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Outlook for Advanced Capture Technology

Post-Combustion CO_2 Capture Workshop
Talloires, July 11-13, 2010

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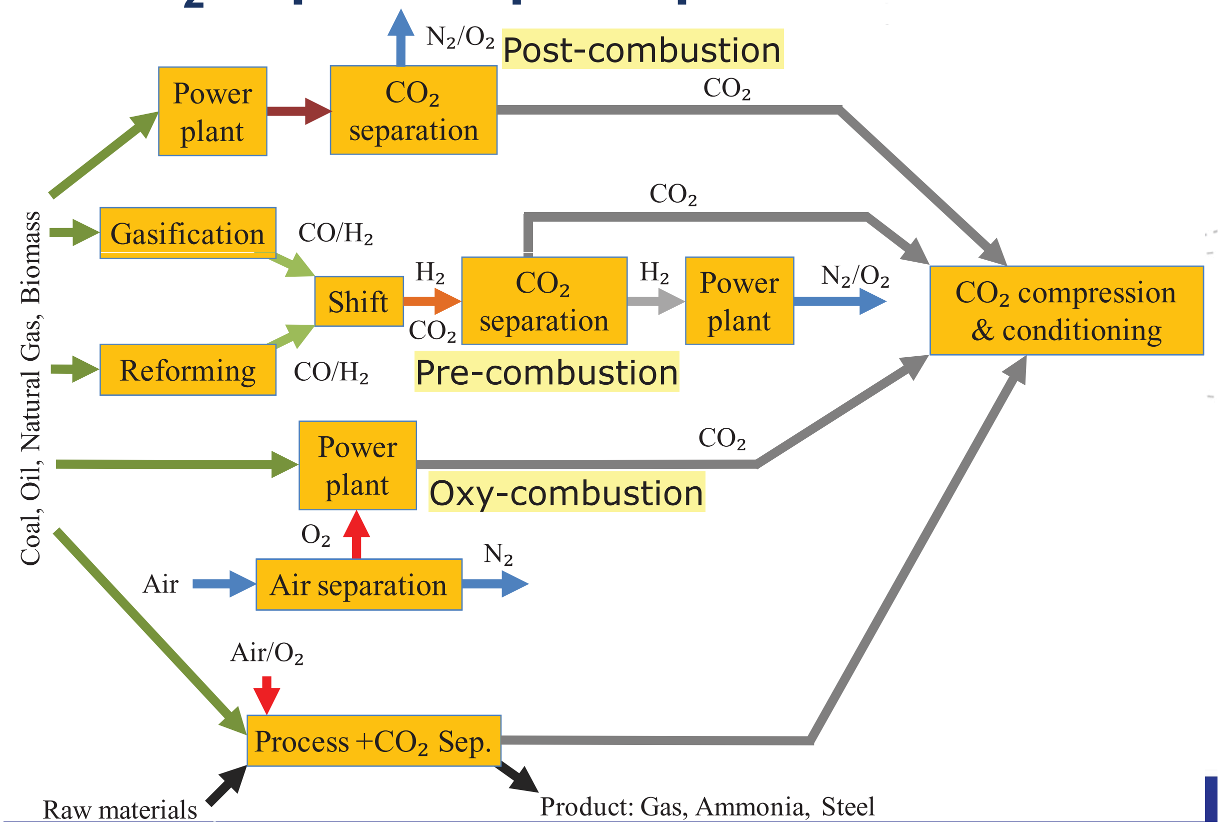
20 000 students

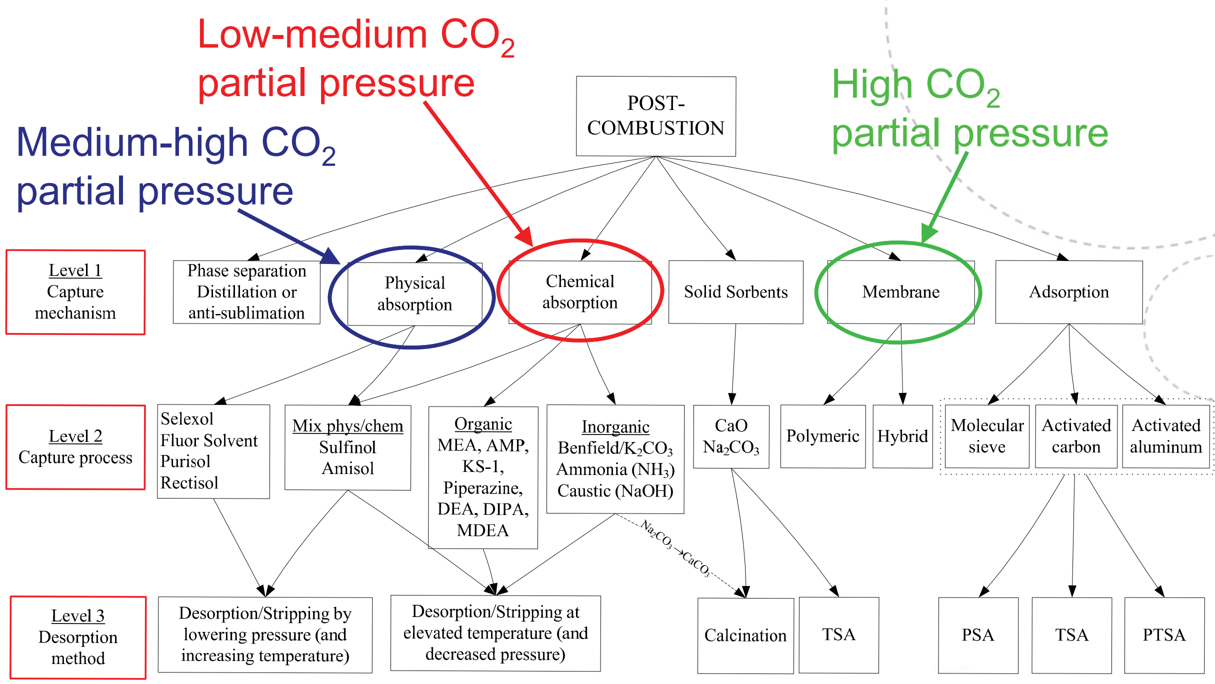
Focus areas:
Oil and Gas
Maritime engineering
Materials
CCS

Close cooperation with research institute **SINTEF**

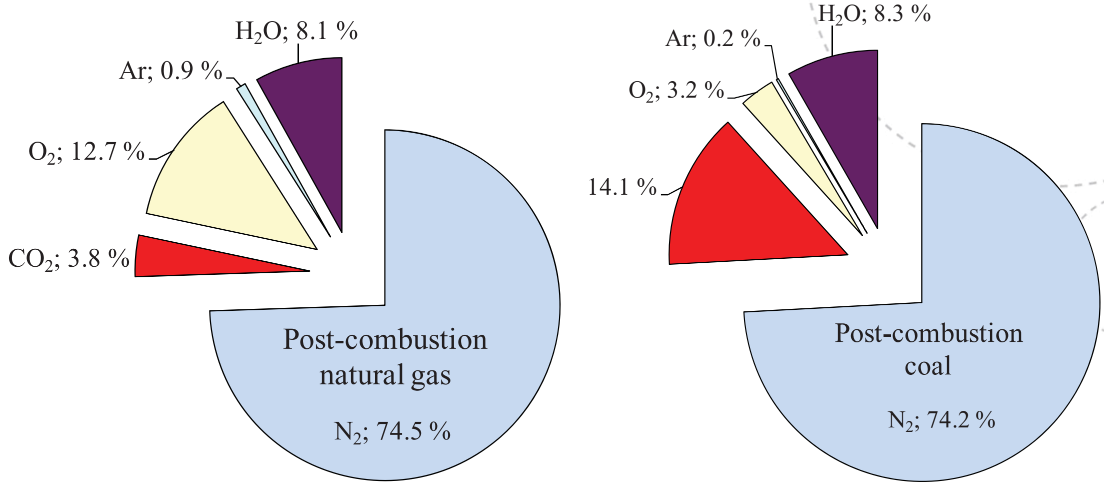
CO_2 capture – principles



Post-combustion



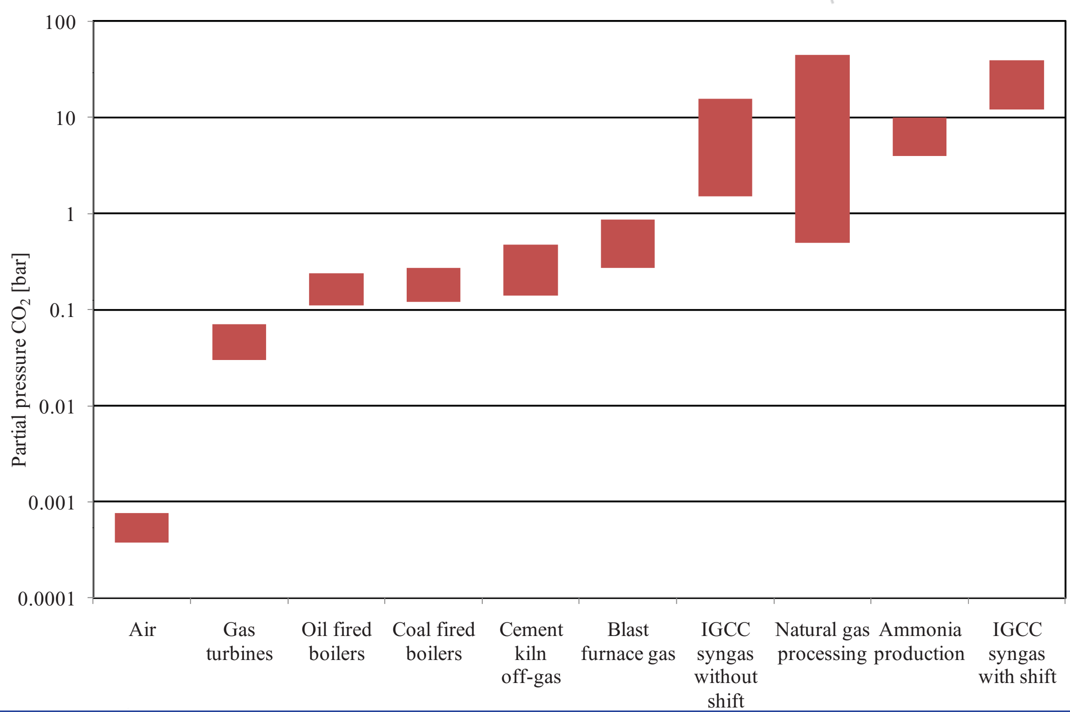
Dilution of CO_2 - Post-combustion



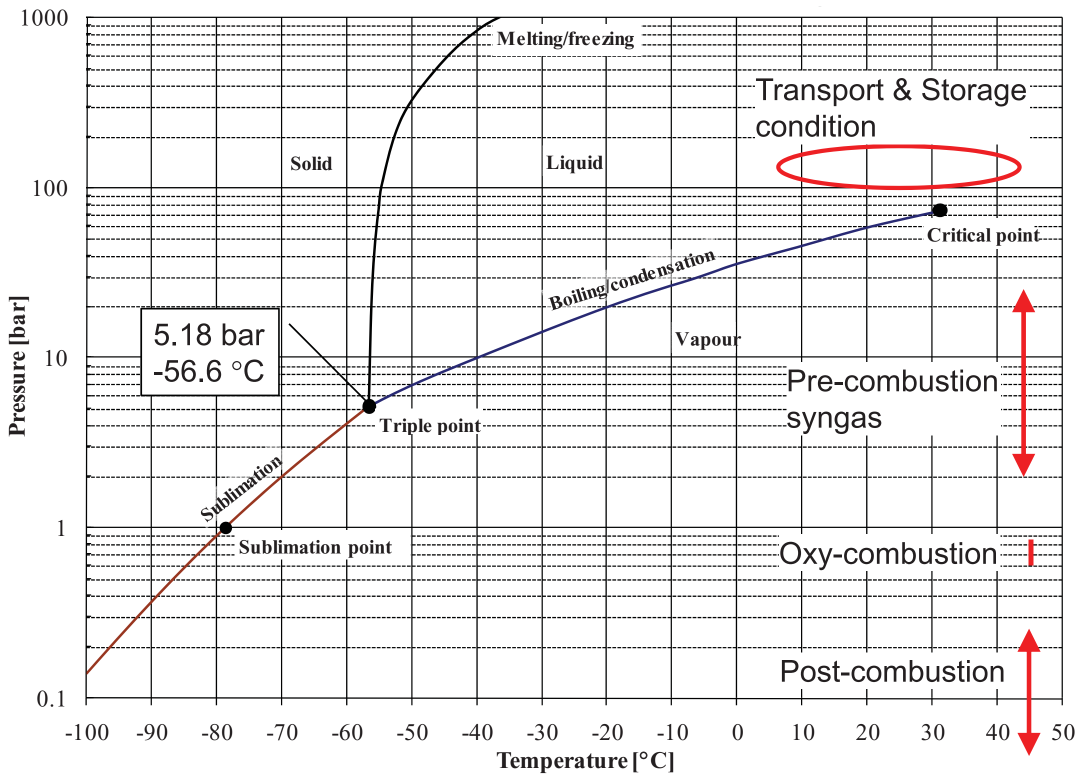
Flue gas pressure ≈ 1 atm

CO_2 partial pressure 0.03-0.15 atm

Partial pressure of CO_2 from various sources



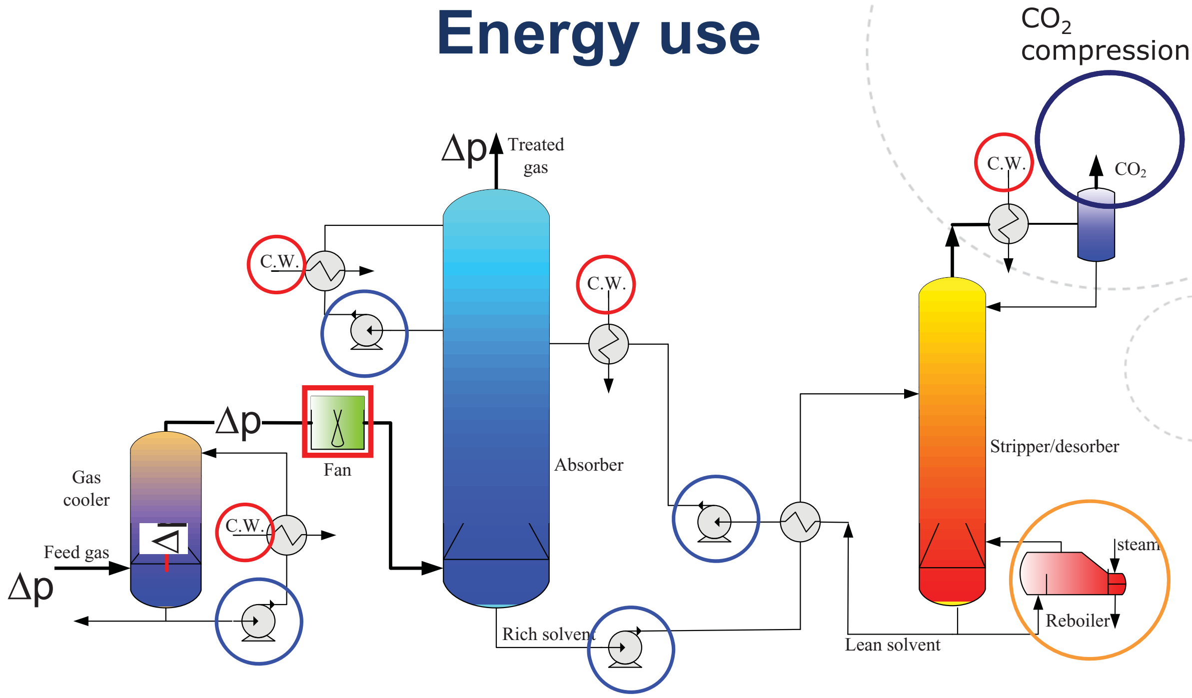
Phase diagram CO_2



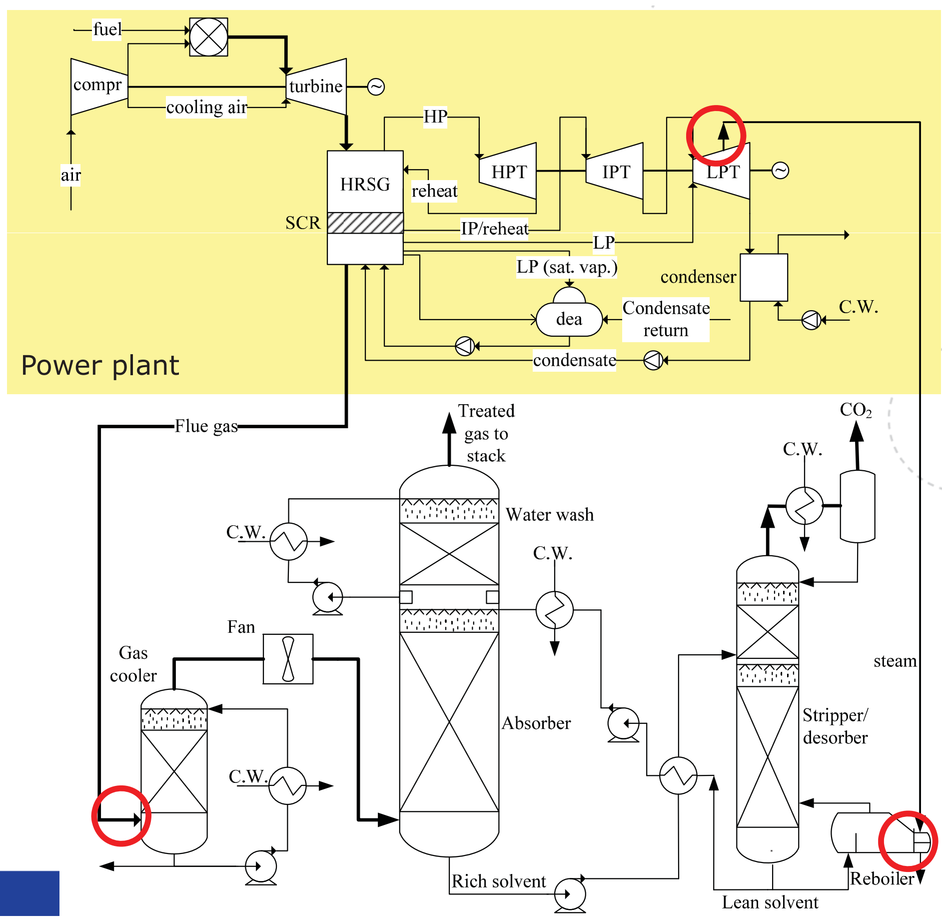
Power plant efficiency penalty for CO_2 capture

Where are we?

Energy use



CO2
compression
Δp
Treated
gas
C.W.
C.W.
C.W.
CO2
Δp
Fan
Absorber
Stripper/desorber
Gas
cooler
C.W.
Feed gas
Δp
steam
Reboiler
Rich solvent
Lean solvent



fuel
compr
turbine
cooling air
air
HP
HPT
IPT
LPT
HRSG
reheat
SCR
IP/reheat
LP
LP (sat. vap.)
condenser
dea
Condensate
return
C.W.
condensate
Power plant
Flue gas
Treated
gas to
stack
CO2
C.W.
Water wash
C.W.
C.W.
Fan
Gas
cooler
steam
Absorber
Stripper/
desorber
C.W.
Rich solvent
Lean solvent
Reboiler

Efficiency penalty $\Delta\eta$ [%-points]

How much CO_2 is released from combustion of the fuel — X $\left[\frac{\text{kg } CO_{2,\text{ formed}}}{MJ_{LHV}}\right]$

Work or work equivalent needed for ’capture’ — $w_{\text{'capture'}}$ $\left[\frac{MJ_{\text{power}}}{\text{kg } CO_2}\right]$

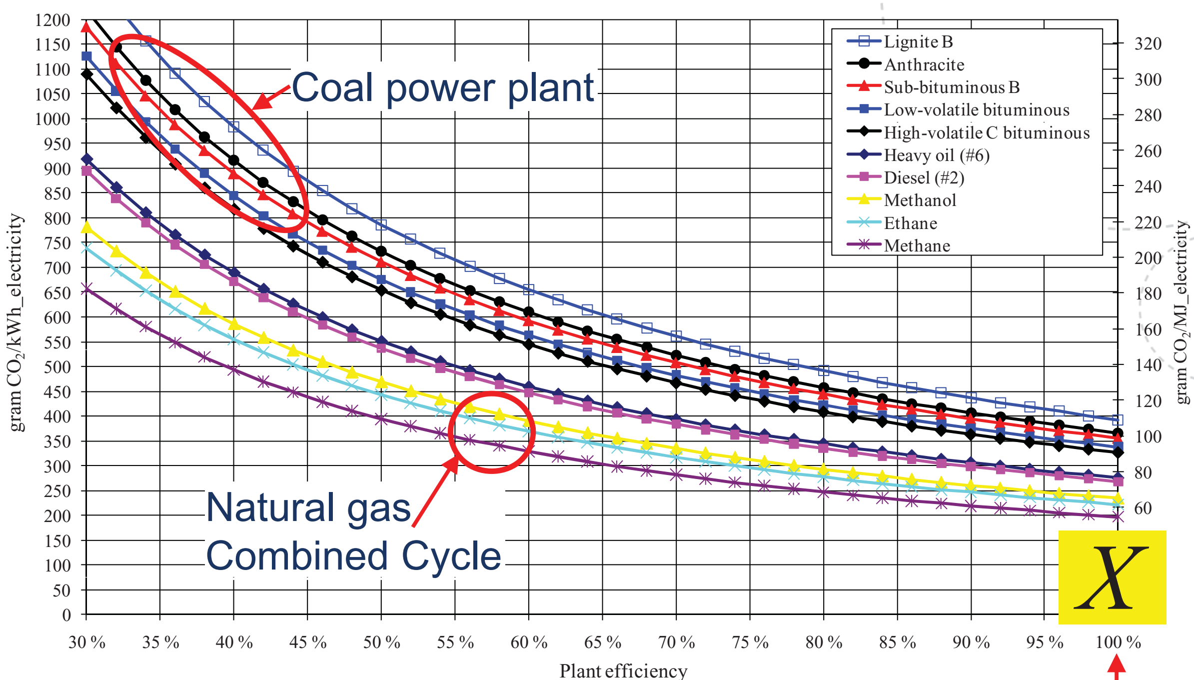
Capture ratio — $\phi_{cap-ratio}$ $\left[\frac{\text{kg } CO_2\text{, captured}}{\text{kg } CO_2\text{, formed}}\right]$

$$\Delta\eta = X\, w_{\text{'capture'}}\, \phi_{cap-ratio}$$

or

$$\Delta\eta = X\, w_{\text{'capture'}}$$

Emission of CO_2 from fossil fuels



Per fuel lower heating value

$X_{COAL} = 91\text{-}109$ $\quad X_{NATURAL\ GAS} = 55-63$ $\left[\frac{\text{gram } CO_2}{MJ_{LHV}}\right]$

Work/work equivalent

$w_{\text{'capture'}}$

Steam consumption (stripping) q_{steam} $\left[\frac{\text{MJ}_{\text{heat}}}{\text{kg CO}_{2,\text{ captured}}}\right]$

$$2.8-4.0$$

Work equivalent $\alpha = \left|\frac{q}{\Delta w_{steam}}\right|$ $\left[\frac{\text{MJ}_{\text{heat}}}{\text{MJ}_{\text{power}}}\right]$

$$\alpha > 1 \Rightarrow \left|\Delta w_{steam}\right| < q$$

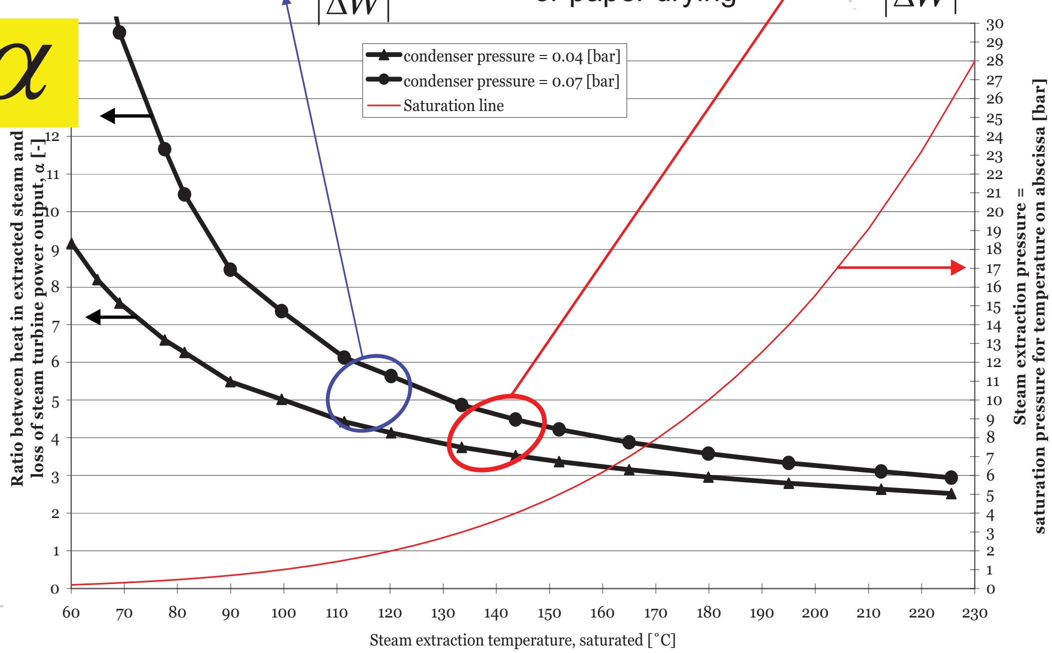
$$w_{steam} = \frac{q}{\alpha} \quad \left[\frac{\text{MJ}_{\text{power}}}{\text{kg CO}_{2,\text{ captured}}}\right]$$

Steam turbine steam extraction

District heating $\alpha = \left|\frac{Q}{\Delta \dot{W}}\right| \cong 5$

Typical amine boiling or paper drying $\alpha = \left|\frac{Q}{\Delta \dot{W}}\right| \cong 3.5-5$

α



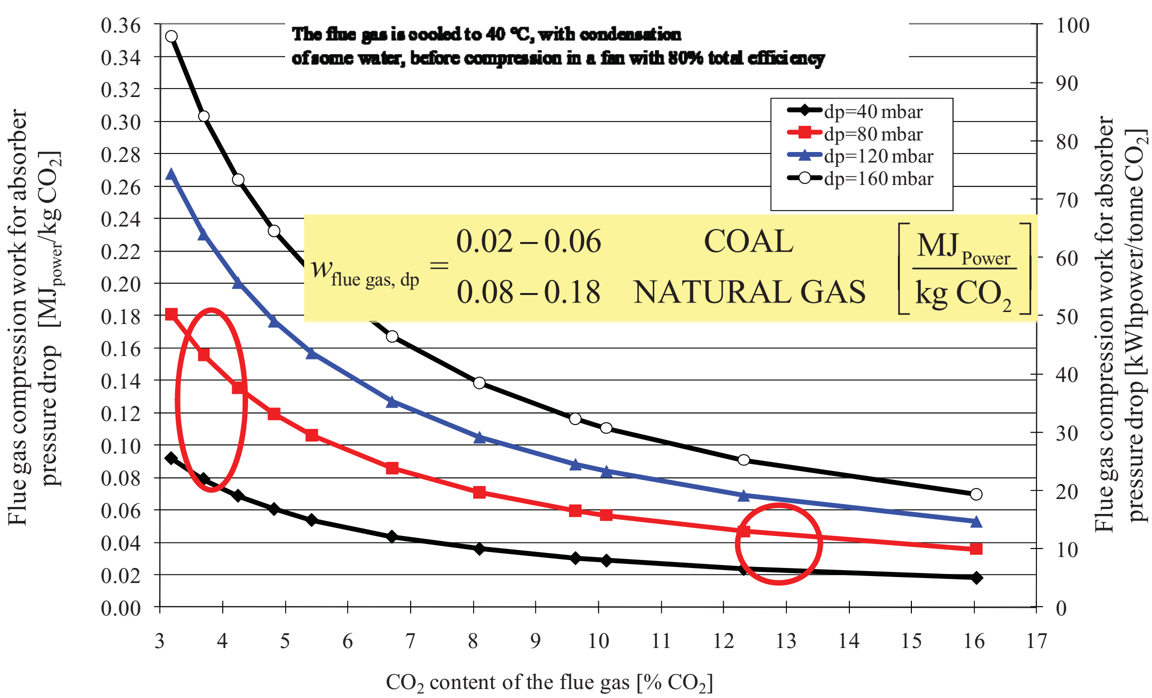
Work - flue gas pressure drop

$w_{\text{'capture'}}$

Flue gas pressure drop (in addition to the boiler/HRSG + gas cleaning system)

- Flue gas cooler
- NO_X scrubber (SCR), if required
- Bypass-stack system with dampers (bypassing the CO_2 capture absorber), if used
- Flue gas recycle (dampers, ducting), if used
- Absorber, packing and water wash
- Ducting & stack

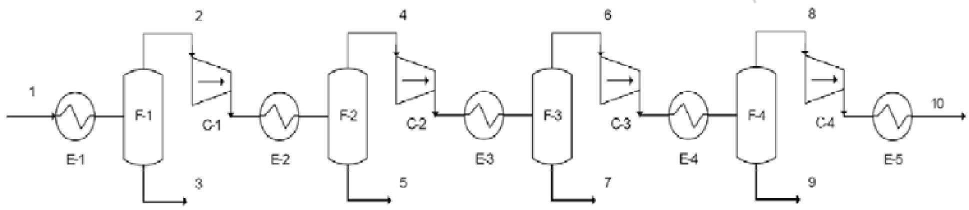
Flue gas pressure drop



$$w_{\text{flue gas, dp}} = \begin{matrix} 0.02-0.06 & \text{COAL} \\ 0.08-0.18 & \text{NATURAL GAS} \end{matrix} \left[\frac{MJ_{Power}}{kg\ CO_2}\right]$$

Work - CO_2 compression

$w_{'capture'}$



Intercooled compression with removal of liquid water

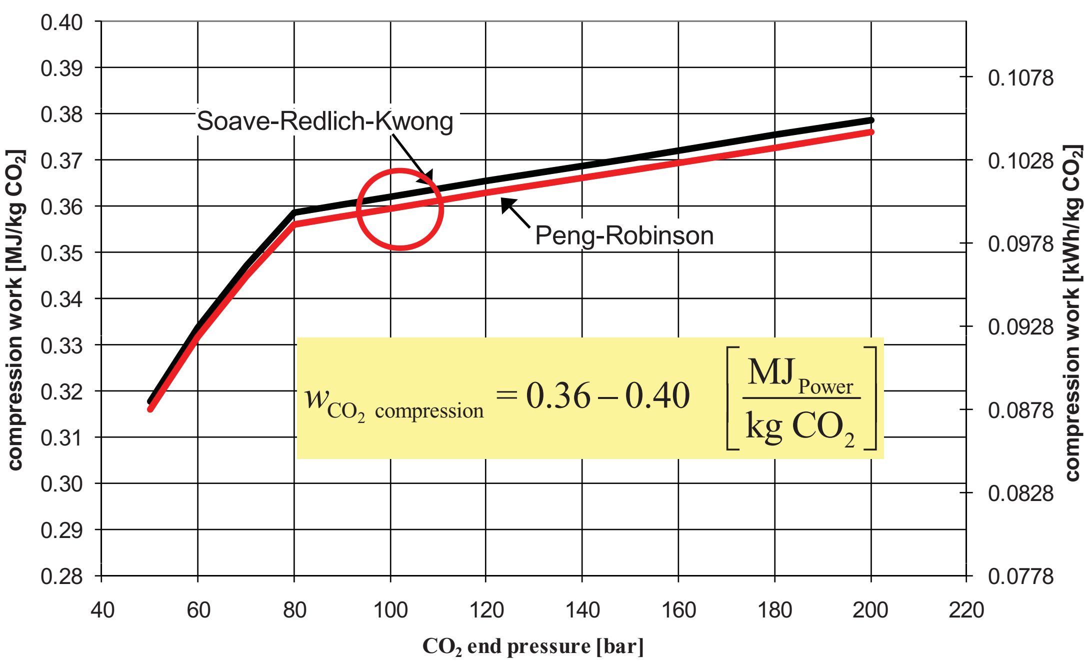
Components more volatile then CO_2

N_2, O_2, NO, Ar

Components less volatile then CO_2

SO_2, H_2S, COS, NO_2

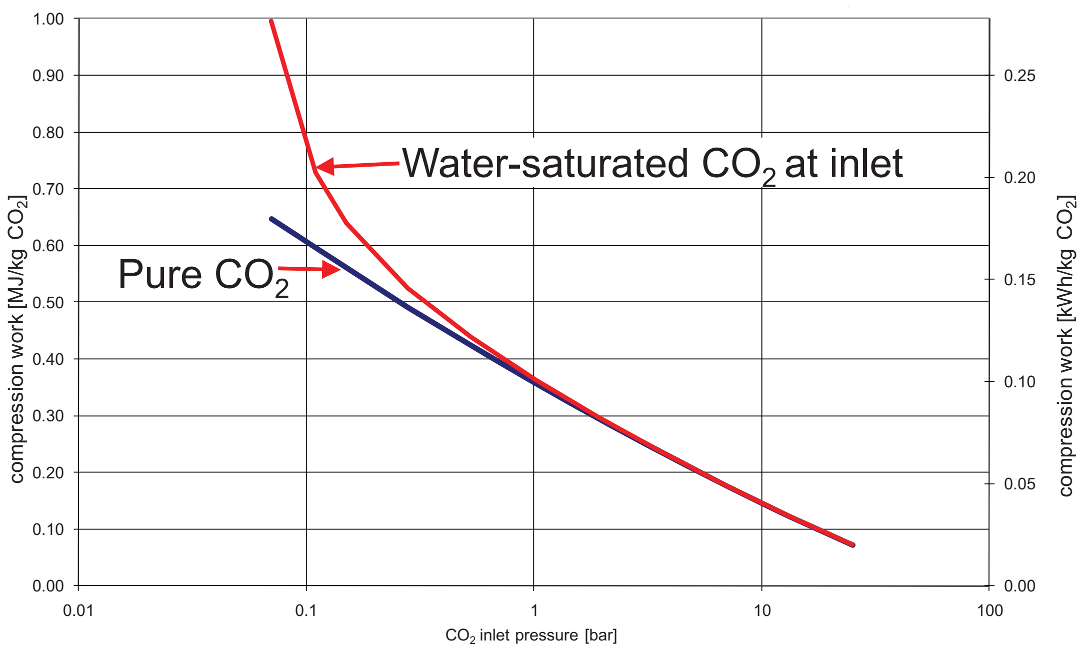
CO_2 compression, 1-110 bars



$$w_{CO_2\ compression} = 0.36 - 0.40 \left[\frac{MJ_{Power}}{kg\ CO_2}\right]$$

Work for compression CO_2 from 1.013 bar and 30 °C, saturated with water, to a given end pressure. Compression with 3 aftercooled (22 °C) compressors up to 80 bar, with equal pressure ratios, and a pump from 80 bar and up to the end pressure, 110 bars. Water is removed after each aftercooler, according to the water dew point. Compressor isentropic efficiencies for compressor 1 is 85%, for comp. 2 is 85%, for compr. 3 is 80%, and for the pump 75%. Aftercooler pressure drop is for each assumed 1%. Pressure loss for CO_2 drying is not included.

CO_2 compression, x-110 bars



Work for compression CO_2 from a given inlet pressure and 30 °C to a fixed end pressure of 110 bar. The upper curve assumes that the CO_2 feed is saturated with water at 30 °C, and the lower curve assumes pure CO_2. Compression with 3 aftercooled (22 °C) compressors up to 80 bar, with equal pressure ratios, and a pump from 80 bar and up to the end pressure. Water is removed after each aftercooler, according to the water dew point. Compressor isentropic efficiencies for compressor 1 is 85%, for comp. 2 is 85%, for compr. 3 is 80%, and for the pump 75%. Aftercooler pressure drop is for each assumed 1%. Pressure loss for CO_2 drying is not included. Use with caution at low pressures because the water vapour content may get very high and cause a very high compression work per kg of CO_2.

Efficiency penalty - 1

Reduction efficiency steam consumption
Reduction efficiency flue gas pressure drop
Reduction efficiency pumps and aux — $0.05 \left[\frac{\text{MJ}_{\text{power}}}{\text{kg CO}_2\text{, captured}}\right]$
Reduction efficiency CO_2 compression

$$\Delta\eta_{\text{steam}} = X\, w_{\text{steam}}\, \phi_{\text{cap-ratio}}$$

$$\Delta\eta_{\text{flue gas dp}} = X\, w_{\text{flue gas dp}}$$

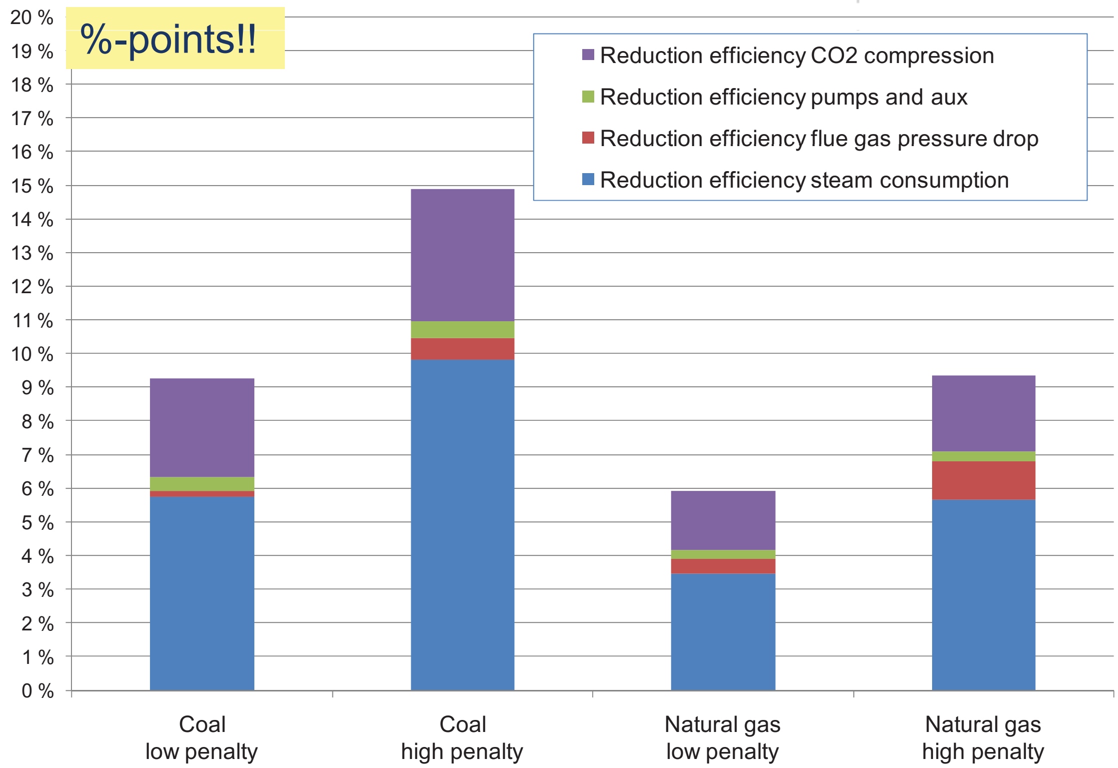
$$\Delta\eta_{\text{aux}} = X\, w_{\text{aux}}\, \phi_{\text{cap-ratio}}$$

$$\Delta\eta_{\text{CO}_2\text{ compression}} = X\, w_{\text{CO}_2\text{ compression}}\, \phi_{\text{cap-ratio}}$$

Here assumed 0.9

$$\Delta\eta_{\text{capture}} = \Delta\eta_{\text{steam}} + \Delta\eta_{\text{flue gas dp}} + \Delta\eta_{\text{aux}} + \Delta\eta_{\text{CO}_2\text{ compression}}$$

Efficiency penalty - 2

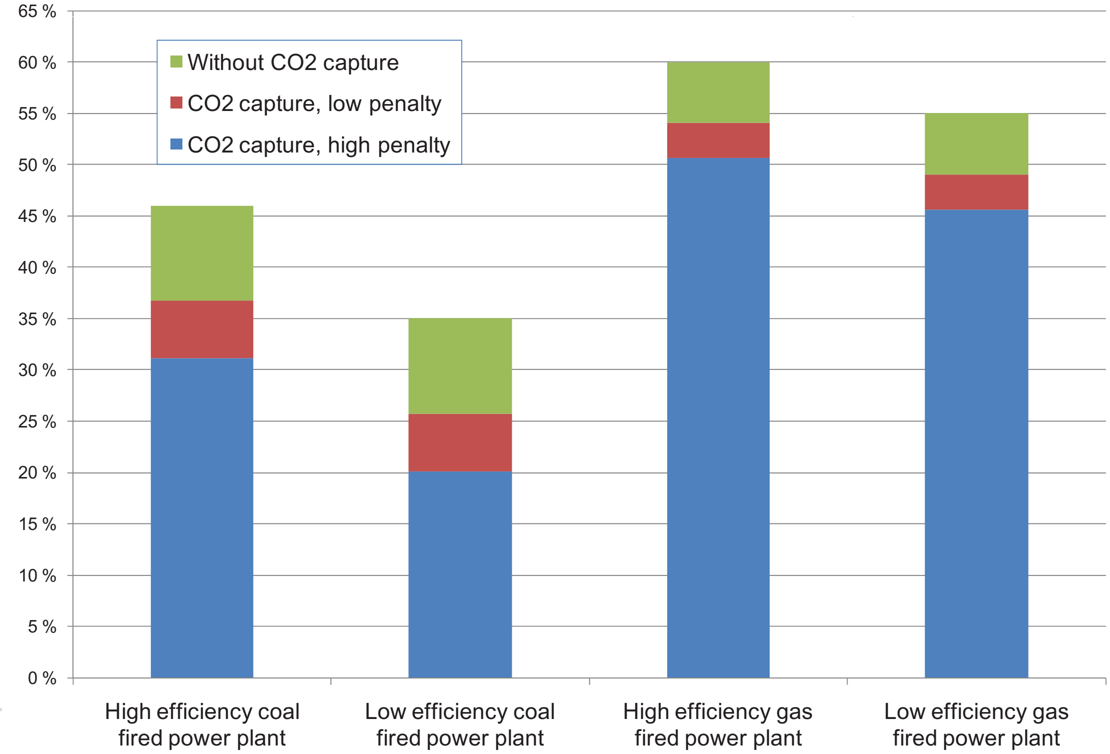


Power plant efficiency penalty

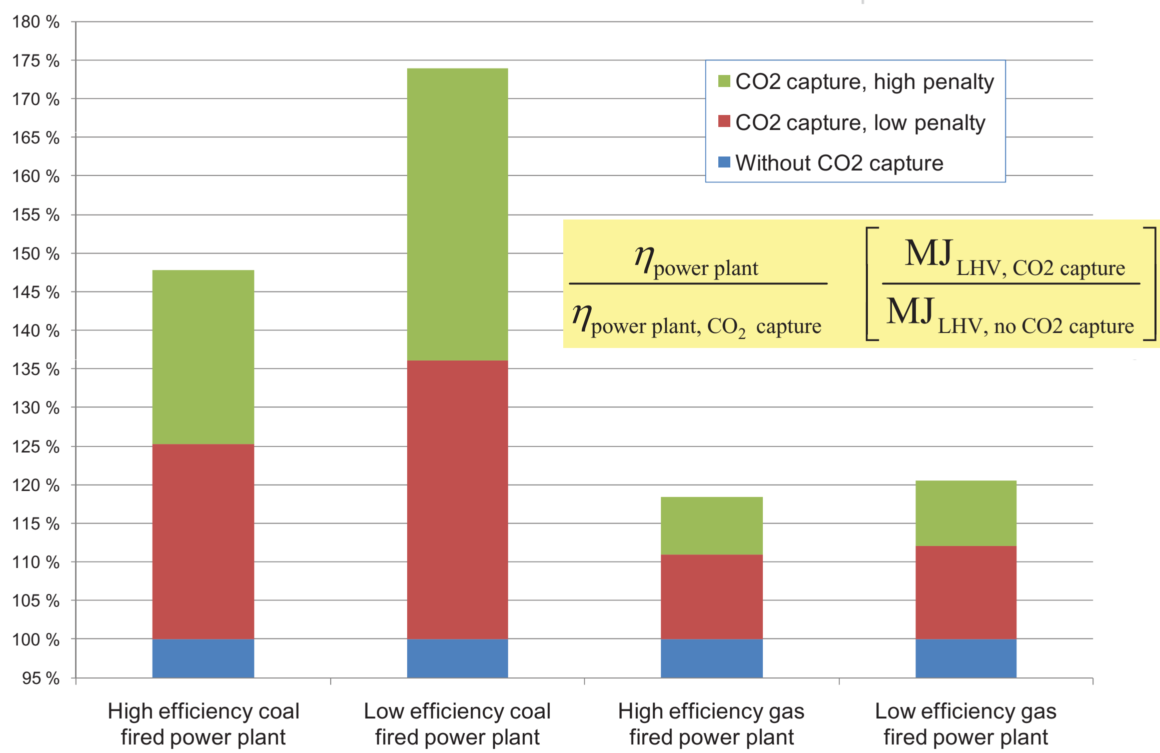
<u>Assuming power plant efficiencies without CCS</u>

46.0 %	High efficiency coal fired power plant
35.0 %	Low efficiency coal fired power plant
60.0 %	High efficiency gas fired power plant
55.0 %	Low efficiency gas fired power plant

Power plant efficiency penalty



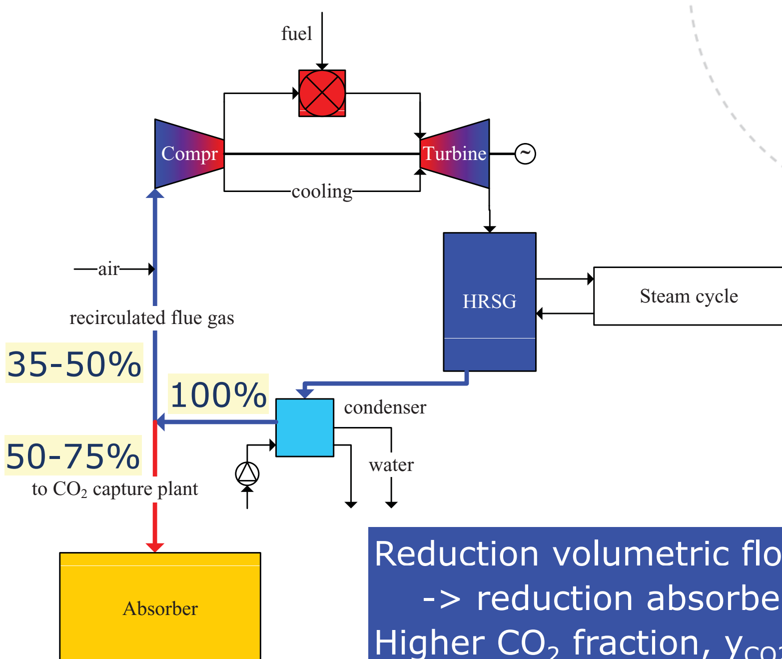
Additional fuel consumption for CCS



$$\frac{\eta_{\text{power plant}}}{\eta_{\text{power plant, CO}_2\text{ capture}}} \left[\frac{\text{MJ}_{\text{LHV, CO2 capture}}}{\text{MJ}_{\text{LHV, no CO2 capture}}} \right]$$

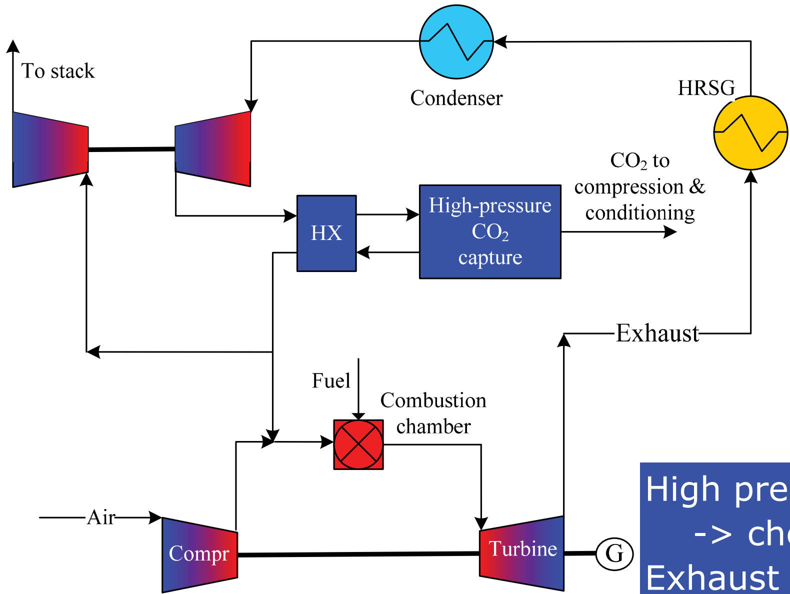
Alternative Power Cycles

Absorption – Exhaust gas recycle



Reduction volumetric flow rate
-> reduction absorber diameter
Higher CO_2 fraction, y_{CO2}=6-8%
-> reduction absorber height

Absorption – integrated at higher pressure in the power cycle

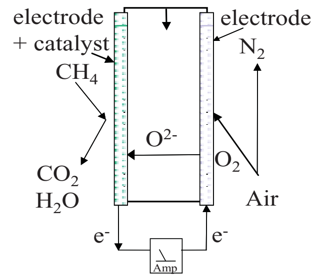


High pressure
-> chem → physical solvents
Exhaust gas recycle
-> reduced O_2 excess

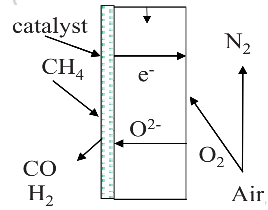
High-temperature membranes

Oxygen ion transport membranes

ZrO_2-Y_2O_3,
CeO_2,
$La_{1-x}Sr_xCo_{1-y}Fe_yO_{3-d}$
$Sr_2Fe_2O_5$,
$LaGaO_{3-d}$,
$(Bi_2O_2)(A_{n-1}B_nO_x)$,
La_2NiO_{4+d}



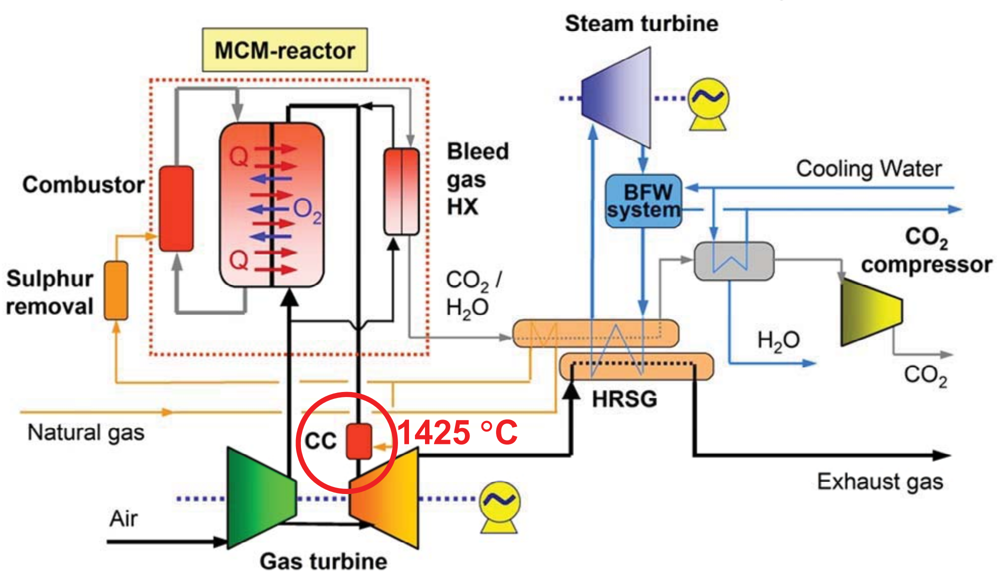
Oxygen ion conducting membrane, e.g. SOFC



Mixed conducting membrane OMCM,

Efficiency potential very good

Oxy-combustion - OMCM

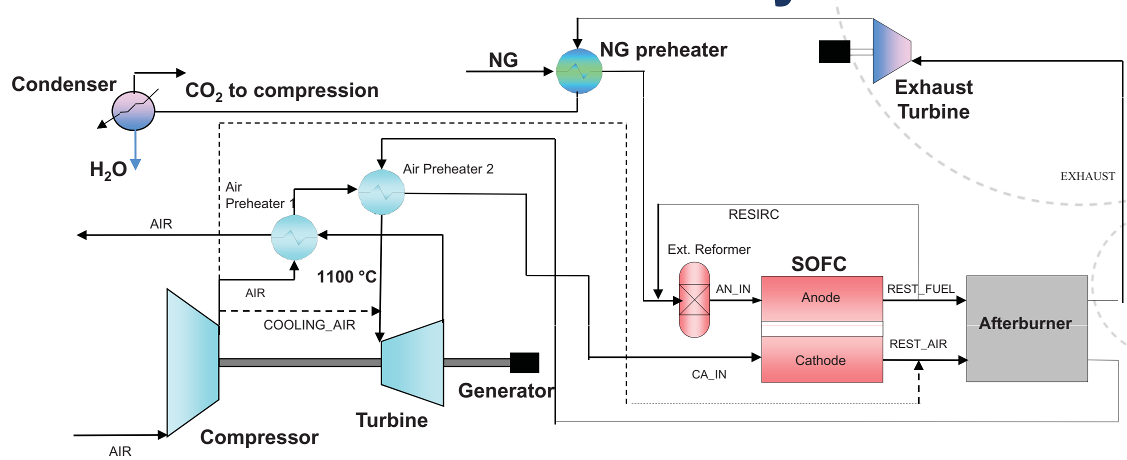


2003

- Gas turbine process + steam turbine process
- The GT combustor is replaced with a mixed conductive membrane reactor (MCM)
  - Separation of O_2 from air by the membrane
  - Combustion of fuel without presence of N_2
  - Heat exchange (combustion heat to depleted air)

Solid Oxide Fuel Cell (SOFC) with CO_2 capture

SOFC/GT with CO_2 capture – 65% efficiency

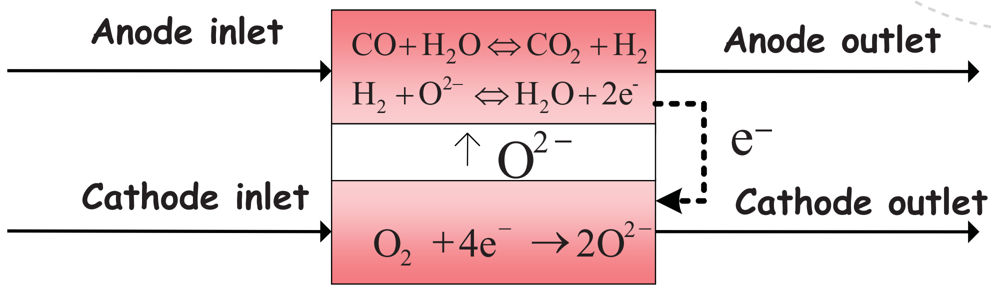


- A hybrid power cycle combining a SOFC-system and a gas turbine
- The SOFC-system replaces the combustion chamber and consists of a SOFC-unit + afterburner

Source: Kvamsdal, Maurstad, Jordal, and Bolland, "Benchmarking of gas-turbine cycles with CO2 capture", GHGT-7, 2004

SOFC/GT with CO_2 capture - 'afterburner'

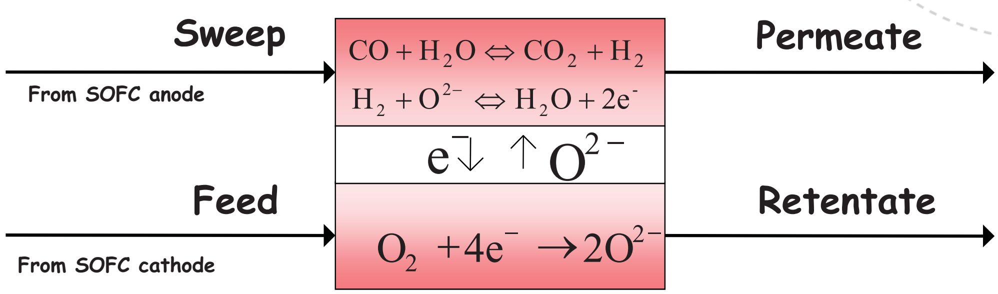
T1: Second SOFC unit



- Low voltage to reduce surface area
- Here, 0.3 V vs. 0.7 V in main SOFC unit

SOFC/GT with CO_2 capture - 'afterburner'

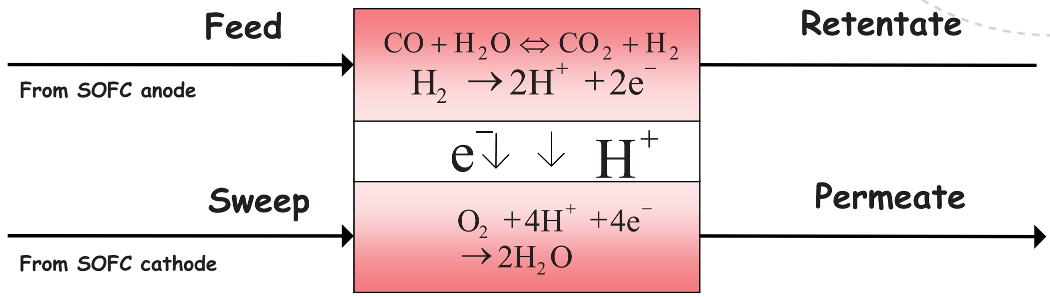
T2: Oxygen separation membrane reactor



- Similar to SOFC
- Both eletrons and oxygen ions trough the membrane
- No electrodes, simplified unit

SOFC/GT with CO_2 capture - 'afterburner'

T3: Hydrogen separation membrane reactor



- Protons and electrons through the membrane

CO_2 Capture from Air

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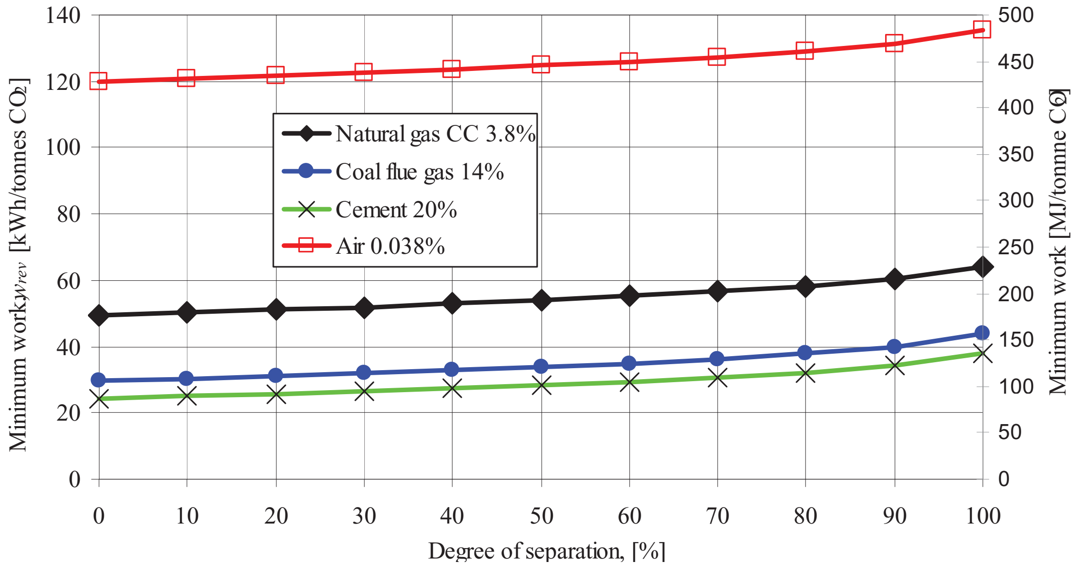
Minimum work requirement for separation of CO_2 from mixtures



Minimum work requirement for separation, depending on the degree of separation and fraction of CO_2 in the ingoing gas mixture. It is here assumed that CO_2 ends up at 1 bar, when separated. The values at the left end of the lines represent an extreme case where a very small amount of CO_2 is removed from the gas mixture.

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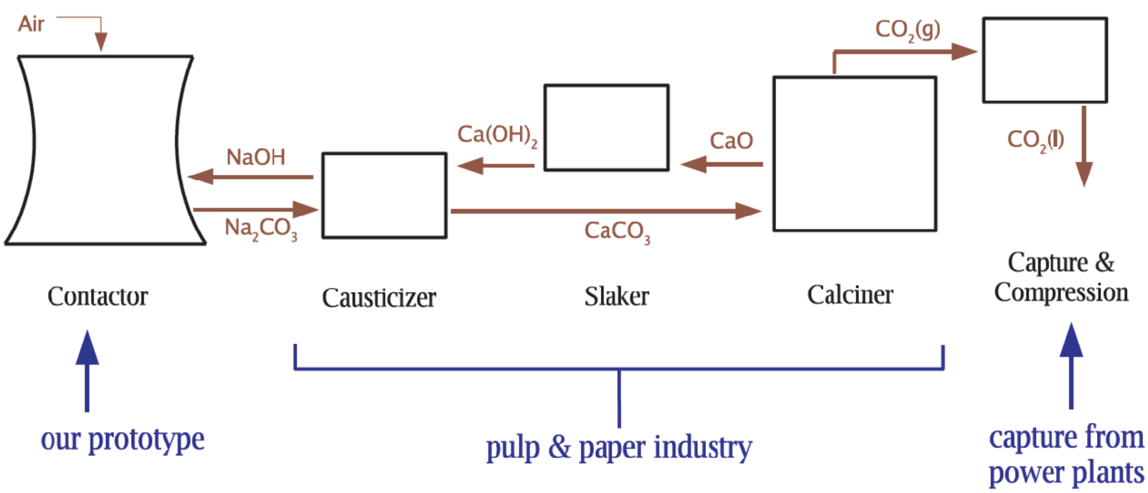
Air Capture: Collection & Regeneration

Anion exchange resin: carbonate polymer – binding CO_2 through carbonate/bicarbonate swing

Scientific American, June 2010, Klaus Lackner, Columbia University

Direct Air Capture: large scale?

Direct Air Capture –
Prof. David Keith, U of Calgary



Comments to Direct Air Capture

The cost of direct air capture is one magnitude higher than capture from power plants

Energy needed for the capture of CO_2 is high

$\Rightarrow$ Avoided CO_2 is much less than captured CO_2

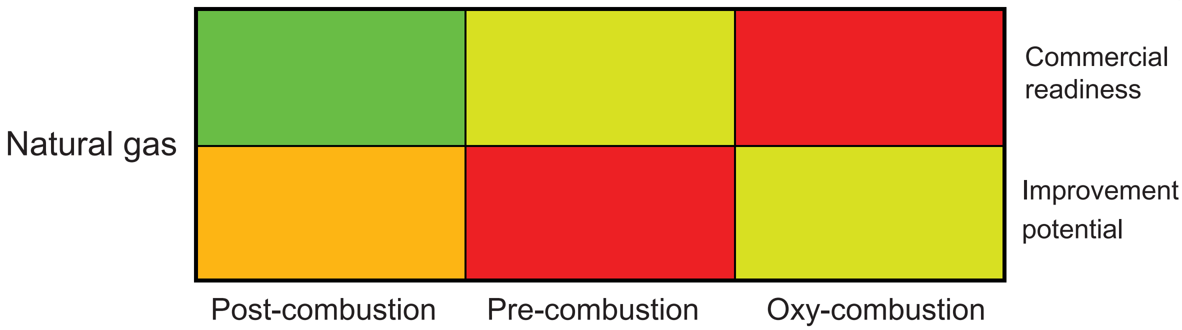
The requirements to infrastructure are comprehensive:

- land use
- consumption of water
- supply of natural gas or other fuel
- supply of power
- chemicals
- maintenance
- purification of CO_2
- transport and storage of CO_2

Technology status

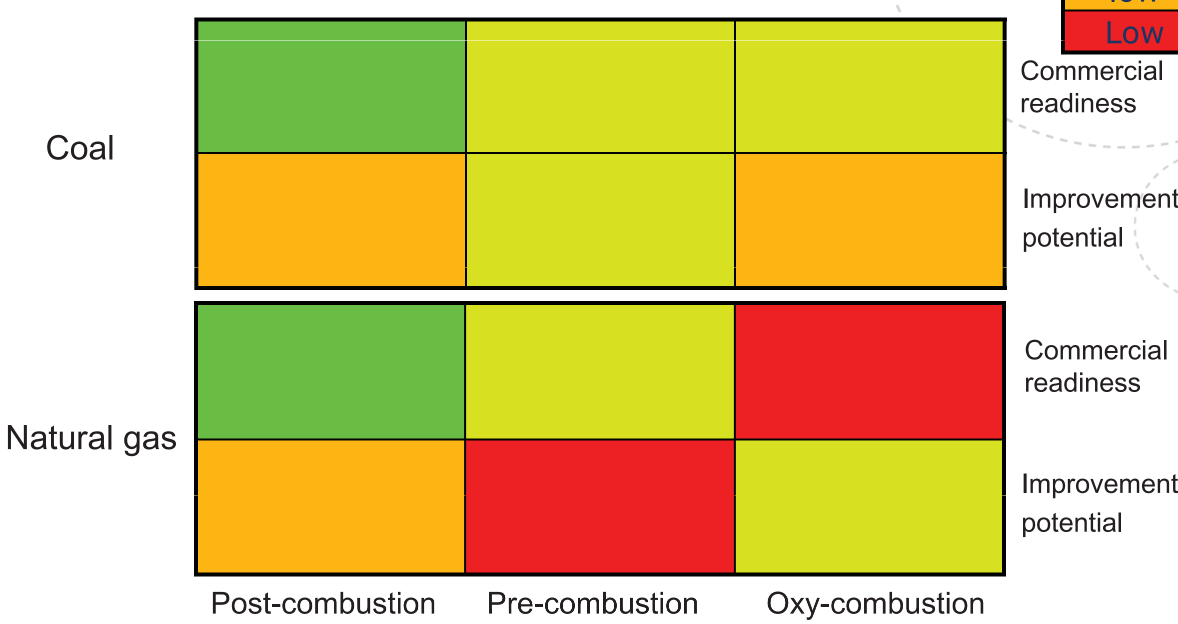
Technology status

CO_2 capture in power plants



Technology status

CO_2 capture in power plants



Thank you!