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Institute for
Thermal Turbomaschinery
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Thermodynamic and Economic Investigation of an Improved Graz Cycle Power Plant for CO_2 Capture

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Background

- Kyoto Protocol demands the reduction of greenhouse gases
- CO_2 is responsible for about 60 % of the greenhouse effect
- About 30 % of the anthropogenic CO_2 emissions come from fossil fuel fired heat and power generation
- Possible measures:
  - efficiency improvement
  - use of fuels of lower carbon content (methane)
  - use of renewable (or nuclear) energy
  - development of advanced fossil fuel power plants enabling CO_2 capture

Possible New Technologies

- Fossil fuel pre-combustion decarbonization to produce pure hydrogen or hydrogen enriched fuel for a power cycle (e.g. steam reforming of methane)
- Power cycles with post-combustion CO_2 capture (membrane separation, chemical separation, ...)
- Chemical looping combustion: separate oxidation and reduction reactions for natural gas combustion leading to a CO_2/H_2O exhaust gas
- Oxy-fuel power generation: Internal combustion with pure oxygen and CO_2/H_2O as working fluid enabling CO_2 separation by condensation

Pros and Cons of Oxy-Fuel Combustion

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

\+ CO_2 can be easily separated by condensation, no need for very penalizing scrubbing

\+ Very low NOx generation (only nitrogen from fuel)

\+ Flexibility regarding fuel: natural gas, syngas from coal or biomass gasification, ...

\- New equipment required

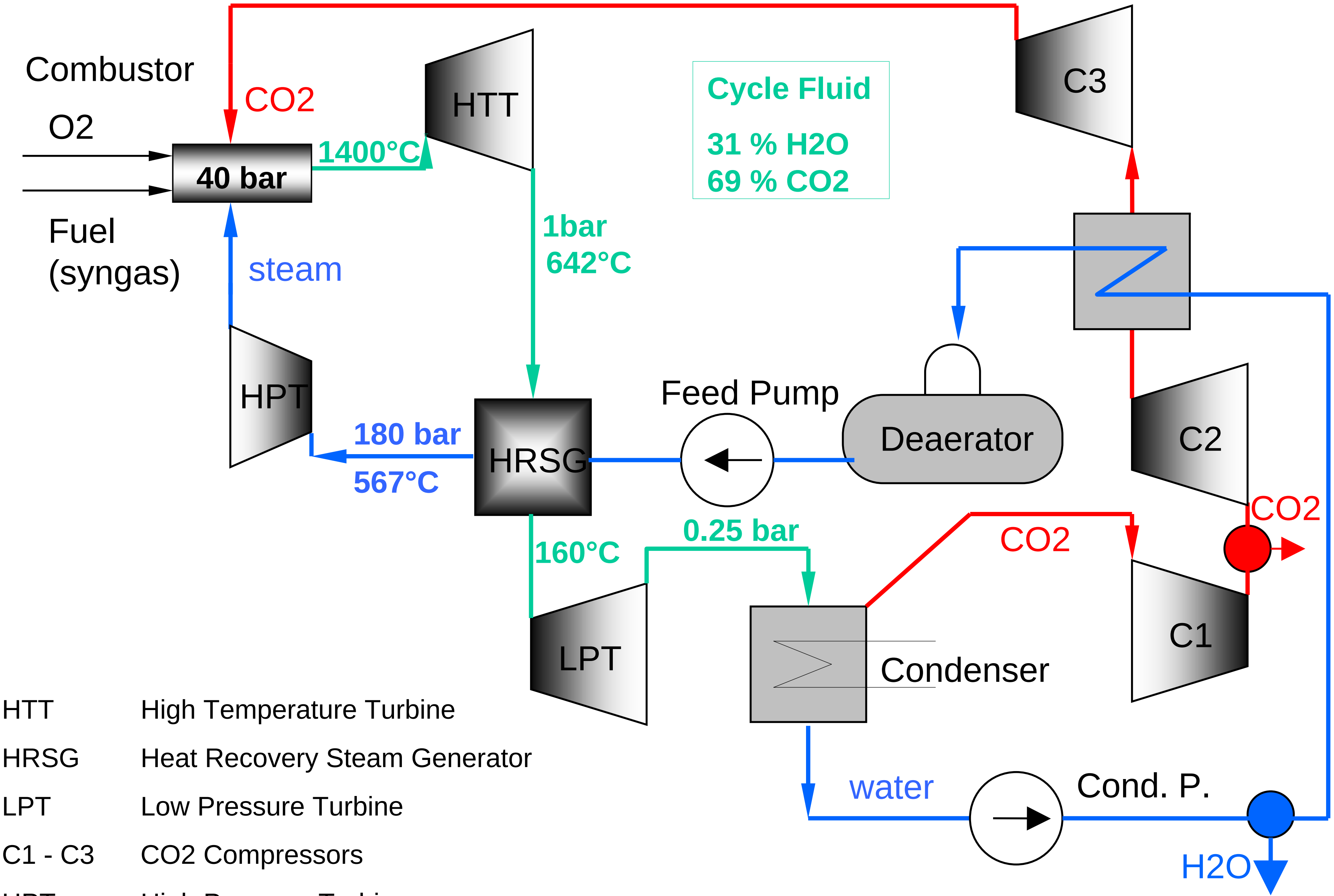
\- Additional high costs of oxygen production

\+ New cycles are possible with efficiencies higher than current air-based combined cycles (Graz Cycle, Matiant cycle, Water cycle,...)

History of the Graz Cycle

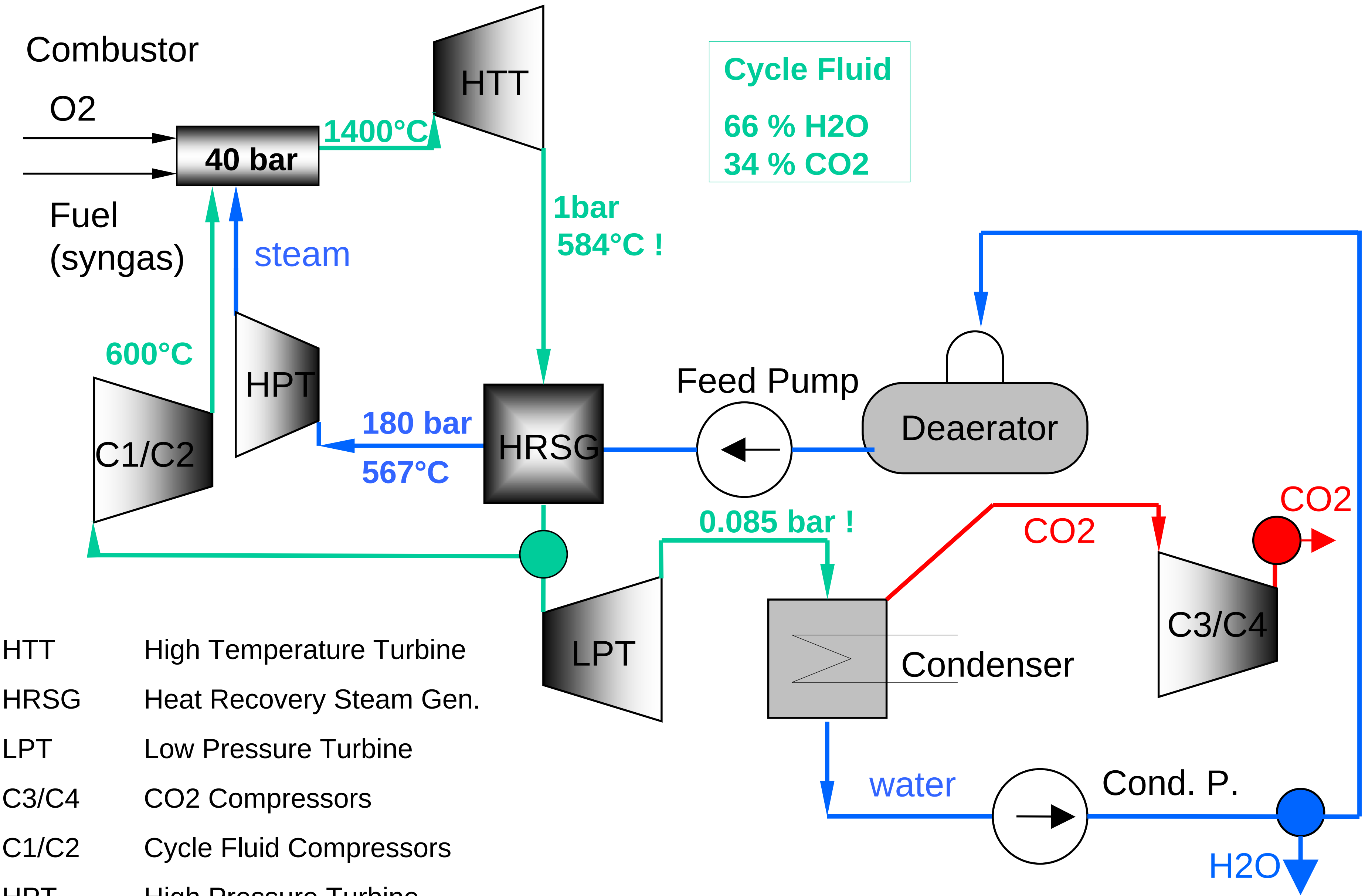
- **1985: presentation of a power cycle without any emission**
  - H2/O2 internally fired steam cycle, as integration of top Brayton cycle with steam and bottom Rankine cycle
  - efficiency 6 % - points higher than state-of-the art CC plants
- **1995: Graz cycle adopted for the combustion of fossil fuels like methane (CH4)**
  - cycle fluid is a mixture of H2O and CO2
  - thermal cycle efficiency: 64 %
- **2000: thermodynamically optimized cycle for all kinds of fossil fuel gases (syngas, gas from gasification processes, ...)**
- **2002/2003: conceptual layout of turbomachinery relevant components of prototype Graz Cycle power plant**

Graz Cycle (ASME 2003, Atlanta)



HTT	High Temperature Turbine
HRSG	Heat Recovery Steam Generator
LPT	Low Pressure Turbine
C1 - C3	CO2 Compressors
HPT	High Pressure Turbine

High Steam Content Graz Cycle (S-GC)



HTT	High Temperature Turbine
HRSG	Heat Recovery Steam Gen.
LPT	Low Pressure Turbine
C3/C4	CO_2 Compressors
C1/C2	Cycle Fluid Compressors
HPT	High Pressure Turbine

Assumptions for Thermodynamic Simulation

- Fuel: syngas from coal gasification with
  mole fractions: 50 % H_2, 40 % CO, 10 % CO_2
- Complete stoichiometric combustion at 40 bar
  (pressure found in aircraft engines)
- Turbine inlet temperature in the range of high power
  stationary gas turbines: 1400° C
- Turbine isentropic efficiency: 92 % (HPT 90 %)
- Compressor isentropic efficiency: 88 %
- Turbomachinery mechanical efficiency: 99 %
- Generator electrical efficiency: 98.5 %
- Cooling water temperature in condenser: 20° C
- HRSG: cold side pressure loss: 5 bar
  Pinch point: 5° C
- CO_2 released at 1bar

Power Balance

	Graz Cycle	S-Graz Cycle
HTT power [MW]	91	127.5
Total turbine power [MW]	111	150.4
Total compression power [MW]	18.8	50.5
Net shaft power [MW]	**92.2**	**99.9**
Total heat input [MW]	143.4	143.4
Thermal cycle efficiency [%]	**64.3**	**69.6**
Electrical cycle efficiency [%]	**63.3**	**68.6**

Additional Losses and Expenses (S-GC)

- Oxygen production (0.15 - 0.3): 0.25 kWh/kg (8 MW)

  Oxygen compression (1 to 40 bar, inter-cooled):

  0.125 kWh/kg (4 MW)

  Efficiency: 60.3 %

- Compression of separated CO_2 for liquefaction (1 to 100 bar, inter-cooled): 0.075 kWh/kg (3.7 MW)

  Efficiency: 57.7 %

Methane firing:

Higher oxygen demand, less CO_2 emitted

Respective efficiencies: 56.8 % / 55.3 %

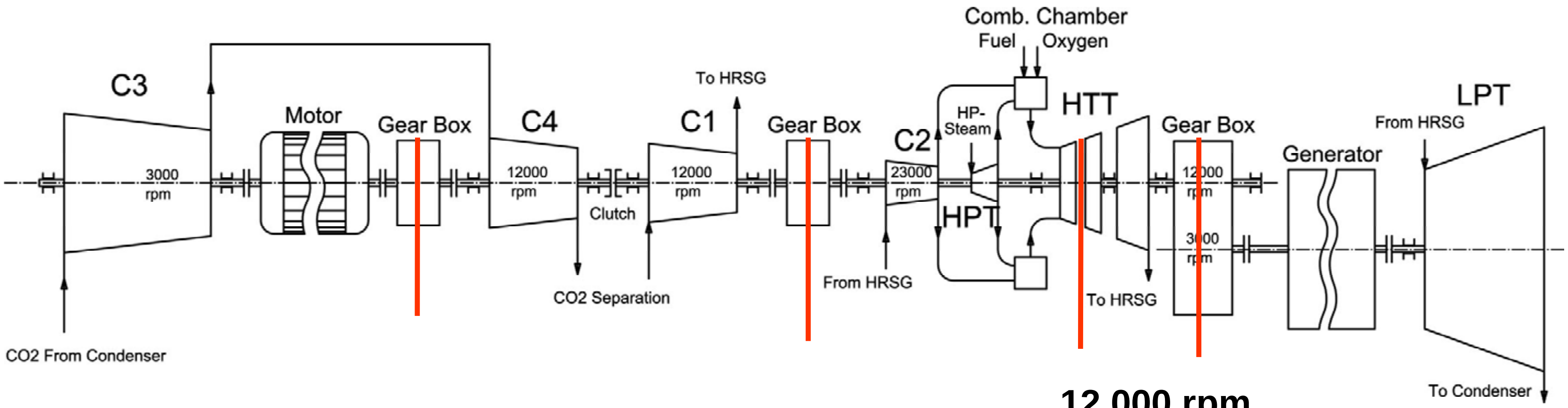
(steam reforming of methane ??)

Lay-out of Components

- **Critical components**
  - **Combustion chamber**
    for stoichiometric combustion with O_2 and cooling with steam and CO_2
  - **High temperature turbine HTT**
    unusual working fluid of 2/3 H_2O and 1/3 CO_2 cooling with steam
- **Non-critical components**
  - **Low pressure turbine LPT**
  - **High pressure turbine HPT**
  - **CO_2 compressors**
  - **H_2O/CO_2 compressors**
  - **Heat exchangers**

Turbomachinery Arrangement S-Graz Cycle

- Different turbomachinery arrangement with 2 shafts
- First shaft: balance of compessor and turbine power
- Second shaft drives generator
- Turbo set with 3 different speeds
  23 000 rpm: HTT first stage + HPT + C2 WF-compressor
  12 000 rpm: HTT 2nd-4th stage + C1 WF-compressor + C4 CO2-compr.
  3 000 rpm: LPT + C4 CO2-compressor
- First layout for 100 MW plant: reasonable turbomachinery dimensions

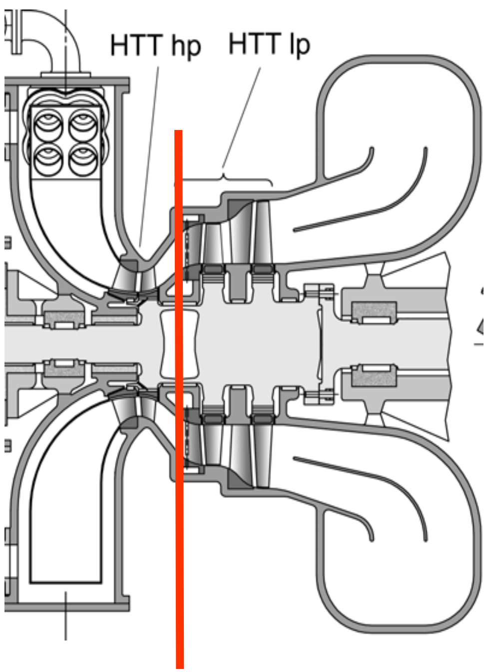


3 000 rpm   12 000 rpm   23 000 rpm   12 000 rpm   3 000 rpm

High Temperature Turbine HTT

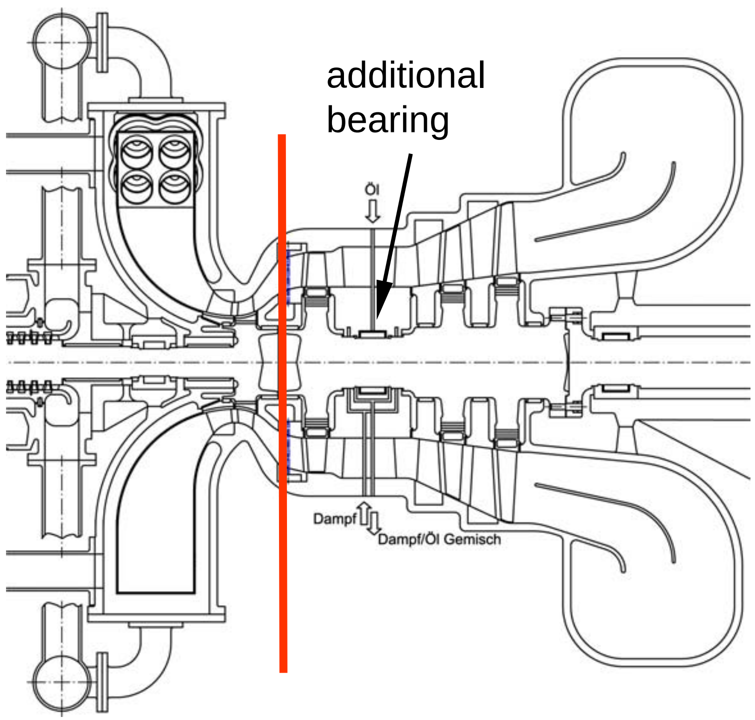
- Pressure drop: 40 bar - 1 bar
- Enthalpy drop:
  Graz Cycle: 965 kJ/kg (similar to air-turbine exhaust gas) -> 3 stages
  S-Graz Cylce: 1510 kJ/kg -> 4 stages
- High rotational speeds to keep number of stages low
- Split into two overhang shafts to obtain optimal speeds

Graz Cycle



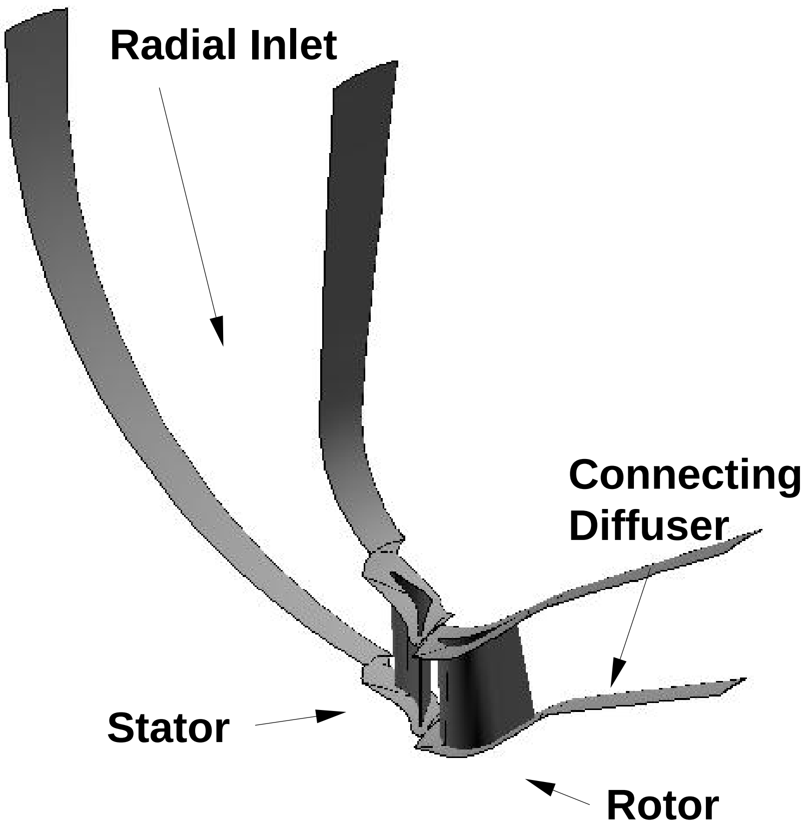
20 000 rpm　　12 000 rpm

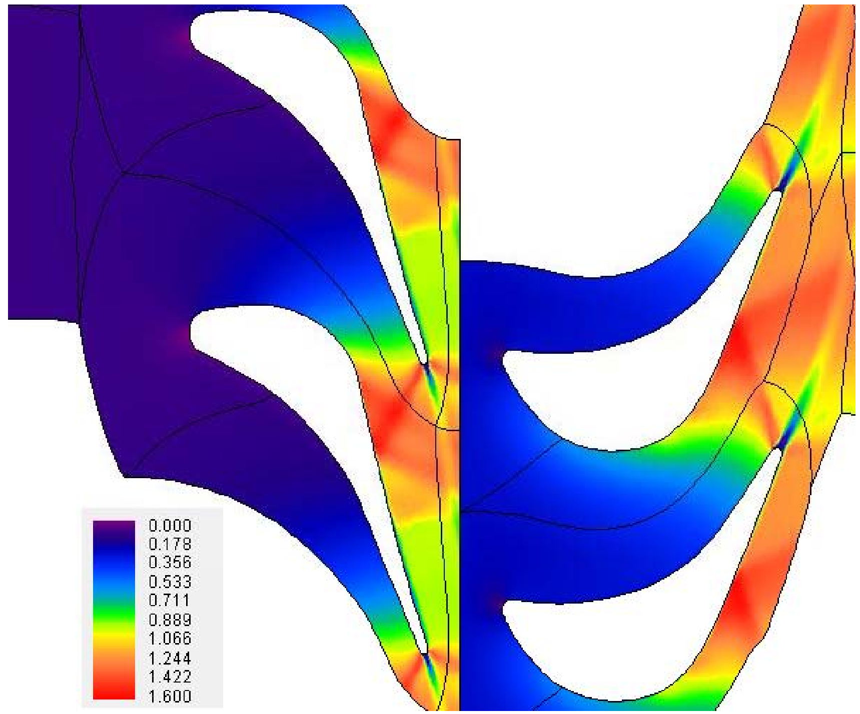
S-Graz Cycle



23 000 rpm　　12 000 rpm

GC HTT First Stage Design





Mach number distribution at mid section

- **Pressure drop: 40 bar - 10 bar**
- **Enthalpy drop: 450 kJ/kg**
- **Mach number up to 1.3 (800 m/s)**
- **Minimal twist of rotor blades due to stream line curvature**

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: 6500 hrs/yr
- capital charge rate: 15%/yr
- syngas is supplied at 3.5 ¢/kWh$_{th}$
  (alternatively methane firing at 1.3 ¢/ kWh$_{th}$)

Economical Analysis S-GC - II

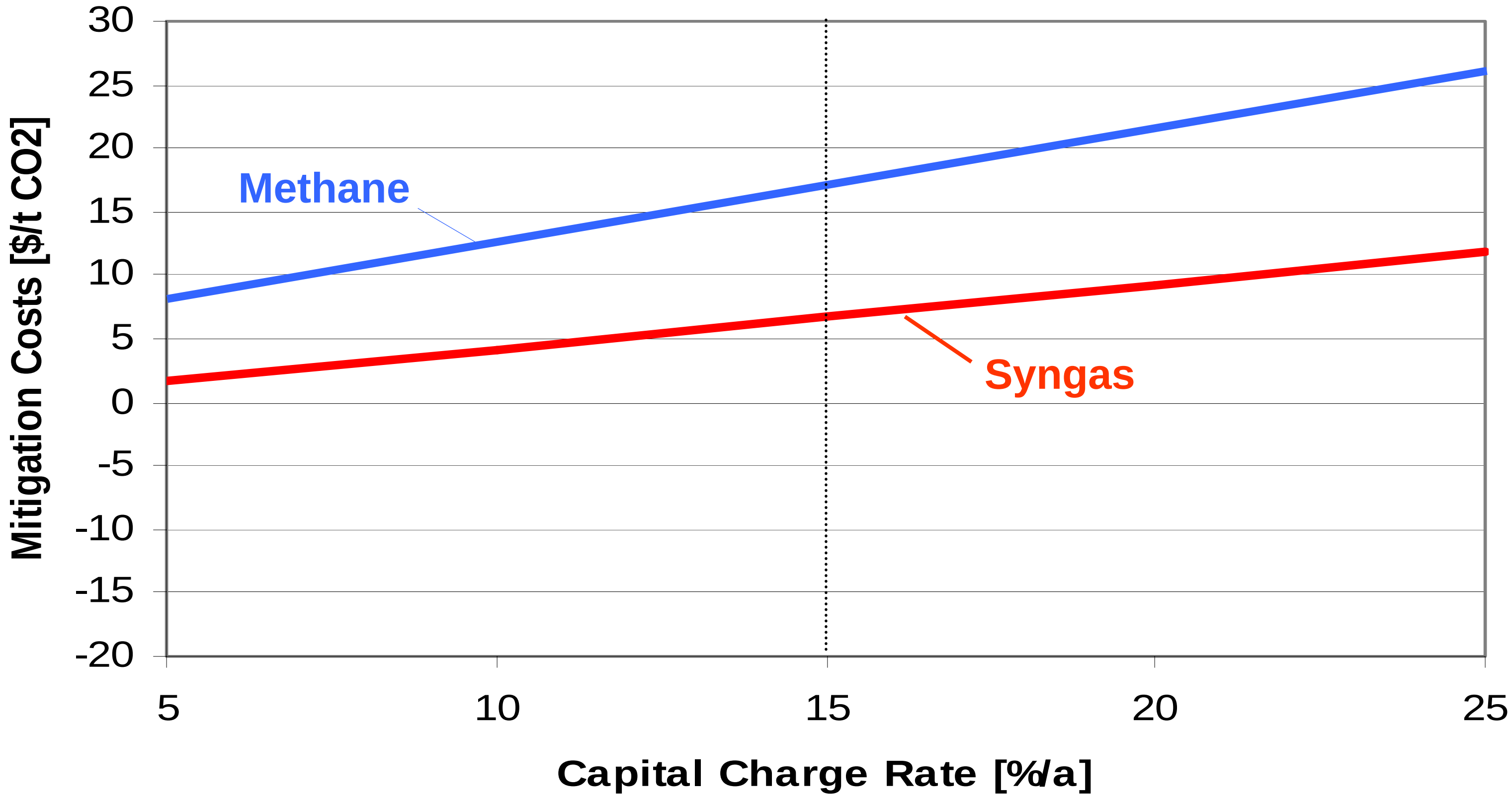
COE ...

Cost of Electricity

	Reference plant [13]	S-Graz Cycle	S-GC + CO_2 at 100 bar
Plant capital costs [$/kW$_{el}$]	414	414	414
Addit. capital costs [$/kW$_{el}$]		148	209
CO_2 emitted [kg/kWh$_{el}$]	0.629	0.0	0.0
Net plant efficiency [%]	56.2	60.3	57.7
COE for plant amort. [¢/kWh$_{el}$]	0.96	1.3	1.44
COE due to fuel [¢/kWh$_{el}$]	6.22	5.8	6.06
COE due to O&M [¢/kWh$_{el}$]	0.7	0.8	0.8
Total COE [¢/kWh$_{el}$]	7.88	7.9	8.30
Comparison			
Differential COE [¢/kWh$_{el}$]		0.02	0.42
Mitigation costs [$/ton CO_2]		0.3	6.7

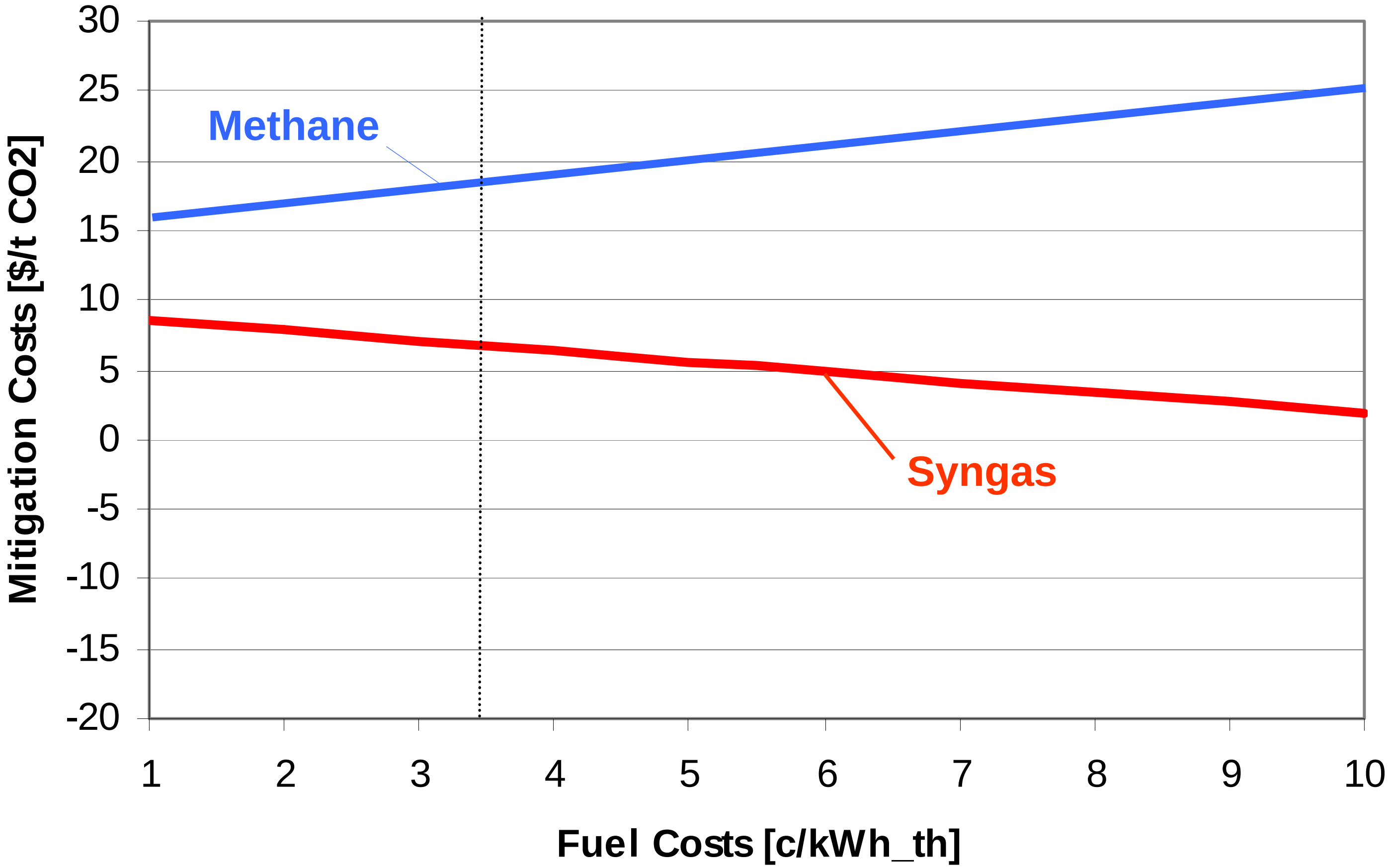
Mitigation costs methane [$/ton CO_2]	13.0	17.5

Influence of Capital Charge Rate S-GC



Syngas Firing: MC varies between 1.5 and 12 $/ton CO2 for charge rate variation between 5 % and 25 % -> relatively small sensitivity

Influence of Fuel Costs S-GC

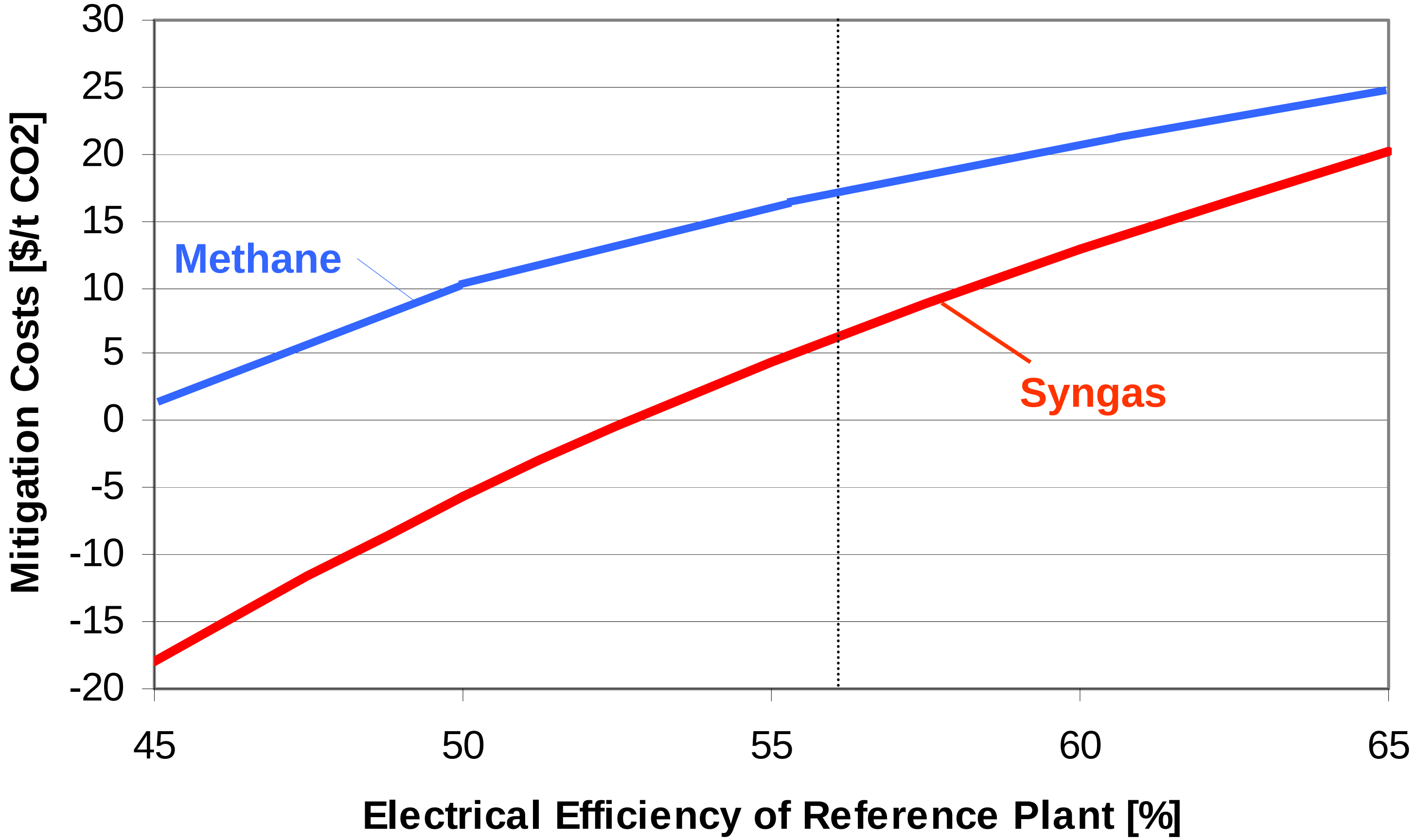


<u>Syngas Firing:</u> Higher fuel costs decrease the MC because of higher efficiency of S-GC

Fuel costs: 1-10 c/kWh -> MC: 9 – 3 $/ton

Small influence on investment decision

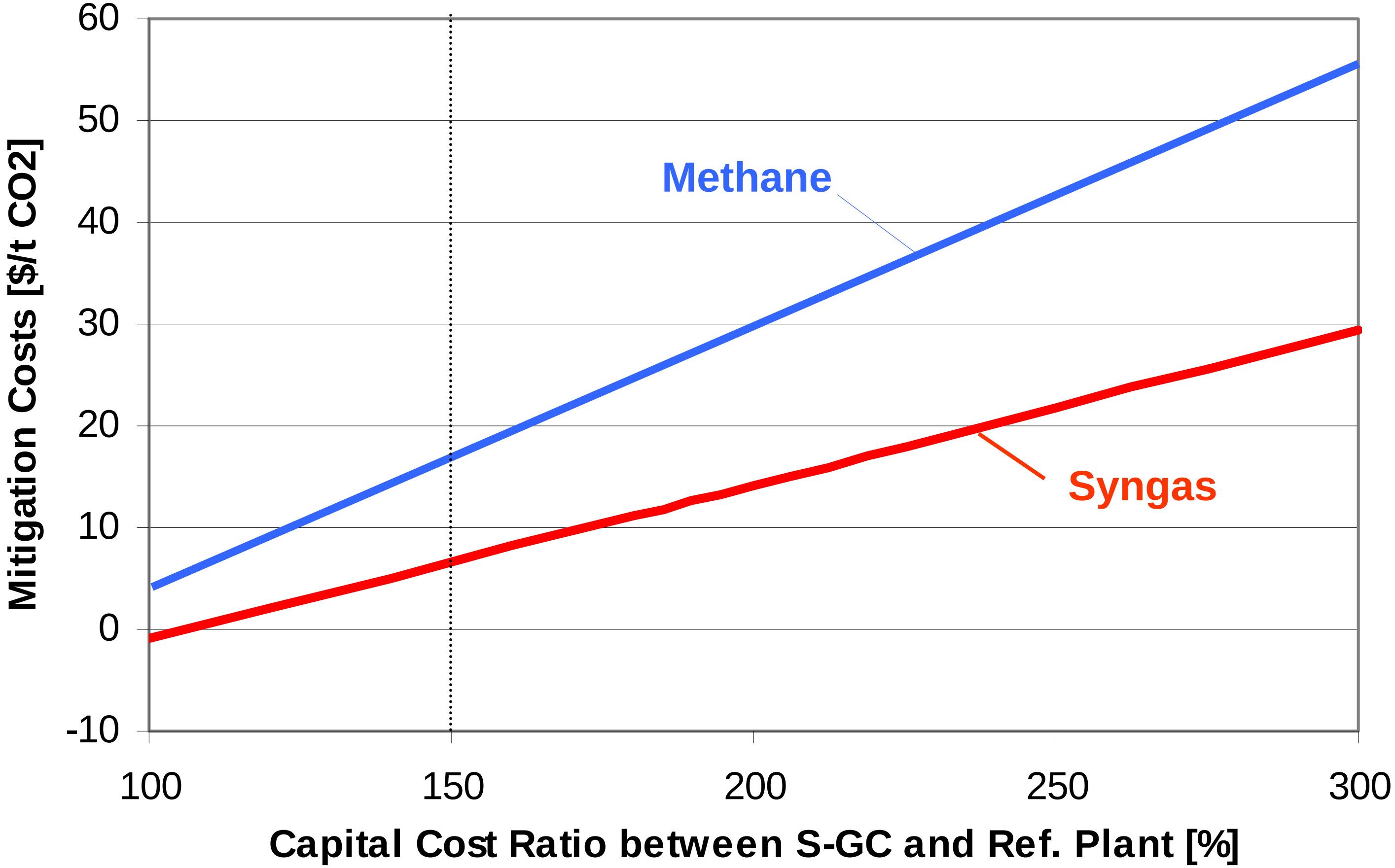
Influence of Reference Plant Efficiency S-GC



This parameter covers all influences on cycle efficiency

Reference plant of 60 %: MC 7 -> 13 $/ton (26 $/ton for methane)

Influence of Capital Costs S-GC



Large uncertainty in cost esimation

ASU and CO2 separation: 50 % higher costs than reference plant

Double costs: MC = 15 $/ton CO2, 3 x costs: MC = 30 $/ton CO2

Conclusions

- Presentation of an improved version of the Graz Cycle, the High-Steam-Content S-Graz Cylce as "zero-emission gas turbine cycle" with oxy-fuel combustion and CO_2 retention
- Thermodynamic layout promises efficiencies up to 69 % (60 % if expenses of O_2 supply are considered)
- Possible arrangement of turbomachines is presented showing feasibility
- Economic comparison with reference plant show competitiveness to state-of-the-art combined cycle power plants, especially for syngas firing
- Mitigation costs of about 7 $/ton CO_2 are promising under the prospect of a future CO_2 tax