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THERMODYNAMIC AND ECONOMIC EVALUATION OF AN IGCC PLANT BASED ON THE GRAZ CYCLE FOR CO2 CAPTURE

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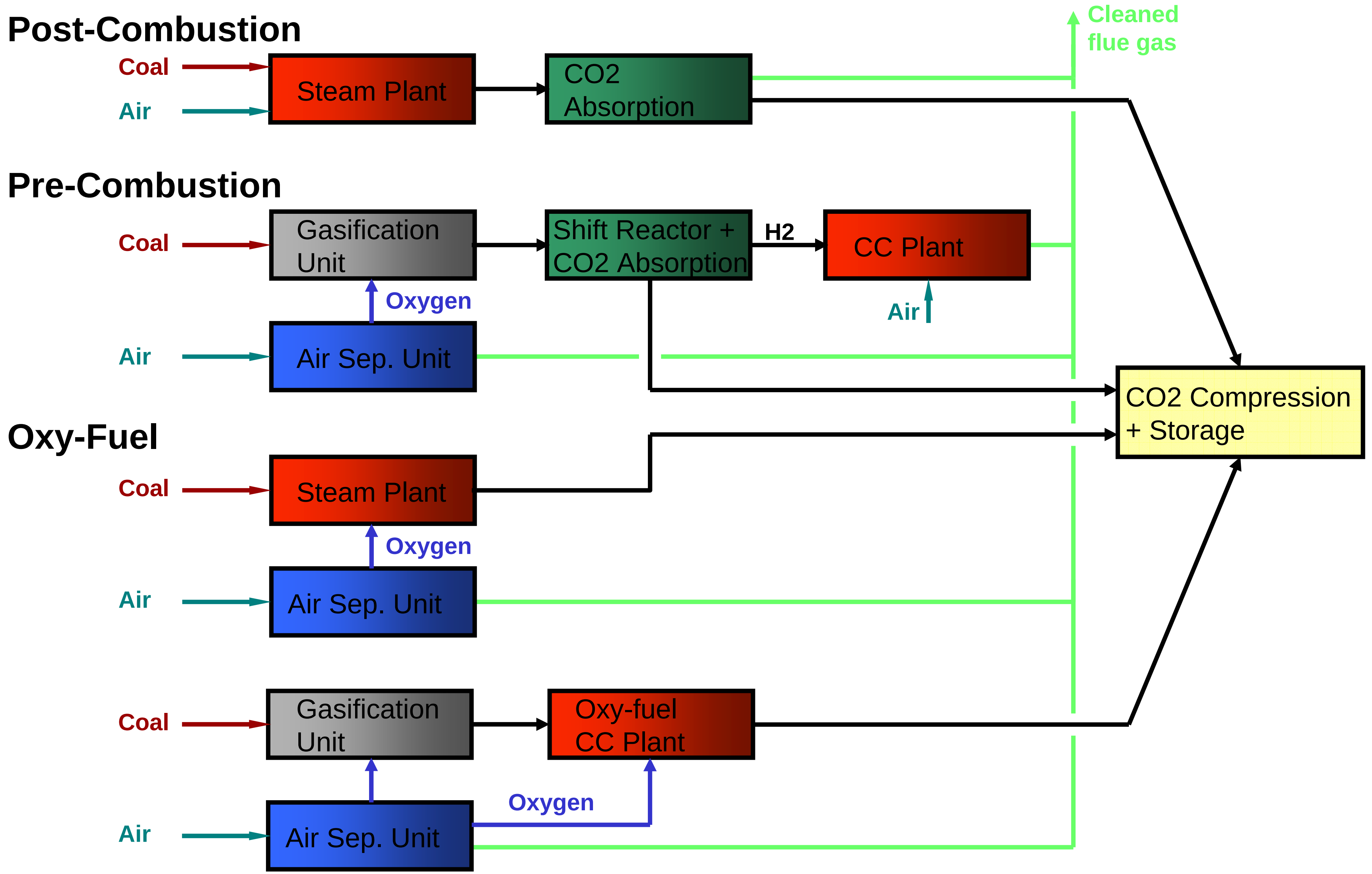
Background

- Worldwide ever-rising emissions of greenhouse gases to atmosphere -> global warming and environmental changes
- World's thirst for energy is still growing (IEA World Energy Outlook 2009: +40 % till 2030)
- Fossil fuels: dominant source of energy in the near future
- Coal: vast reserves, relatively even distribution worldwide, but high carbon content
- Therefore innovative coal technologies are indispensable for climate protection -> carbon capture and storage (CCS)

CO2 Separation Technologies



Objective

- Combined Cycle plants promise higher efficiencies due to their higher working temperatures
- Shift reaction + pre-combustion sequestration + CC with H2

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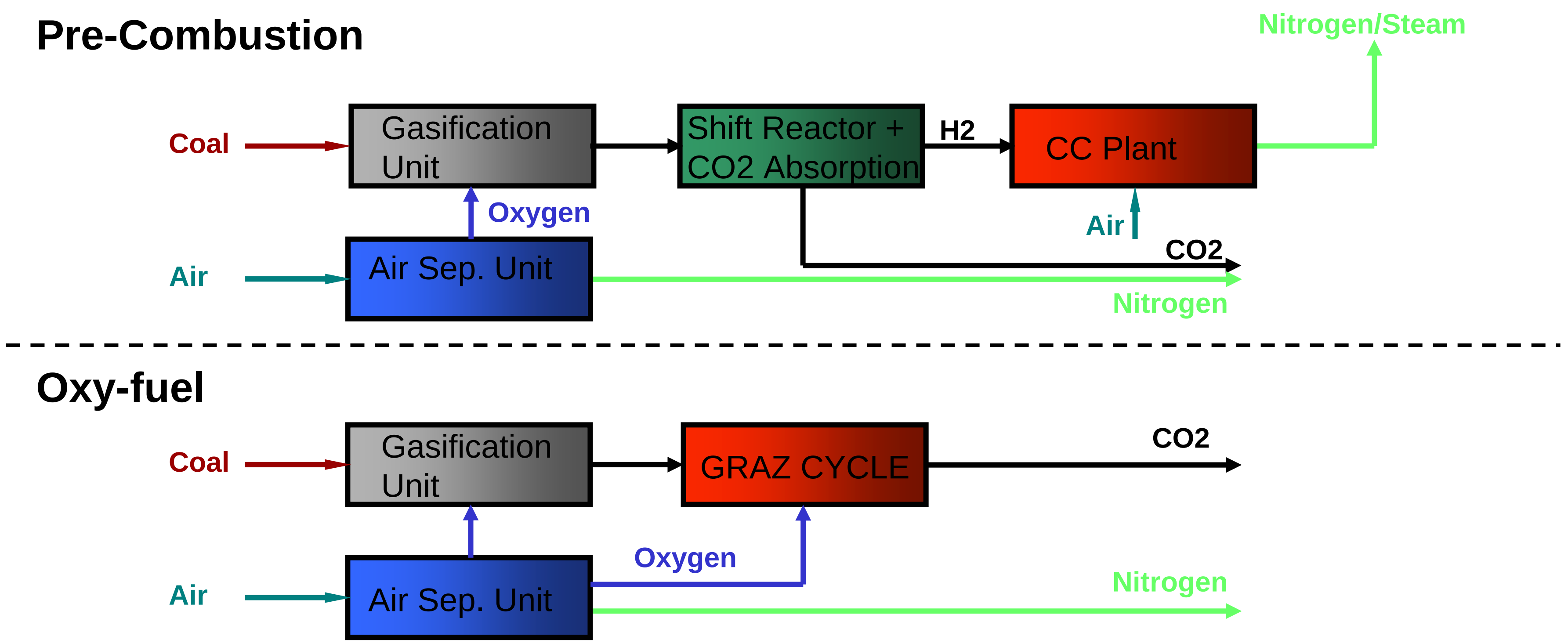
Oxyfuel firing of syngas in a Graz Cycle Plant



Graz Cycle

- **Oxy-fuel cycle with internal combustion with pure oxygen leading to a working fluid consisting mainly of CO2 and H2O**
- **CO2 can be easily separated by condensation**

\+ **Flexibility regarding fuel: natural gas, syngas from coal, biomass or refinery residue gasification, high CO2 content natural gas**

\+ **Very low NOx generation (fuel bound N2), captured together with CO2**

\- **New equipment required, based on modern gas turbine technology**

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

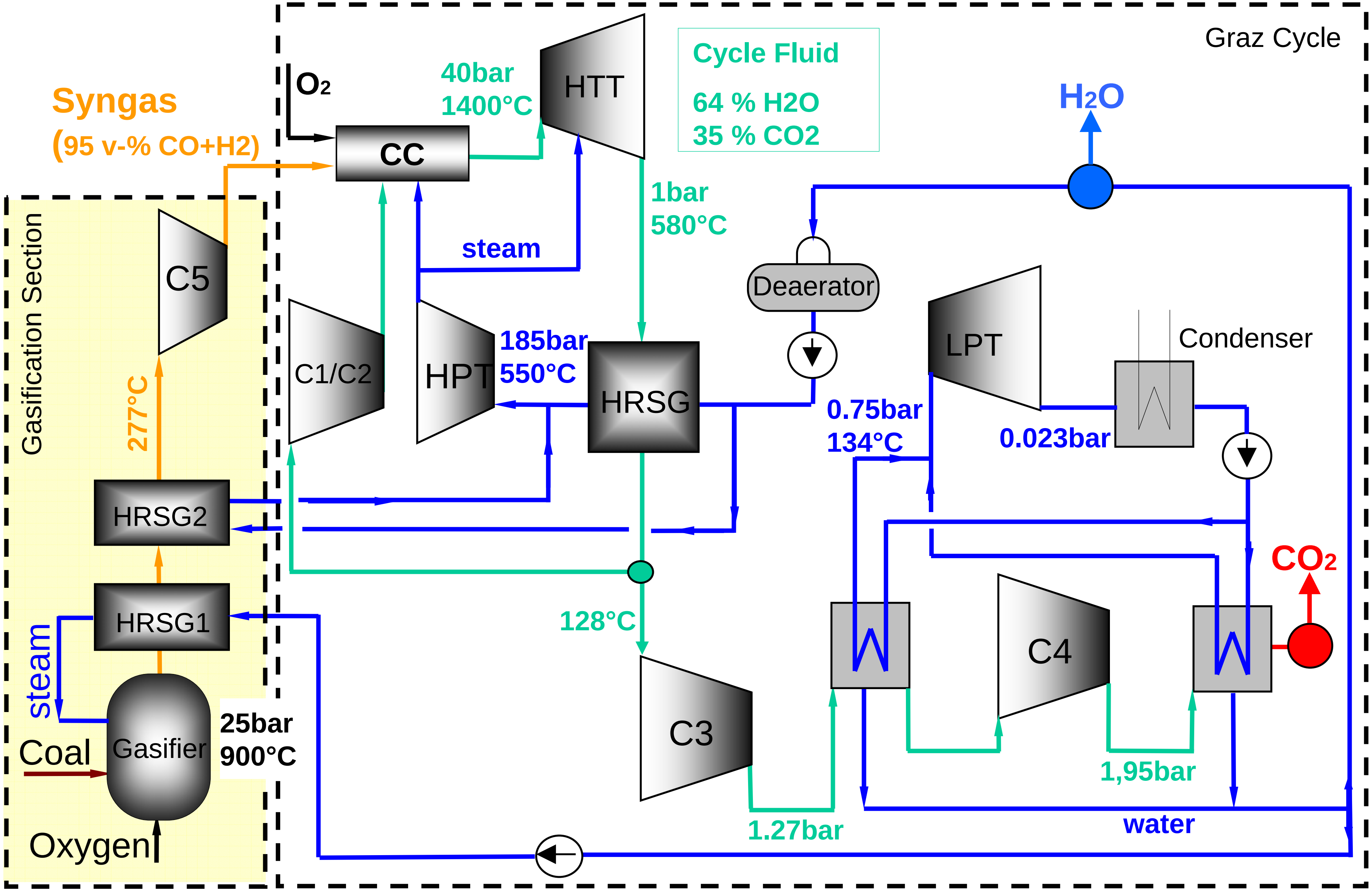
\+ **High Efficiency due to the unusual working fluid**

Coal Gasification

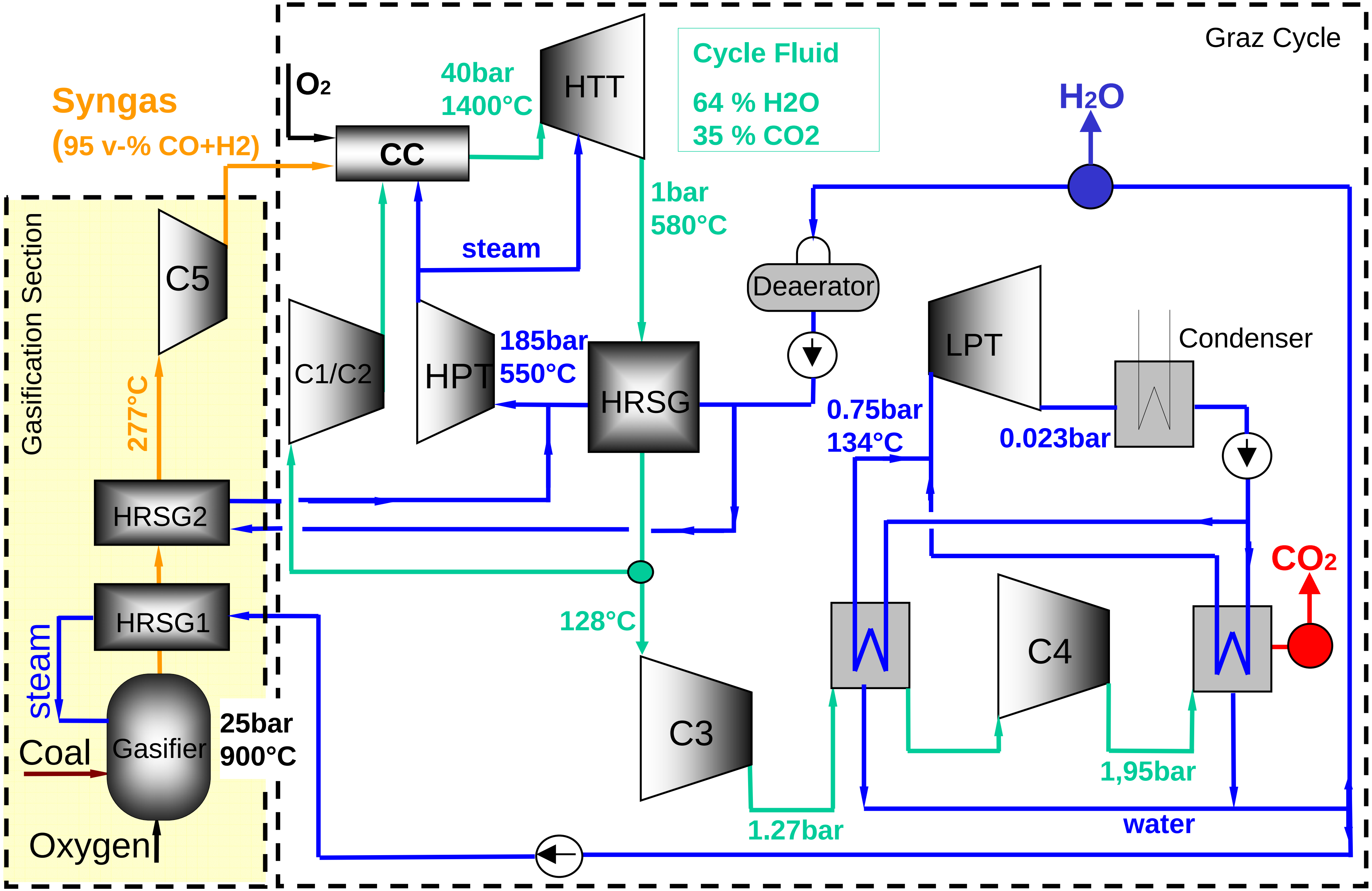
Simplified explanation:

Coal (C), H_2O, O_2 + heat → H_2, CO (CO_2)

Graz Cycle Scheme (based on ASME 2006)



Graz Cycle Scheme (based on ASME 2006)



Main Assumptions – Graz Cycle

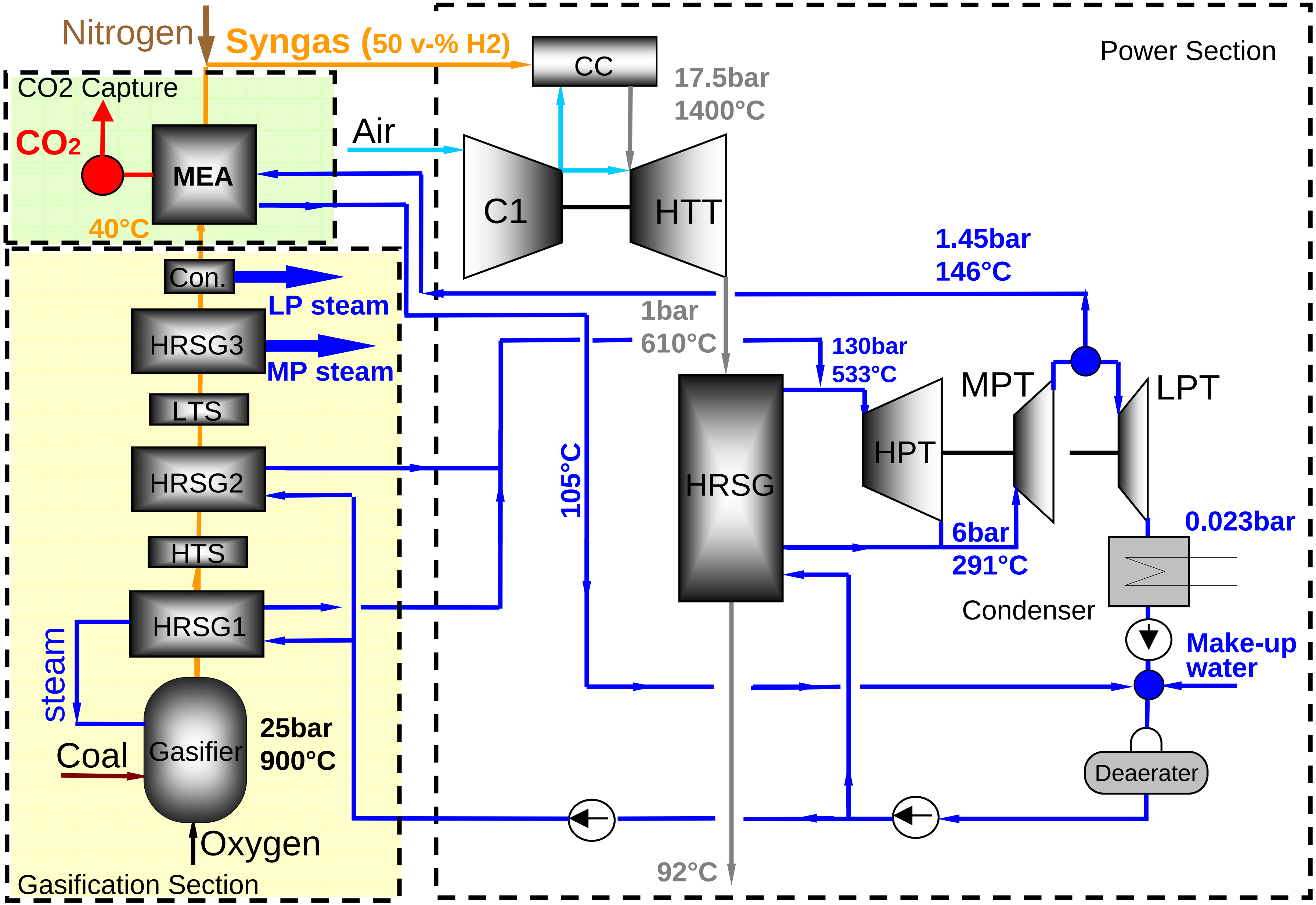
- Coal composition: 73.2% C, 4.9% H, 1.6% N, 6.6% O, 4.1% water and 9.6 % ash
  LHV: 29.342 MJ/kg.
- Generic gasifier with relatively low gasifier pressure and temperature (25 bar/900°C) to increase refractory life and reduce costs
- Thermal heat input to gasifier is adjusted to achieve a net power cycle output of 400 MW
- Dry coal feed
- Sulfur reactions are not considered, but losses for sulfur handling
- Oxygen for gasifier and combustion produced by stand-alone cryogenic air separation unit at a purity of 99 % (slightly higher power consumption, but less non-condensable gases)

Alternative: Shift Reaction

After gasification:

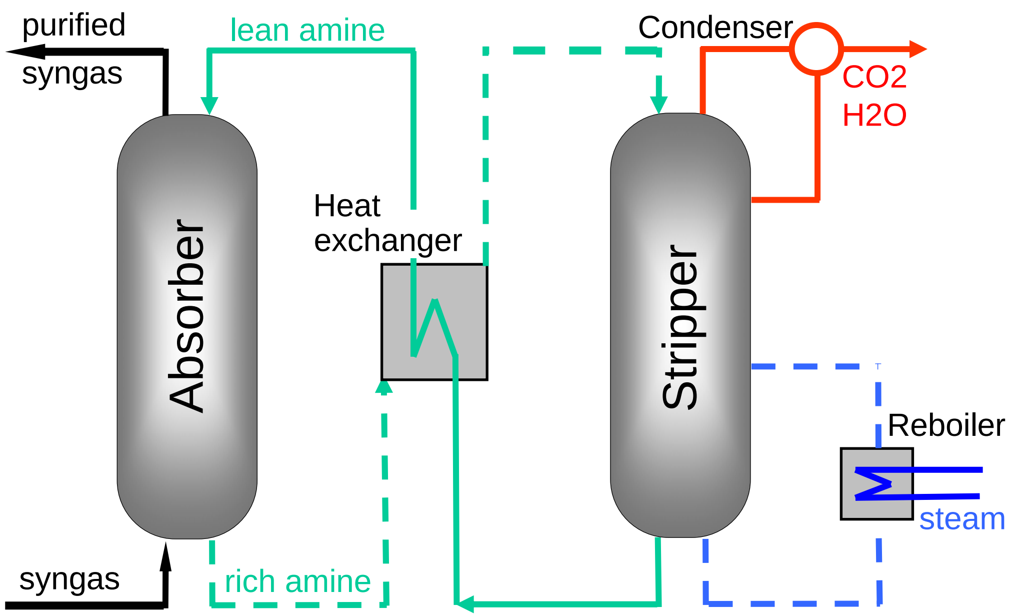
$$CO + H_2O \longrightarrow CO_2 + H_2 + heat$$

“Conventional” IGCC-CCS plant

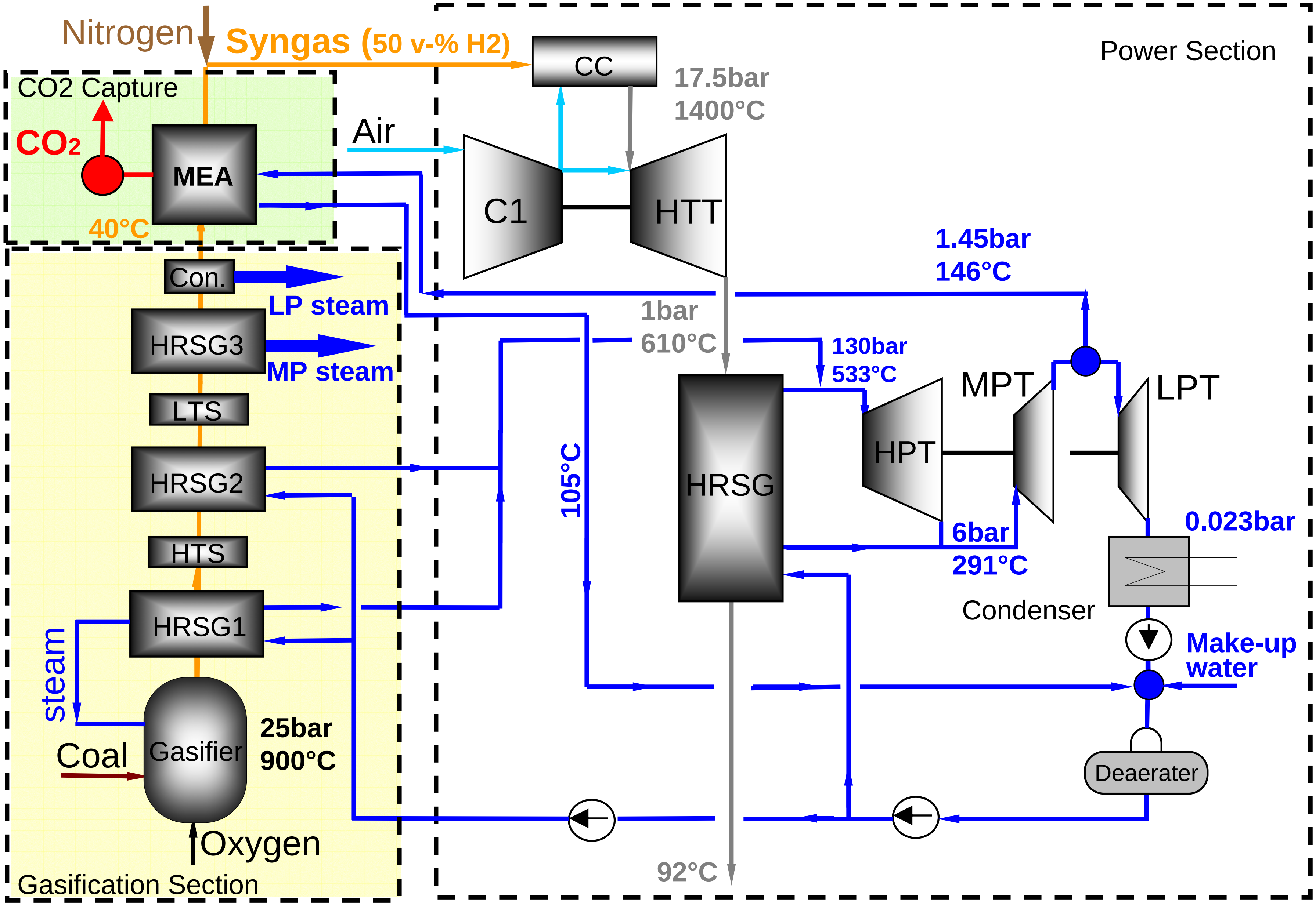


Chemical Absorption (MEA)

- Absorber: CO_2 reacts exothermically with MEA to form a water soluble salt
- Stripper: reaction is reversed by addition of heat, CO_2 leaves through the top
- Regeneration heat: the main loss of the chemical absorption system
  Value of 3.8 MJ/kg CO_2 from literature (323 MJ/s to capture 85 kg/s CO_2)
- Heat provided by steam cycle: Steam of 1.45 bar taken in front of LP turbine, fed to reboiler (condensation) and is returned to feed water of steam cycle
- Loss in LP turbine power of 73 MW or efficiency drop of 7 %-points
- Removal rate of about 95 %, leading to capture of 90 % of the carbon
- Working pressure: 20 bar, thus smaller size and higher CO_2 capture capability

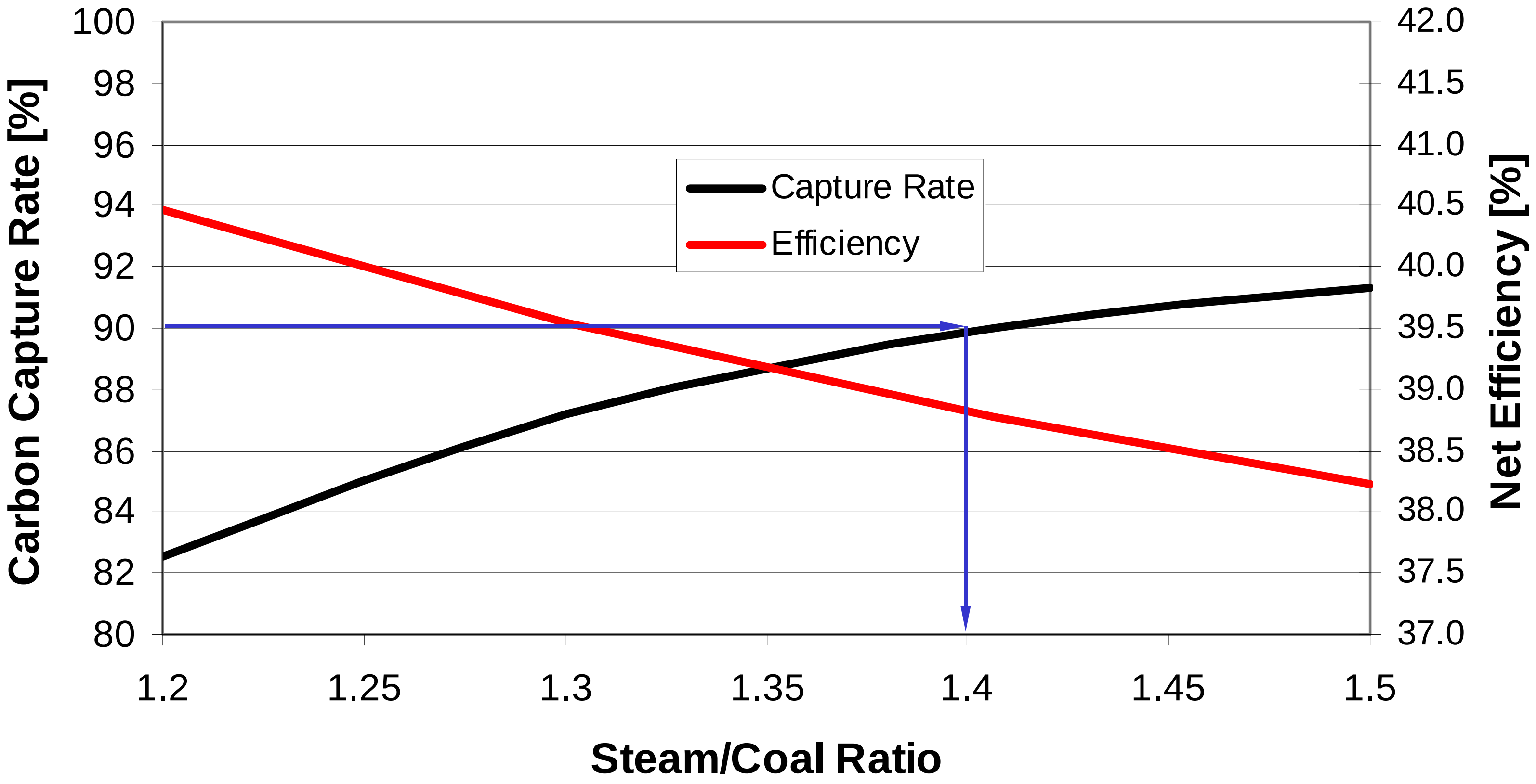


"Conventional" IGCC-CCS plant



Steam to Coal Ratio

- Gasifier steam-to-coal ratio of 1.4 found by an imposed carbon capture rate of 90 % (0.3 for the Graz Cycle)
- Reduction to 1.2, only 82.5 % of the carbon can be retained, but net plant efficiency would increase by 1.7 %-points.



Thermodynamic Simulation

- **Comparison of both CCS plants with an IGCC plant w/o carbon capture**
- **Commercial software IPSEpro by SIMTECH Simulation Technology with user-defined fluid properties and components (etc. gasifier)**
- **Oxygen: 900 kJ/kg (0.25 kWh/kg) at a purity of 99% and at 2.38 bar**
- **CO_2 is compressed from different delivery pressures to 100 bar for transport and storage**
- **Auxiliary losses, as gasifier and combustion chamber heat loss, coal treatment, operation of cooling water pumps or the syngas cleaning, are considered with 3 % of the total heat input**

Turbomachinery Comparison

	Reference IGCC Plant	IGCC - CCS	Graz Cycle plant
Gas turbine expander/ HTT [MW]	556	643	669
HP steam turbine [MW]	70	85	63
MP steam turbine [MW]	33	43	
LP steam turbine [MW]	60	13	68
Total turbine power [MW]	**719**	**784**	**800**
GT compressor / C1+C2 [MW]	262	262.5	208.4
Nitrogen compressor [MW]		39	
Syngas compressor [MW]			11.2
C3+C4 compressor [MW]			25.3
Total compression power [MW]	**264**	**304**	**252**
Net shaft power [MW]	**455**	**478.0**	**548.2**

Power Balance

	Reference IGCC Plant	IGCC - CCS	Graz Cycle plant
Net shaft power [MW]	455	478	548.2
Total heat input [MW]	788	1033	889
Thermal cycle efficiency [%]	**57.47**	**46.32**	**61.72**
Electrical power output [MW] considering. mechanical, electrical & auxiliary loss	420.7	438.0	509.6
Electrical cycle efficiency [%]	**53.41**	**42.40**	**57.34**
Oxygen generation/compr. [MW]	20.7	30.8	84.5
Efficiency w.oxygen supply [%]	**50.79**	**39.41**	**47.84**
CO2 compression (100 bar) [MW]	-	7.2	25.2
Net power output [MW]	**400.0**	**400.0**	**400.0**
Net efficiency [%]	**50.79**	**38.71**	**45.01**

Economic Analysis - Assumptions

Reference plant: „conventional“ IGCC plant of 50.8 % efficiency

Investment costs

- PhD thesis Rodewald (2008): IGCC-CCS: 2328 €/kW_{el}
- IPCC report (2005): IGCC investment costs increase by 30 % due to CCS
- same specific investment costs for both CCS technologies assumed

Additional assumptions

- yearly operating hours: 7800 hrs/yr
- interest rate of 8 % and a depreciation period of 15 years, leading to a capital charge rate of 12%/yr
- coal is supplied at 1.1 ¢/kWh_{th}
- O&M: 10 % of yearly capital costs
- transport and storage are not considered

Economic Balance

	Reference IGCC Plant	IGCC - CCS	Graz Cycle plant
Plant capital costs [€/kW$_{el}$]	1629	2328	2328
CO2 emitted [kg/kWh$_{el}$]	0.649	0.085	0.0
Net plant efficiency [%]	50.79	38.71	45.01
COE for plant amortisat. [¢/kWh$_{el}$]	2.51	3.58	3.58
COE due to fuel [¢/kWh$_{el}$]	2.17	2.84	2.44
COE due to O&M [¢/kWh$_{el}$]	0.25	0.36	0.36
Total COE [¢/kWh$_{el}$]	**4.92**	**6.78**	**6.38**
Comparison			
Differential COE [¢/kWh$_{el}$]		**1.86 (+38%)**	**1.46 (+30%)**
Mitigation costs [€/ton CO2 av.]		**33.0**	**22.5**

Summary

- Two coal fired power plants with carbon capture technologies:
  - IGCC plant with pre-combustion separation and firing of the hydrogen-rich syngas in a combined cycle plant
  - Graz Cycle with oxygen firing of syngas
- High energy penalties for the CO2 scrubber of the IGCC plant and for the oxygen supply of the Graz Cycle plant
- Graz Cycle plant shows an efficiency of 5.8 %-points lower, IGCC-CCS plant of 12.1 %-points lower than a reference plant without CO2 capture.
- Graz Cycle plant has a remarkably higher shaft power
- CO2 mitigation costs of Graz Cycle of 22.5 €/ton CO2 are lower by a third than of IGCC-CCS
- Oxygen firing of syngas in a Graz Cycle plant is a very efficient and feasible solution for coal usage in a future CCS scheme