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A Further Step Towards a Graz Cycle Power Plant for CO_2 Capture

Presentation at the
ASME Turbo Expo 2005
Reno-Tahoe, Nevada, USA, June 6 - 9, 2005

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Background

- Kyoto Protocol demands the reduction of greenhouse gases, mainly CO2
- In EU: strong pressure on utilities and companies to reduce CO2 emissions
- In 2005: emission allowances to about 10 000 companies within the EU covering about 46 % of the overall EU CO2 emissions
- As emission allowances become scarce: CO2 emissions generate costs (estimated between 12 and 25 $/ton CO2 by 2010 and even more by 2015)

Possible New Technologies

Therefore search for economical solutions for the capture of CO2 from power plants:

- 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 CO2 capture (membrane separation, chemical separation, ...)
- Chemical looping combustion: separate oxidation and reduction reactions for natural gas combustion leading to a CO2/H2O exhaust gas
- Oxy-fuel power generation: Internal combustion with pure oxygen and CO2/H2O as working fluid enabling CO2 separation by condensation

Pros and Cons of Oxy-Fuel Combustion

- Combustion with nearly pure oxygen leads to an exhaust gas consisting largely of CO2 and H2O

\+ CO2 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

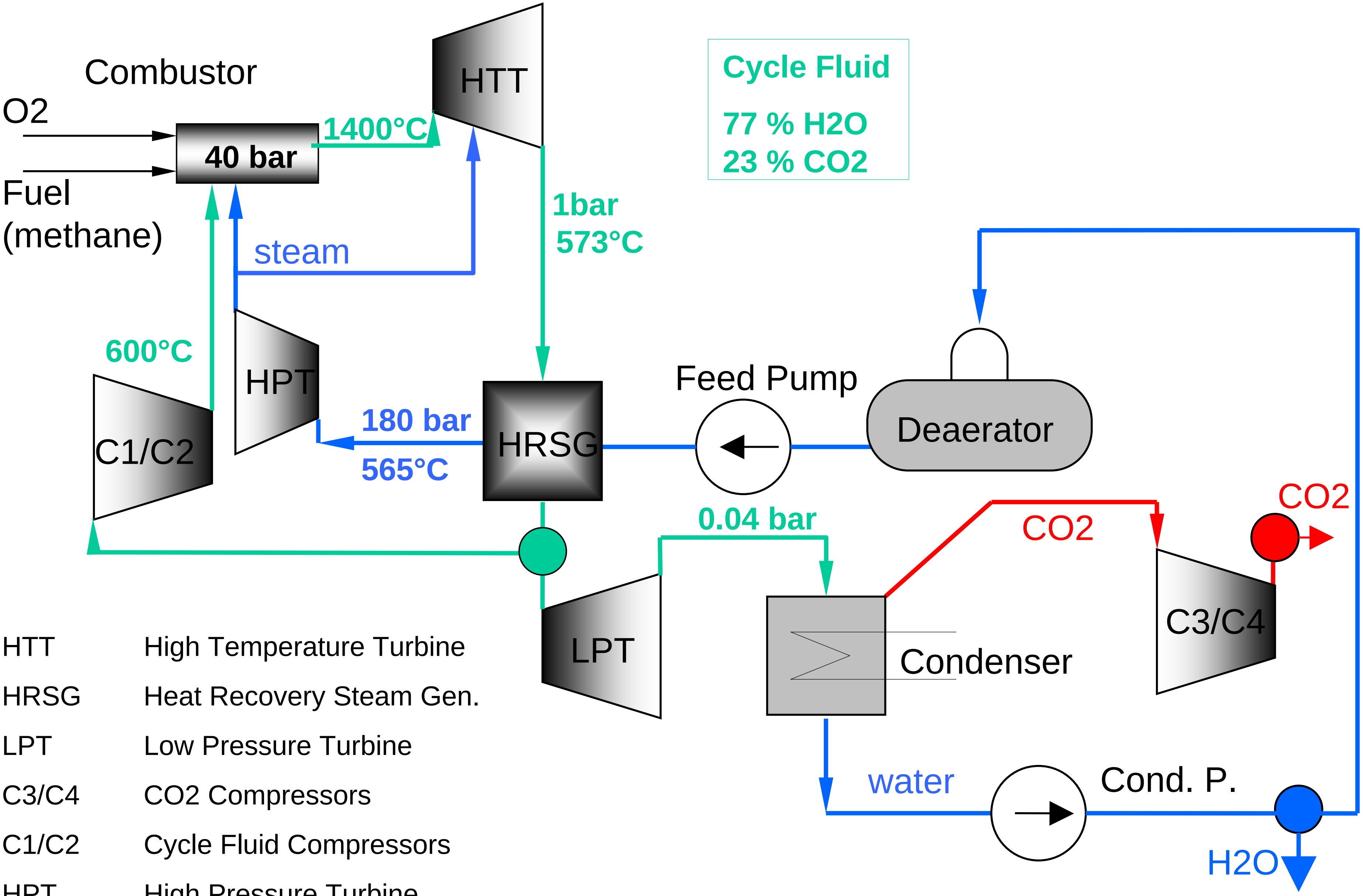
\- Additional high costs of oxygen production

\+ 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 (CIMAC Oslo)
  - H_2/O_2 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 (CH_4) (CIMAC Interlaken & ASME Cogen Wien)
  - cycle fluid is a mixture of H_2O and CO_2
  - thermal cycle efficiency: 64 %
- 2000: thermodynamically optimized cycle for all kinds of fossil fuel gases (VDI Essen)
- 2002/2003: conceptual layout of prototype Graz Cycle power plant: detailed design of components (ASME Amsterdam, VDI Leverkusen, ASME Atlanta)
- 2004: presentation of S-Graz Cycle with nearly 70% thermal efficiency and 57 % net efficiency for syngas firing (ASME Vienna)

High Steam Content Graz Cycle (S-GC)

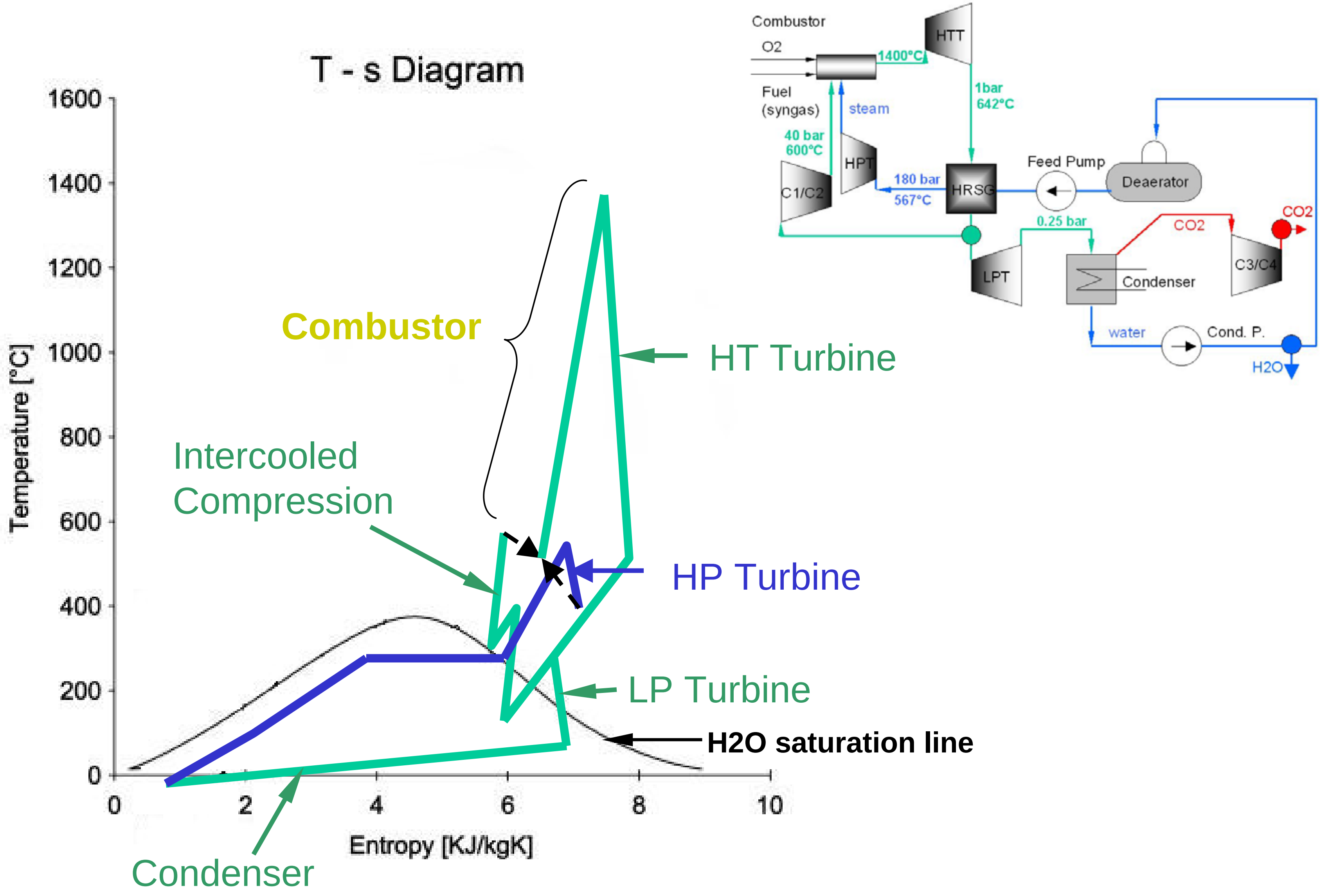


Cycle Fluid

77 % H2O
23 % CO2

HTT	High Temperature Turbine
HRSG	Heat Recovery Steam Gen.
LPT	Low Pressure Turbine
C3/C4	CO2 Compressors
C1/C2	Cycle Fluid Compressors
HPT	High Pressure Turbine

T-s Diagram of S-Graz Cycle



Power Balance ASME 2004

- Electrical cycle efficiency for methane firing:

  Efficiency: 67.6 %

- 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: 56.8 %

- Compression of separated CO2 for liquefaction (1 to 100 bar, inter-cooled): 0.075 kWh/kg (3.7 MW)

  Efficiency: 55.3 %

-> Interest by a possible end-user: technical and economical evaluation of S - Graz Cycle

Conservative Assumptions I

	2004 assumptions	Conservative assumptions
Fuel	methane	natural gas
Combustion pressure	40 bar, no pressure loss	40 bar, 4 % pressure loss
Combustion chamber heat loss	not considered	0.25 %
Combustion temperature	1400 °C	1400 °C
Oxygen excess	0 %	3 % of stoichiometric amount
Turbine efficiency	92 % for all turbines	HTT: 90.3 % HPT: 90 % LPT: 88 %
Compressor efficiency	88 % for all compressors	working fluid: 88 % O2: 85 % CO2: 78 % – 85 %
Pump efficiency	98 %	70 %
Cooling steam mass flow	11.4 % of HTT inlet mass	13.7 % of HTT inlet mass

Conservative Assumptions II

Heat exchanger pressure loss	not considered	3 %
HRSG pressure loss	5 bar	28 bar
HRSG minimum temperature difference	ECO: 5 K SH: 8.6 K	ECO: 5 K SH: 25 K
Condenser exit temperature	18 °C	18 °C
Condenser pressure	0.06 bar	0.0413 bar
Fuel temperature	250 °C	150 °C
Mechanical efficiency	99 %	99.6 %
Generator / Transformer efficiency	98.5 % / 100 %	98.5 % / 99.65 %
Auxilliary losses	not considered	0.35 %
Oxygen production	900 kJ/kg	900 kJ/kg
Oxygen compression	1 – 40 bar: 400 kJ/kg	2.38 – 42 bar: 325 kJ/kg
CO2 compression 1 to 100 bar	245 kJ/kg	350 kJ/kg

Power Balance

	2004	2005
HTT power [MW]	127.6	119.4
Total turbine power [MW]	150.7	142.4
Total compression power [MW]	50.2	47.1
Net shaft power [MW]	**100.5**	**95.3**
Total heat input [MW]	143.4	143.4
Thermal cycle efficiency [%]	**70.1**	**66.5**
Electrical cycle efficiency [%]	**67.6**	**64.6**

Additional Losses and Expenses (S-GC)

- Oxygen production: 0.25 kWh/kg = 900 kJ/kg (10.0 MW)

  Oxygen compression (2.38 to 42 bar, inter-cooled):

  325 kJ/kg (3.6 MW)

  Efficiency: 54.8 %

- Compression of separated CO2 for liquefaction (1 to 100 bar, 8 % steam content): 350 kJ/kg (3.2 MW)

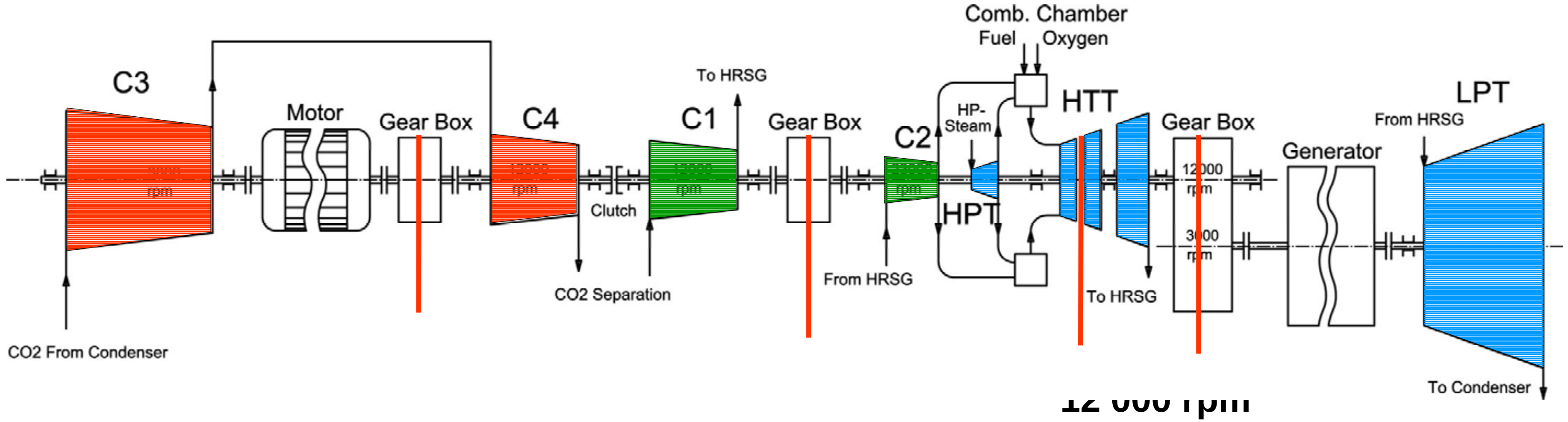
  Efficiency: 52.6 %

2004 assumptions:

Respective efficiencies: 56.8 % / 55.3 %

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

3 000 rpm

Modifications

Possible modifications in order to improve efficiency:

- replacement of the single-pressure HRSG by a dual-pressure HRSG
- condensation of the cycle working fluid at 1 bar and re-vaporization of the separated water
- heat supply to the deaerator by the cooling heat of the CO2 compression intercooler

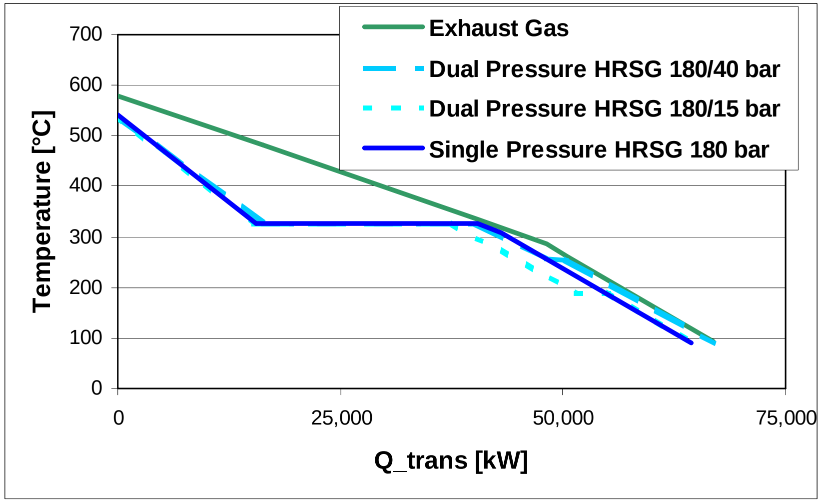
Dual-Pressure HRSG

Goal: reduced heat transfer losses by smaller temperature differences

- HTT cooling steam at 40 bar and 15 bar offers possibility of a second pressure level at either

  - 40 bar (44 % of total HRSG mass flow) or

  - 15 bar (15 % of total HRSG mass flow)



- **Result:**
  reduced HPT steam mass flow and
  higher LPT inlet temperature -> decrease in efficiency

Condensation/Re-Vaporization at 1 bar - I

TUG

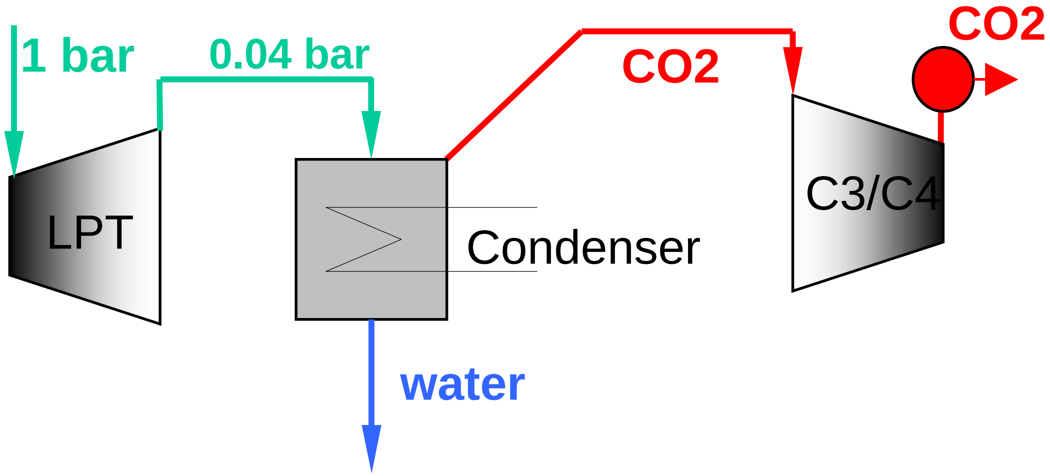
Cooling water temperature: 10°C -> pressure: 0.045 bar

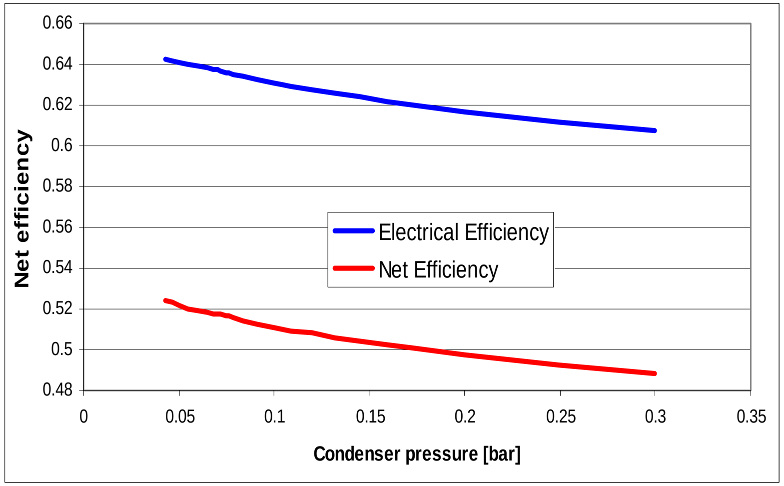
- **Steam/CO2 mixture is expanded in LPT to condenser pressure**
- **After separation CO2 is re-compressed to atmosphere**
- **Difficulties:**

  1. Condenser is very expensive (high volume flow, inert gas)

  2. Difficulty in keeping vacuum condition (high inert gas content): high influence on net efficiency

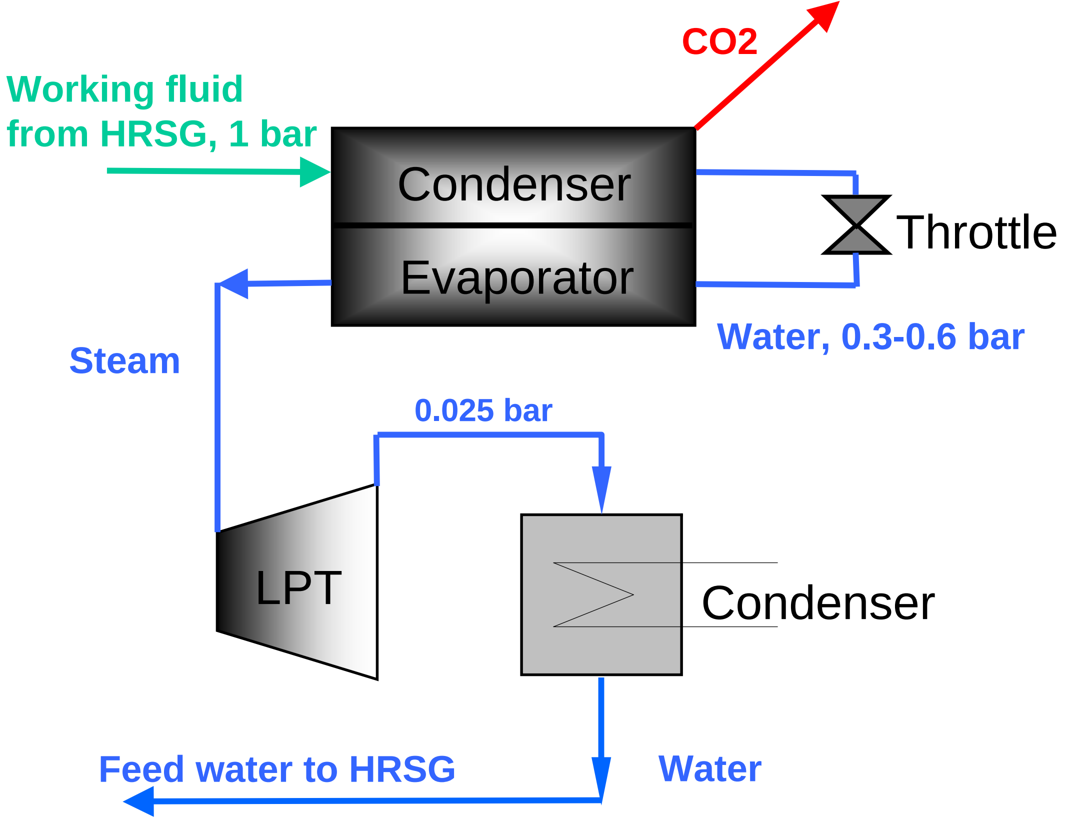
  3. Loss due to different expansion/compression efficiencies





Condensation/Re-Vaporization at 1 bar - II

Alternative 1: Condensation at 1 bar and re-vaporization

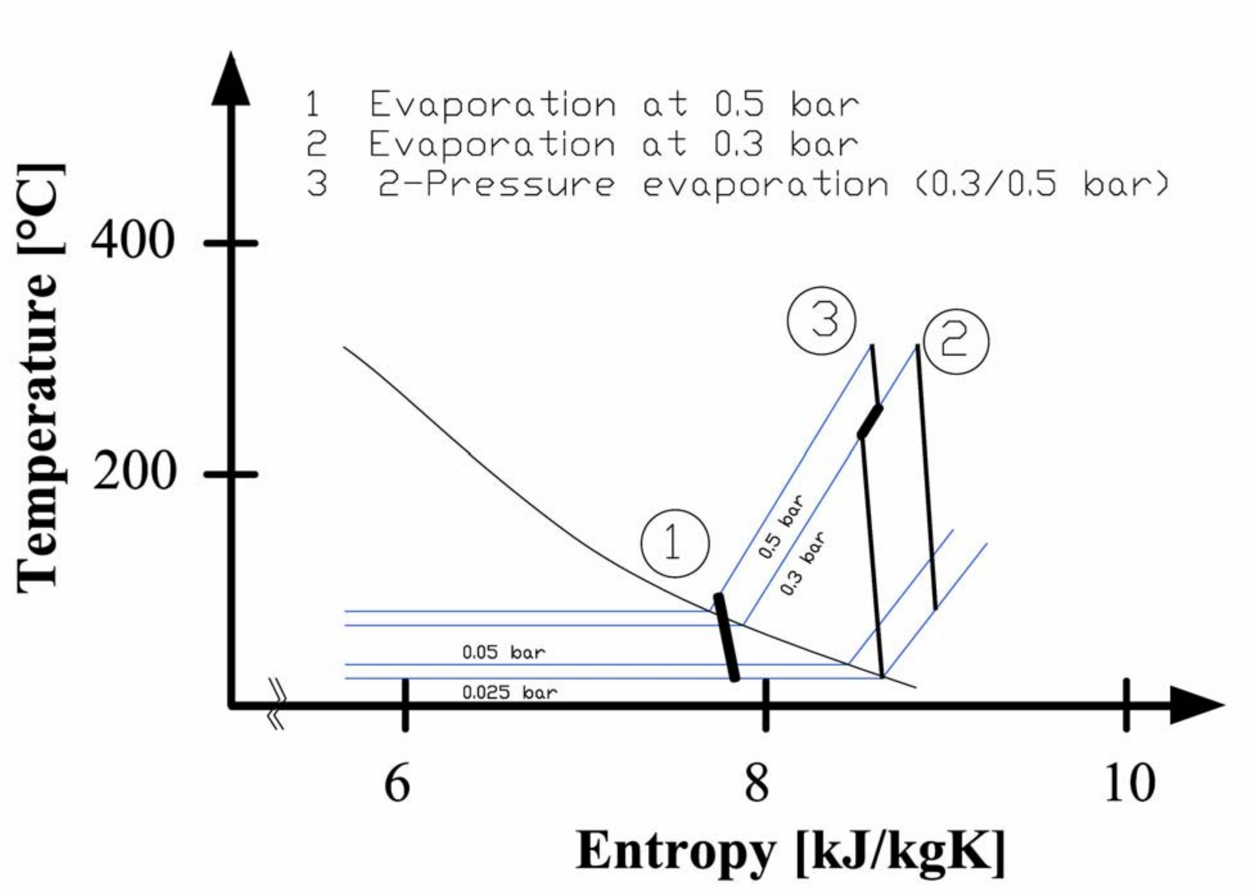


- **Avoidance of difficult condenser at vacuum condition**
- **Avoidance of C3+C4 CO2 compressors**
- **Additional condensation/re-vaporization unit at 1 bar**

Condensation/Re-Vaporization at 1 bar - III

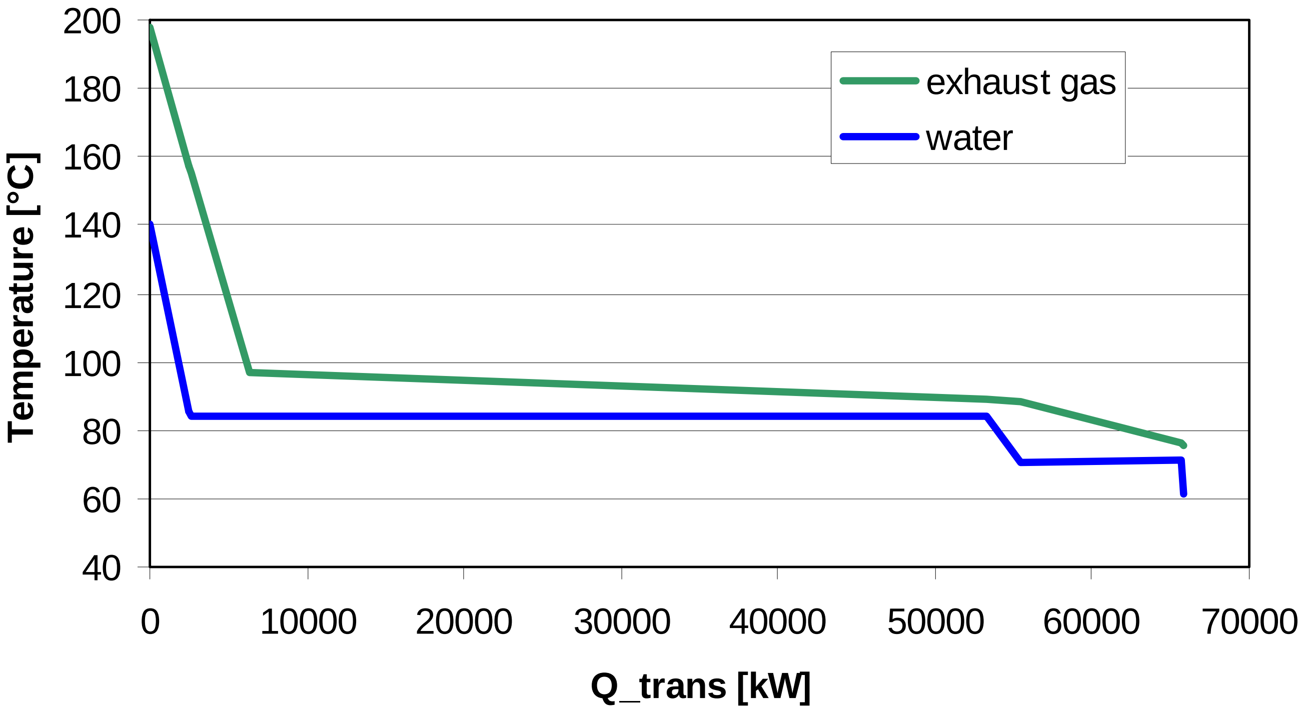
Alternative 1: Condensation at 1 bar and re-vaporization

- **Lower vaporization pressure allows higher super-heating**
- **Best results for a dual pressure vaporization**



Condensation/Re-Vaporization at 1 bar – Var. 1

- **Optimum for dual pressure vaporization at 0.55/0.3 bar**
- **Losses: 0.18 bar for HP and 0.08 bar for LP**
- **Net efficiency remains the same with 52.6 %**
- **Perspective of cost savings and efficiency improvement**



Condensation/Re-Vaporization at 1 bar - V

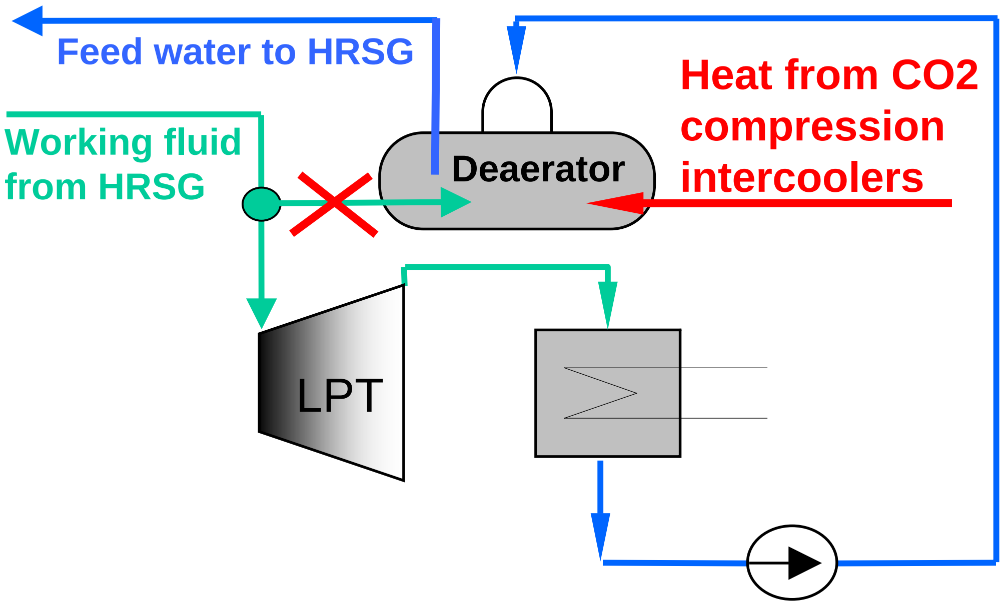
Alternative 2: **Condensation at 1 bar and heat use in a bottoming steam cycle**

- More flexibility
- Easier start-up
- Easier water make-up
- Use of intercooler heat from CO2 compression to 100 bar allows higher vaporization pressure of 0.7 bar

Use of heat of CO2 intercoolers

Graz Cycle is penalized with effort for CO2 compression to 100 bar for transport or further use

- CO2 compression needs several stages with intercooling
- Heat from intercoolers can be utilized in the process
- Water deaeration using intercooler heat instead extraction in front of LPT can increase cycle efficiency by + 0.8 %-points



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**
- **natural gas is supplied at 1.3 ¢/kWh_{th}**

Economical Analysis S-GC - II

COE ...

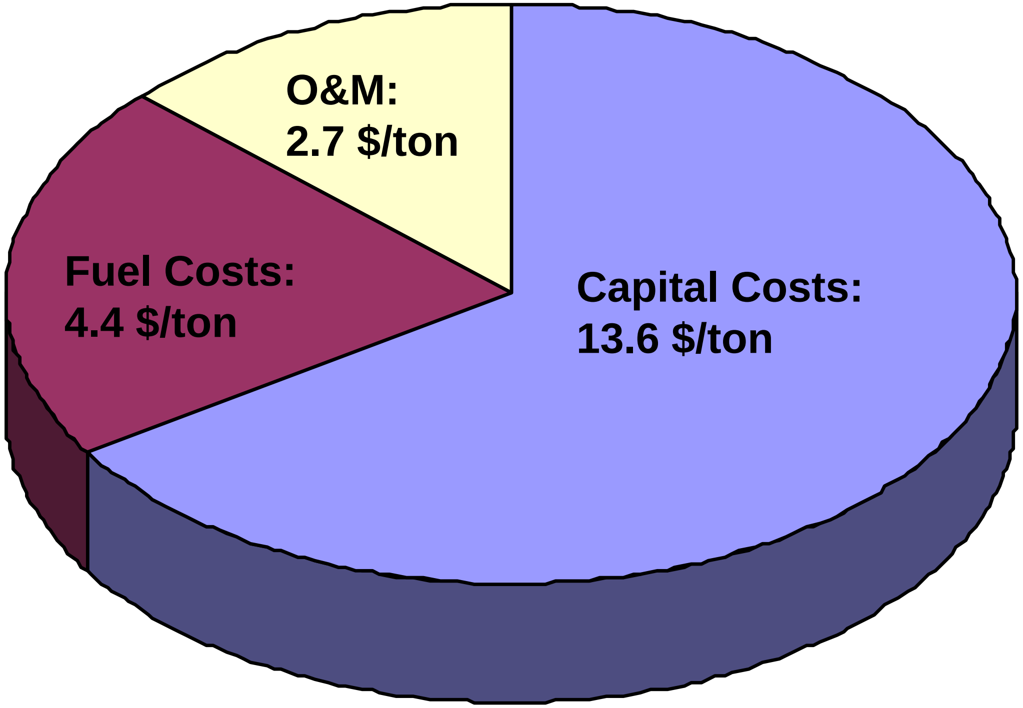
Cost of Electricity

	Reference plant [23]	S-G base version
Plant capital costs [\$/kW$_{el}$]	414	414
Addit. capital costs [\$/kW$_{el}$]		220.5
CO_2 emitted [kg/kWh$_{el}$]	0.37	0.0
Net plant efficiency [%]	56.2	52.6
COE for plant amort. [¢/kWh$_{el}$]	0.96	1.46
COE due to fuel [¢/kWh$_{el}$]	2.31	2.47
COE due to O&M [¢/kWh$_{el}$]	0.7	0.8
Total COE [¢/kWh$_{el}$]	3.97	4.74
Comparison		
Differential COE [¢/kWh$_{el}$]		0.77 (+ 19 %)
Mitigation costs [\$/ton CO_2 capt.]		20.7

Economical Analysis S-GC - III

Composition of Mitigation Costs

Total: 20.7 $/ton CO2



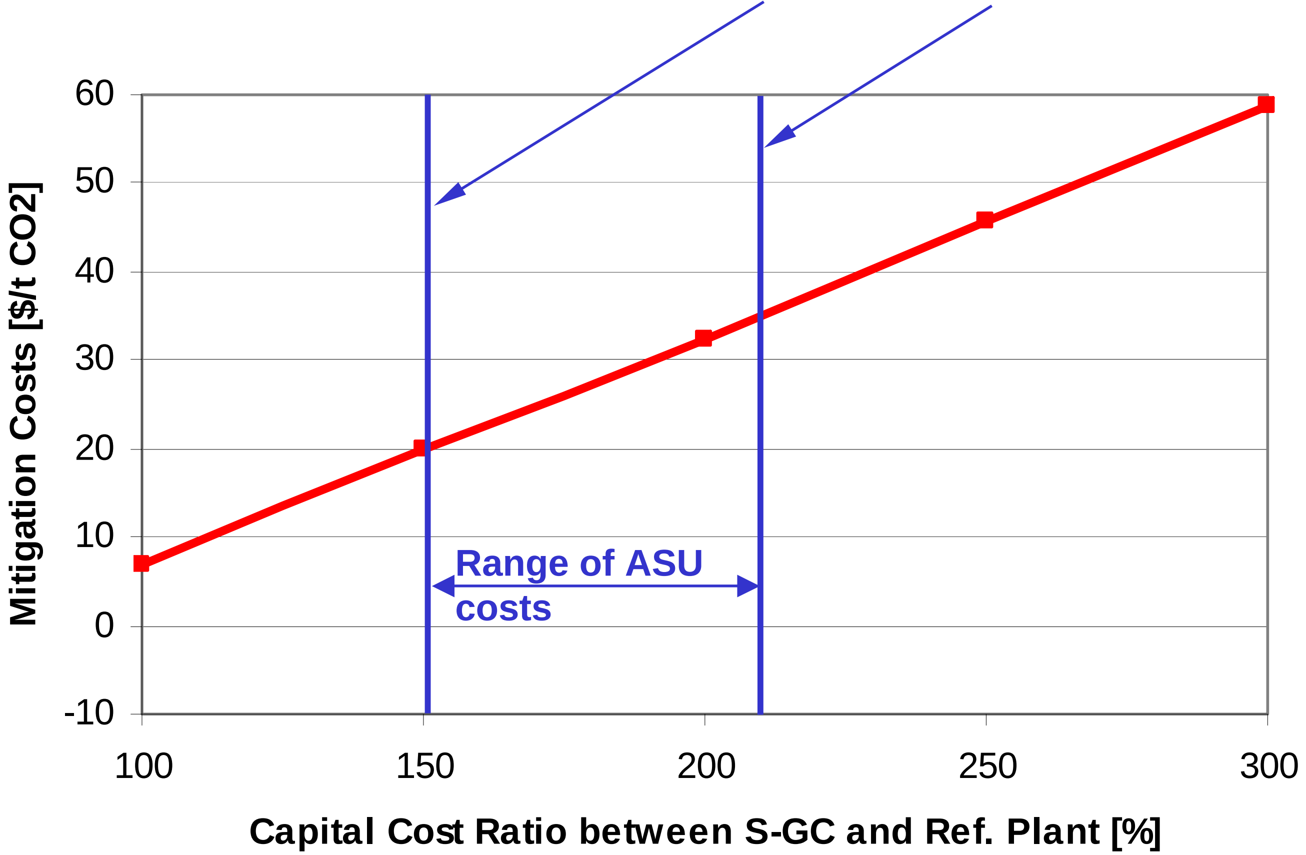
Decisive Influence of Capital Costs

Influence of Capital Costs S-GC

Large uncertainty in cost estimation:

53 % additional capital costs for air supply and CO2 compression [Göttlicher] is favorable

e.g.: ASU: cost estimates differ between 170 and 400 $/kW_el



Conclusions

- Based on the very favorable data of the High-Steam-Content S-Graz Cylce for syngas firing, it is evaluated for natural gas firing
- Thermodynamic layout with conservative component efficiencies results in a cycle efficiency of 64.6 % and a net efficiency of 52.6 % (O2 supply and CO2 compression)
- Possible modifications to improve cycle are investigated: a condenser/evaporator unit at 1 bar promises simpler arrangement and lower costs at the same efficiency
- Economic comparison with reference plant show the strong influence of capital costs on CO2 mitigation costs
- Mitigation costs of 20 $/ton CO2 are only possible for favorable additional investment costs