3 %-points)

CES Oxyfuel Cycle (Water Cycle)

- Clean Energy Systems, CA, operates a simplified pilot plant
- Working fluid is mainly steam
- Efficiency: ~ 45 %, aiming at 50 %



Source: Clean Energy Systems, 2008

Gas Generator

20 MWt CES Gas Generator: Combuster section and 4 sequential water-cooldown sections.

- Gaseous fuel and pure oxygen are combusted in combination with injection of water
- Near stoichiometric combustion.
- Exit condition of CO2/steam: 83 bar, 565 ºC
- Walls are cooled by water flow in internal cooling passages

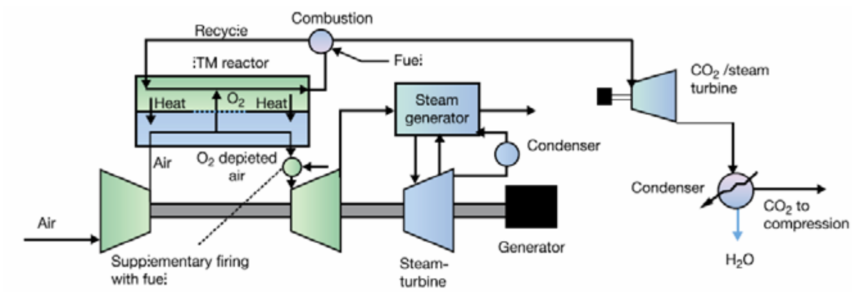
Source: Clean Energy Systems, 2008

ZENG Project Norway

- Water cycle pilot plant planned in Stavanger, Norway
- Close integration of air separation process

Source: Hustad et al., ASME (2005)

Advanced Zero Emission Power Plant (AZEP)

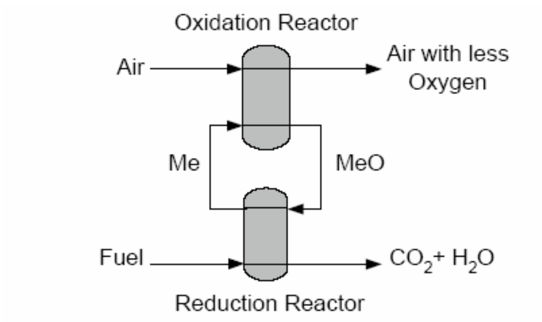


- Oxyfuel combustion in a mixed conducted membrane (MCM) reactor, operating at about 800°C -1000°C :
  1) separation of oxygen from hot air and transport to combustion section
  2) combustion
  3) heat exchange from the combustion products to the compressed air
- Net efficiency of around 49–50% LHV is claimed including CO2 compression.
- Possible afterburner raises inlet temperatures to 1300°C-1400°C, increases efficiency up to 52%, but 15% of CO2 is not captured.

Source: IPCC; Griffin et al., ASME (2005)

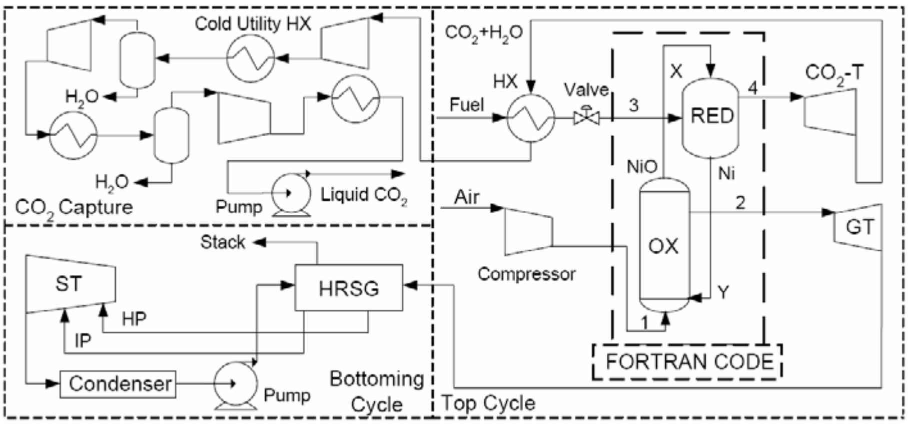
Chemical Looping Combustion (CLC)

- Combustion is split up into intermediate oxidation and reduction reactions by introducing a metal oxide as oxygen carrier between two reactors
- Reaction temperature **below 1000°C**
- No NOX generation
- Oxygen carrier plays central role in the process (reaction rates, chemical and mechanical stability and temperature standing)
  So far NiO/NiAl2O4 is most promising



Source: Naqui et al.,ASME (2004)

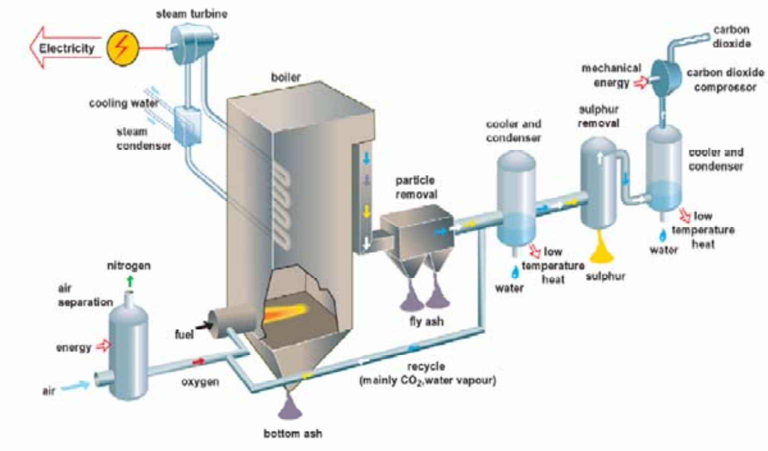
CLC in a combined cycle plant



- CLC replaces gas turbine combustor
- Reaction products CO2/steam expanded in CO2 turbine prior to steam condensation
- Efficiency aimed up to 50 %

Source: Naqui et al., ASME (2004)

Oxyfuel steam cycle for coal

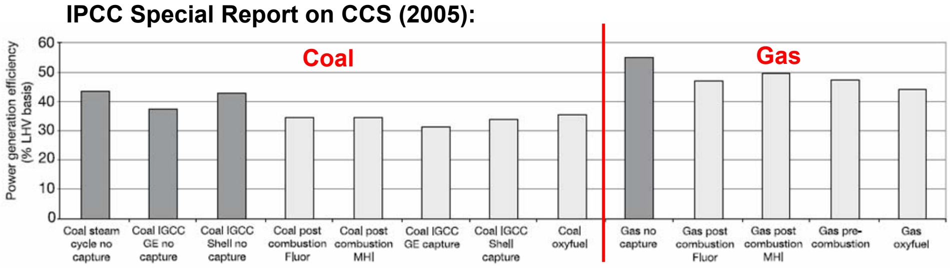


- Combustion of pulverised coal with oxygen and CO2 recirculation
- Steam cycle
- 30 MWth pilot plant „Schwarze Pumpe" near Berlin, Germany
- Mitigation costs close to 20 €/ton CO2 expected

Source: Strömberg, Vattenfall (2005)

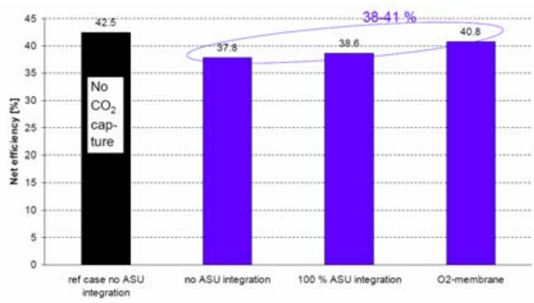
Comparison of Technologies

IPCC Special Report on CCS (2005):



EU Project ENCAP (2006):

Coal/IGCC



Comparison of Technologies

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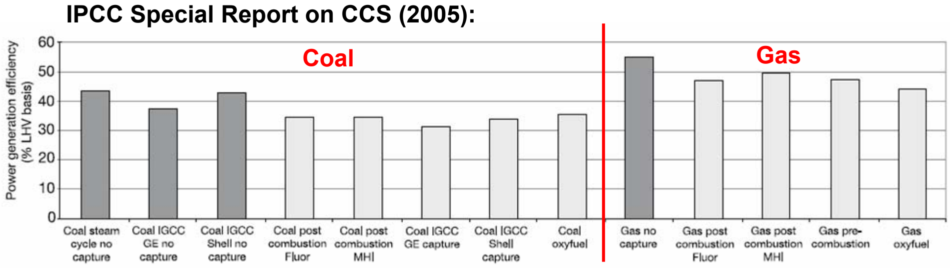
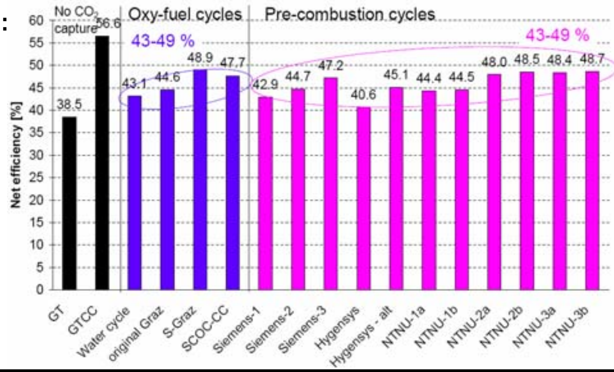
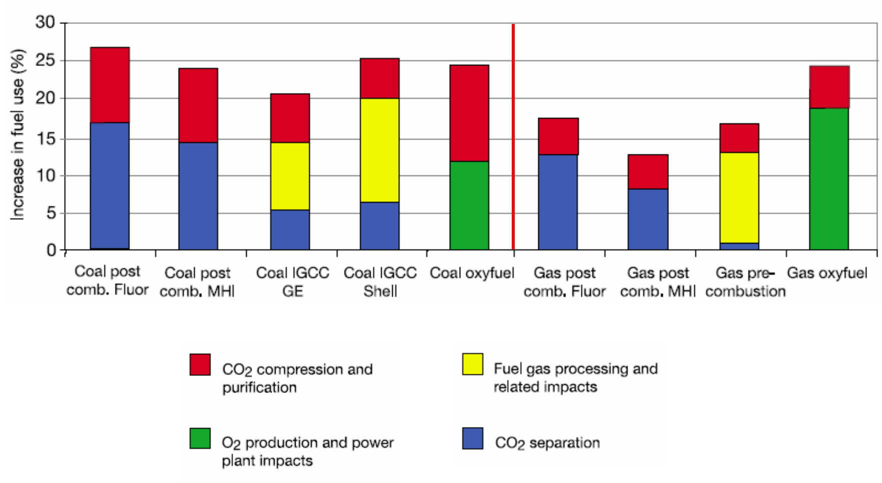


EU Project ENCAP (2006):

Gas

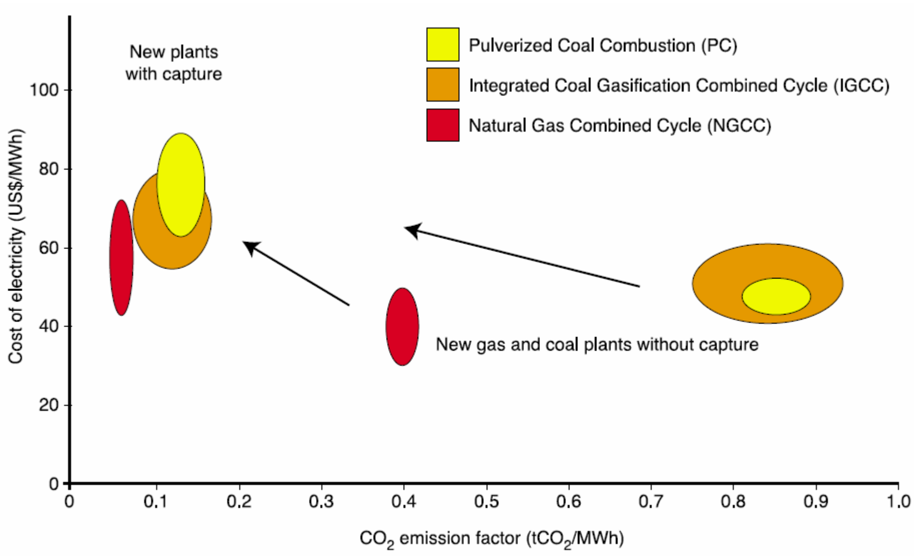


Efficiency Penalties - Comparison



Source: IPCC Special Report on CCS (2005)

CCS costs !



Source: IPCC Special Report on CCS (2005)

Conclusions

Which technology is the best?

Honestly, we do not know …..

BUT

We have to do it!

- Lord Oxburgh, former chairman of Shell Transport and Trading:
  "CCS is absolutely essential if the world is serious about limiting greenhouse gas emissions“
- The new report from the Intergovernmental Panel on Climate Change (IPCC) concludes:
  “CCS could achieve more than half of the emissions reductions necessary to mitigate climate change up to 2100”

From Lars Strömberg, Vattenfall (2005)