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Qualitative and Quantitative Comparison of Two Promising Oxy-Fuel Power Cycles for CO_2 Capture

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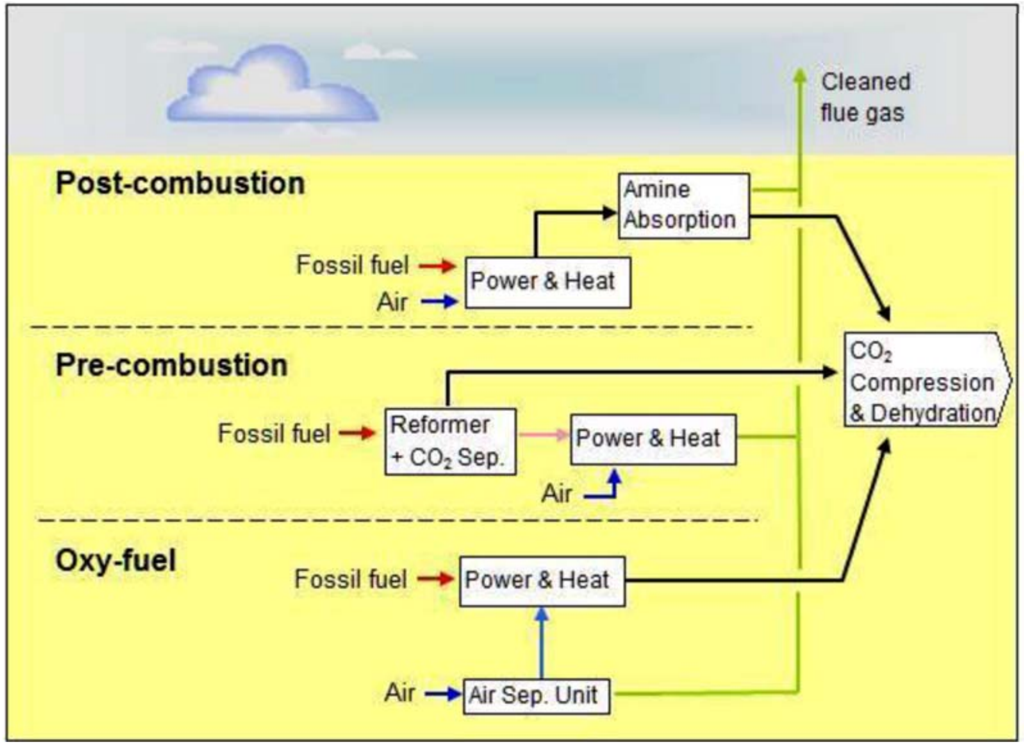
Background - I

- Worldwide ever rising emissions of greenhouse gases to atmosphere -> global warming and environmental change
- Kyoto Protocol demands the reduction of greenhouse gases, mainly CO2
- In EU: strong pressure on utilities and companies to reduce CO2 emissions
- Carbon capture and storage (CCS) as short and mid term solution

Background - II (CCS Technologies)

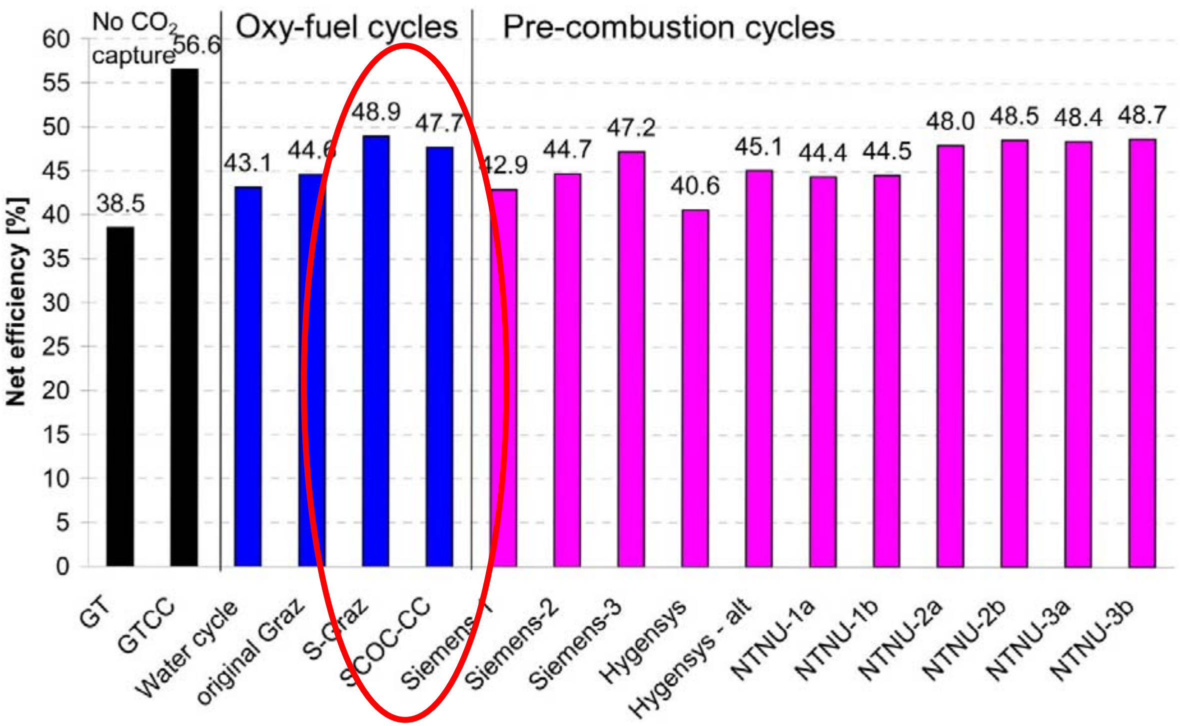
- **Post-combustion:** CO2-Capture from exhaust gas (chemical absorbtion, membranes, …)
- **Pre-combustion:** Decarbonization of fossil fuel to produce pure hydrogen for power cycle (e.g. steam reforming of methane, …)
- **Oxy-fuel power generation:** Internal combustion with pure oxygen and CO2/H2O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



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

Background - III

- **EU project ENCAP (Enhanced CO_2 Capture): benchmarking of a pre-combustion and oxy-fuel cycles**
- **Among oxy-fuel cycles: highest efficiencies for S-Graz Cycle and Semi-Closed Oxy-Fuel Combustion Combined Cycle (SCOC-CC)**
- **ENCAP efficiency for S-Graz Cycle is by 3.6 %-points lower than own results (ASME 2006)**



Background - III

- EU project ENCAP (Enhanced CO_2 Capture):
  benchmarking of a pre-combustion and oxy-fuel cycles
- Among oxy-fuel cycles:
  highest efficiencies for S-Graz Cycle and
  Semi-Closed Oxy-Fuel Combustion Combined Cycle (SCOC-CC)
- ENCAP efficiency for S-Graz Cycle is by 3.6 %-points lower than own results (ASME 2006)
- Feasibility study of key components:
  - SCOC-CC plant was evaluated technically favorable
  - 3 components of S-Graz Cycle were ranked as critical.

Objective

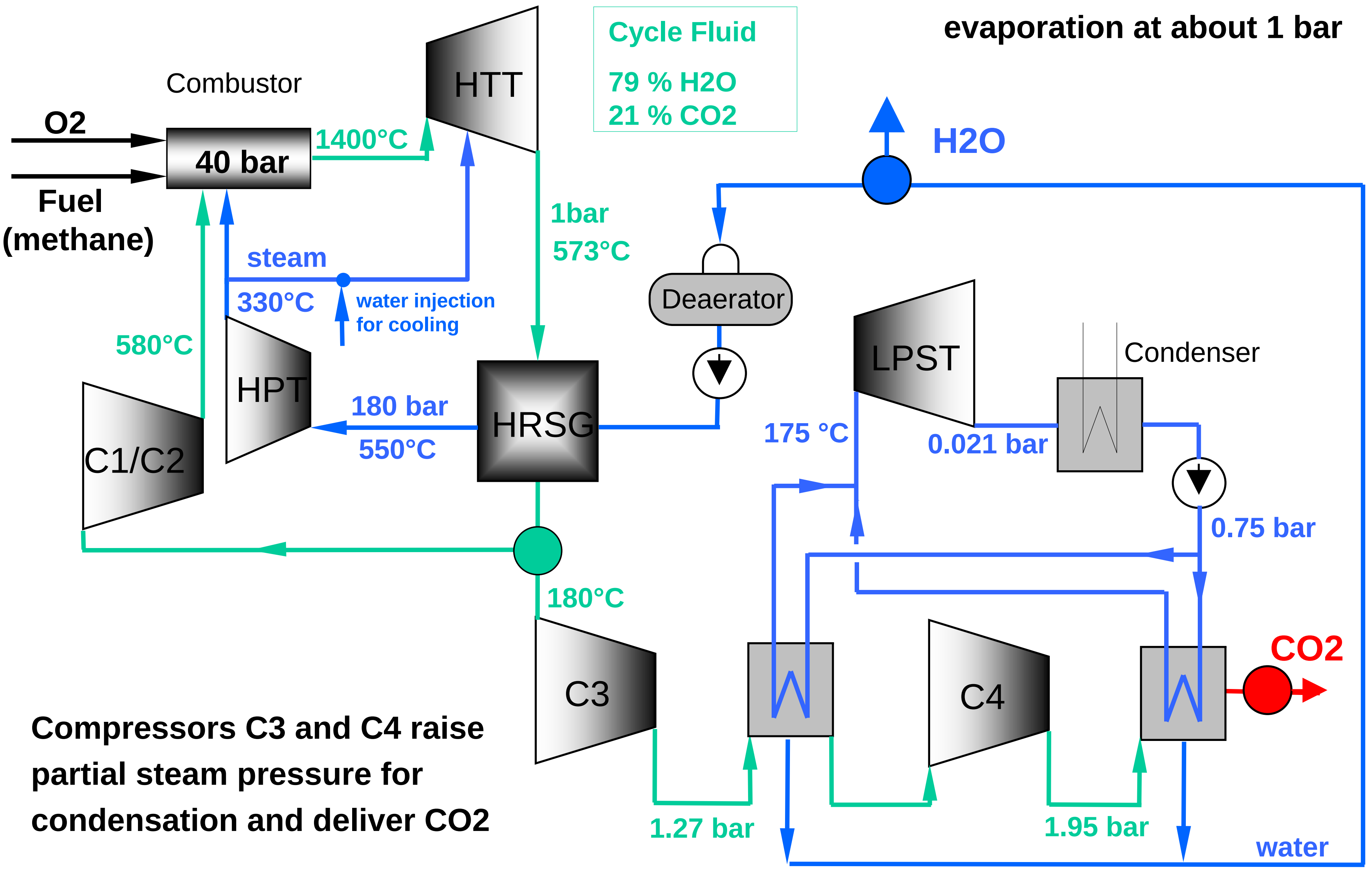
- Differences in efficiency to ENCAP and
- New scheme of the Graz Cycle (ASME 2006) not considered in the study

Thus comparison between both plants is repeated in this work

- Thermodynamic comparison
- Layout and discussion of the main components for a 400 MW power plant.

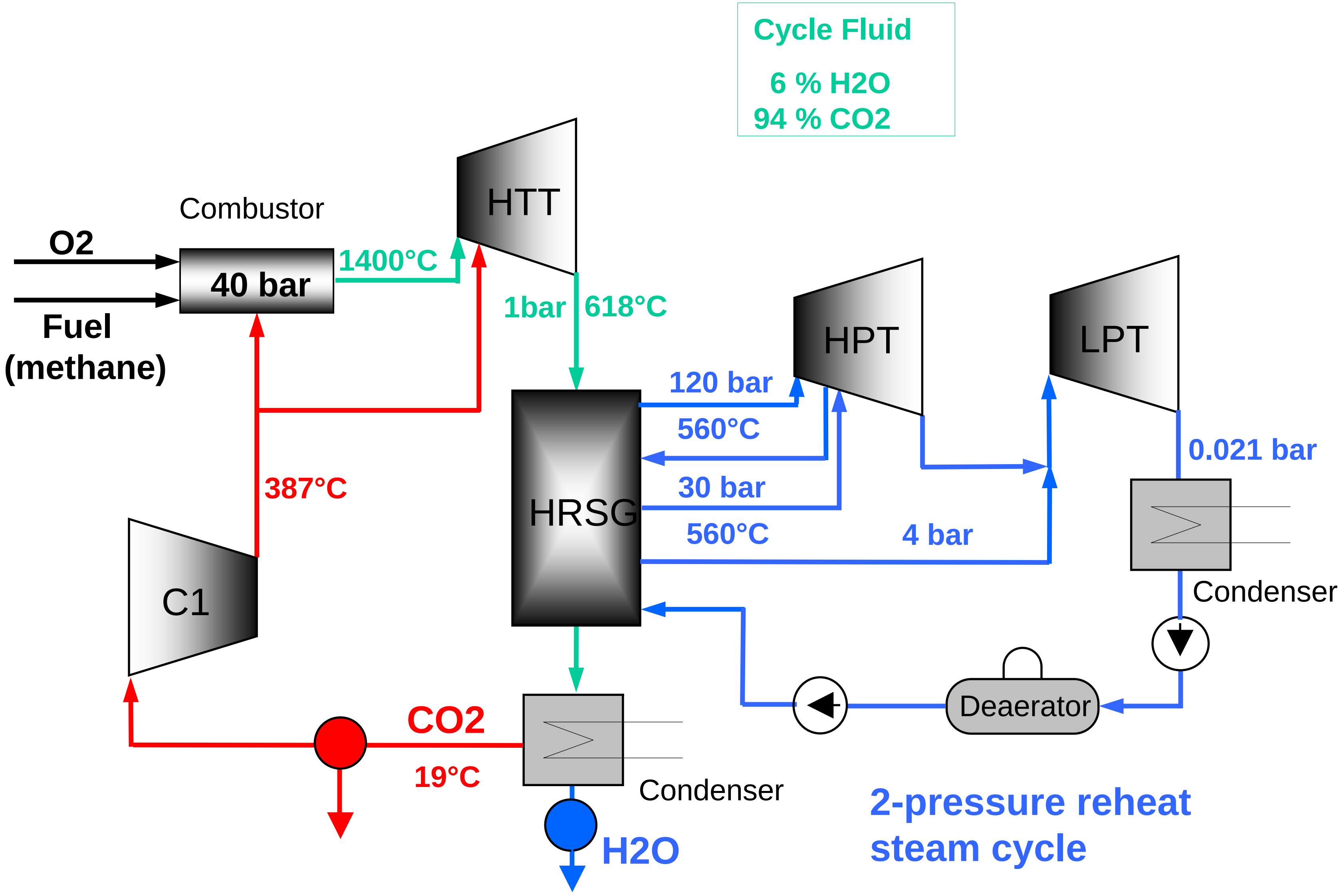
Graz Cycle (ASME 2006)

Condensation and evaporation at about 1 bar



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

SCOC-CC Scheme



Cooling mass flow for HTT - I

Efficiency strongly depends on cooling mass flow demand!

Heat transferred to blades from hot working fluid =

heating of cooling mass flow from T_c to T_m-ΔT_d

Influence of fluid properties

$$\frac{\dot m_c}{\dot m} = \overline{\frac{c_{p,g}}{c_{p,c}}}\,\frac{\bar T - T_m}{T_m - \Delta T_d - T_c}\left(\bar f\, n_{st}\right)\overline{St}\,\frac{1}{\sin \bar\beta}$$

Ratio of specific heats of main flow and cooling flow

Number of stages

Stanton number = dimensionless heat transfer coefficient

Cooling mass flow for HTT - II

SCOC-CC:
double number of cooled stages

$$\frac{\dot m_c}{\dot m} = \frac{\overline{c_{p,g}}}{\overline{c_{p,c}}} \, \frac{\bar T - T_m}{T_m - \Delta T_d - T_c} \left(\bar f \, n_{st}\right) \overline{St} \, \frac{1}{\overline{\sin \beta}}$$

Graz Cycle:
20 % less mass due to steam as cooling medium

Stanton number $\mathrm{St} = \dfrac{\alpha}{\rho \, c_{p,g} \, w}$

$$\mathrm{St} = 0.5 \, \mathrm{Re}^{-0.37} \, \mathrm{Pr}^{-2/3}$$

Small advantages for Graz Cycle conditions, but similar values for both cycles used

Power Balance for 400 MW net power

	Graz Cycle	SCOC-CC
HTT power [MW]	624	557
Cooling mass flow [%]	13.7	30.5
Total turbine power [MW]	743	747
Total compression power [MW]	241	235
Net shaft power [MW]	**502**	**508**
Total heat input [MW]	753	805
Thermal cycle efficiency [%]	**66.5**	**63.2**
Electrical cycle efficiency [%]	**64.7**	**61.5**
Net efficiency (- O2/CO2) [%]	**53.1**	**49.8**

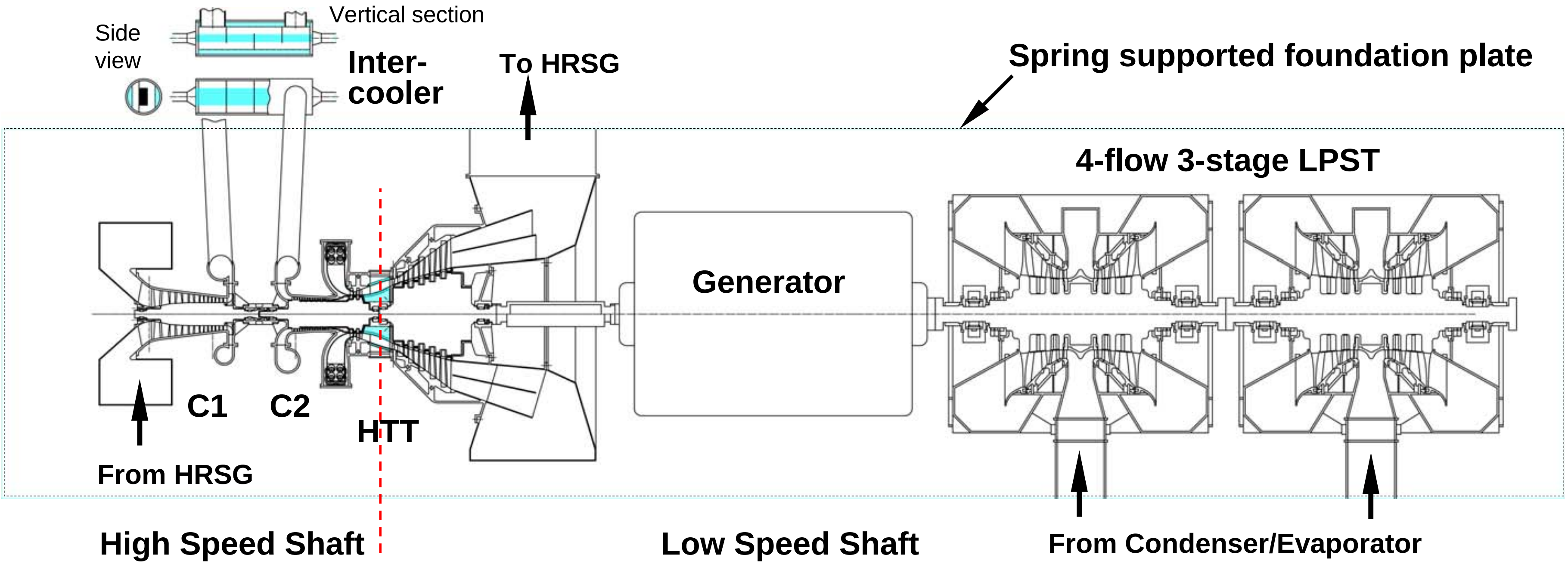
Differences to ENCAP

	Graz Cycle	SCOC-CC
Net efficiency [%]	**53.1**	**49.8**
Net efficiency ENCAP [%]	**48.9**	**47.7**

- **Higher inlet temperature of oxygen and fuel of 150°C**
- **Oxygen is provided with 99 % purity at an energy requirement of 0.25 kWh/kg compared to 95 % purity at 0.30 kWh/kg**
- **Probably different assumptions of component efficiencies and losses**
- **ENCAP: difference of 1.2 %-points**
  this study: difference of 3.3 %-points (1.8 %-points due to higher cooling flow demand of the SCOC-CC HTT)

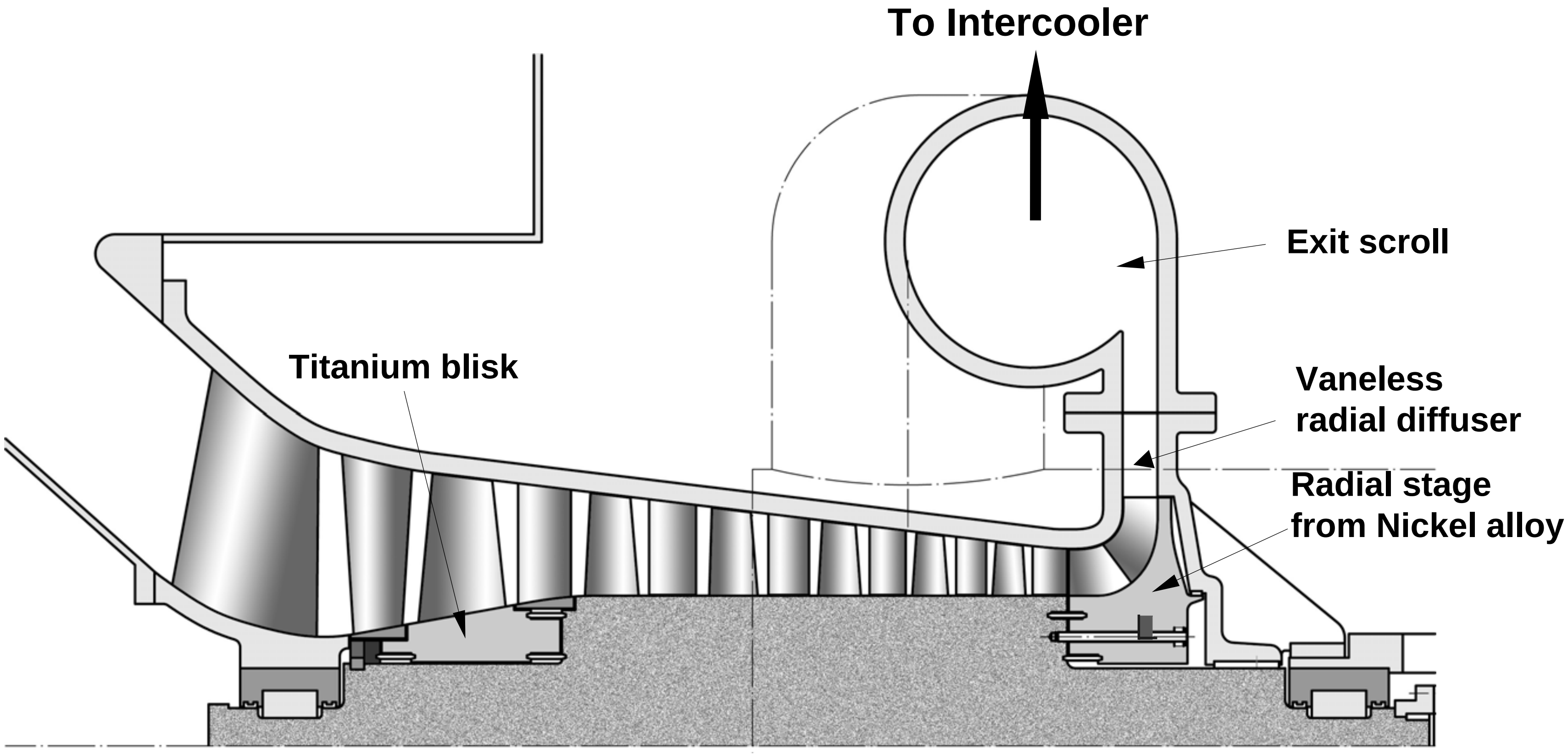
Graz Cycle Turbo Shaft Configuration

- Main gas turbine components on two shafts for 400 MW net output
- 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



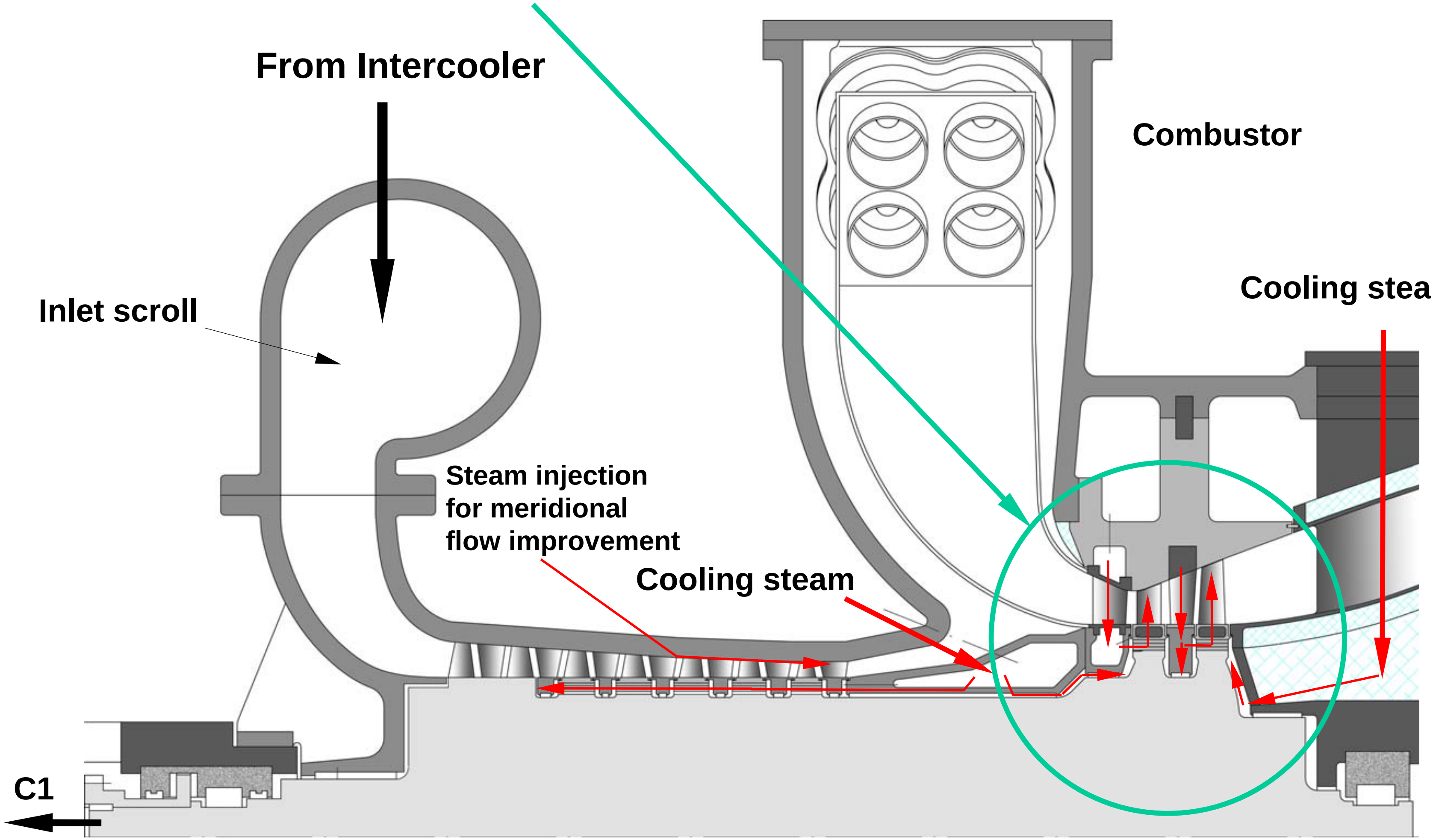
Graz Cycle Compressor C1 Design

- High enthalpy increase of working fluid (3/4 steam) -> high speed
- Maximum allowable inlet tip Mach number of 1.35 -> 8500 rpm
- 7 axial and 1 radial stage
- Uncooled drum rotor of ferritic steel (high temperature 9 %-chrome steel)
- First stage titanium blisk and Nimonic radial last stage



Graz Cycle Compressor C2 + 2-stage HTTC

- **Compression 13 -> 40 bar, 380° -> 580°C , 7 stages, 8500 rpm**
- **Cooled drum rotor of ferritic steel with counterflow of cooling steam to avoid creep**
- **HTTC: high enthalpy drop in 2 cooled stages**



SCOC-CC Compressor C1 Design

- Lower sonic velocity of CO2 (-33 %), thus tip Mach number limit of 1.35 leads to speed of 3000 rpm
- One-shaft design with HTT driving C1 compressor as well as the generator (similar to ENCAP)
- 19 stages are suggested <-> Graz Cycle: 13 axial and one radial stage

\+ Exit temperature is below 400°C (<-> 580°C for C2), thus no rotor cooling is necessary

\+ Much smaller centrifugal load: smaller stresses and cheaper material

\- Long and slender rotor may result in rotordynamics problems.

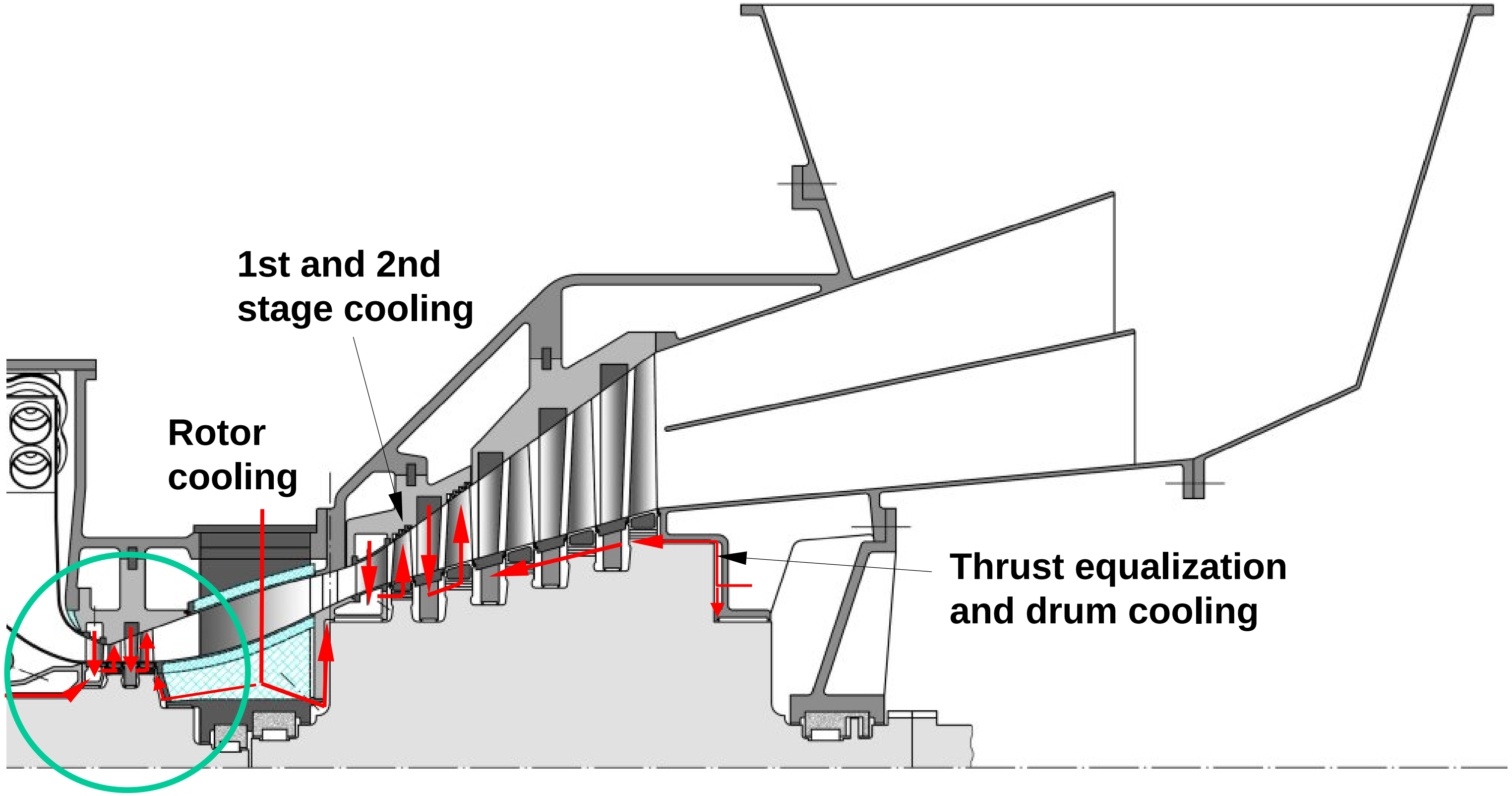
\- Smaller flow efficiency expected due to endwall boundary layer growth towards the last stages, whereas Graz Cycle intercooler enables a compact flow profile at C2 inlet

\+ Intercooler with its associated pressure losses not necessary

\- Inlet working fluid with steam content at saturation: risk of formation of water droplets at inlet which can cause blade erosion.

Graz Cycle HTT (50 Hz)

- 2 stage HTTC running at 8500 rpm
- 5 stages HTTP with strong change of inner radius
- 2+2 stages to be cooled
- Last blade length of 750 mm at 1300 mm inner radius
- Necessary thrust equalization and drum surface cooling on the exhaust side by steam



1st and 2nd stage cooling

Rotor cooling

Thrust equalization and drum cooling

SCOC-CC HTT Design

- Compressor speed -> One-shaft design at 3000 rpm
- Total enthalpy drop: 830 kJ/kg (<-> 1560 kJ/kg for Graz Cycle)
- 8 stages <-> Graz Cycle: 7
- − Lower speed leads to 5 cooled stages in hot section (<-> 2 !!)
- − Cooling flow demand: 30.5 % (<-> 13.7%) due to more cooled stages, lower heat capacity of CO2 and higher cooling medium temperature
- + Much smaller centrifugal load in hot section: smaller stresses
- − Cooling is done with nearly pure CO_2 passing the combustors -> danger of accumulation of fine particles from combustion and thus risk of clogging the cooling flow passages and film cooling holes

  In contrast Graz Cycle uses pure steam

Economic Analysis - I

Investment costs

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

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

Comparison of Component Size

400 MW net power output

	Convent. CC plant	**Graz Cycle**	**SCOC-CC**
turbine of "gas turbine"/ HTT	**667 MW**	**623 MW**	**557 MW**
compressor of "gas turbine"/C1+C2+C3+C4	**400 MW**	**241 MW**	**235 MW**
steam turbines/ HPT+LSPT	**133 MW**	**120 MW**	**190 MW**
HRSG	**380 MW**	**360 MW**	**461 MW**
Generator	**400 MW**	**487 MW**	**495 MW**

Conventional plant vs. Graz Cycle/SCOC-CC:

- **total turbine power of same size**
- **compressor power smaller**
- **generator power higher**

Economical Analysis - II

COE ...

Cost of Electricity

	Reference plant	GC plant	SCOC-CC plant
Plant capital costs [\$/kW$_{el}$]	414	414	414
Addit. capital costs [\$/kW$_{el}$]	-	288	300
CO_2 emitted [kg/kWh$_{el}$]	0.342	0.0	0.0
Net plant efficiency [%]	58.0	53.1	49.8
COE f. plant amort. [¢/kWh$_{el}$]	0.58	0.99	1.01
COE due to fuel [¢/kWh$_{el}$]	2.24	2.45	2.61
COE due to O&M [¢/kWh$_{el}$]	0.7	0.8	0.8
Total COE [¢/kWh$_{el}$]	3.52	4.24	4.42
Comparison			
Differential COE [¢/kWh$_{el}$]		0.72	0.90
Mitigation costs [\$/ton CO_2]		21.0	26.2

Conclusions

- **ENCAP study of oxy-fuel power cycles:**
  two very promising variants Graz Cycle and SCOC-CC
  Graz Cycle: high efficiency, SCOC-CC: relatively low complexity
- **This work: thermodynamic and design study of both cycles**
- **SCOC-CC: lower efficiency because of very high HTT cooling demand due to less favorable properties of CO_2.**
- **Both cycles need new designs for HTT and compressors**
  SCOC-CC: low sonic velocity of CO_2 leads to one shaft of 3000 rpm -> more stages for compressor and HTT
  Lower operating temperature of SCOC-CC compressor
- **All turbomachinery of both cycles is regarded as feasible and of similar complexity.**
- **Mitigation costs vary between 20 - 30 $/ton CO2 depending on additional investment costs (ASU), 5 $/ton lower for Graz Cycle**
- **So Graz Cycle is a very efficient and feasible solution for a future CCS scheme**