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Design Optimisation of the Graz Cycle Prototype Plant

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Outline

- Motivation
- Oxy-Fuel Combustion
- Graz Cycle
- Efficiency and Parameter Study
- Layout of turbomachinery components
- Economical Aspects
- Conclusion

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 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

TUG

- 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

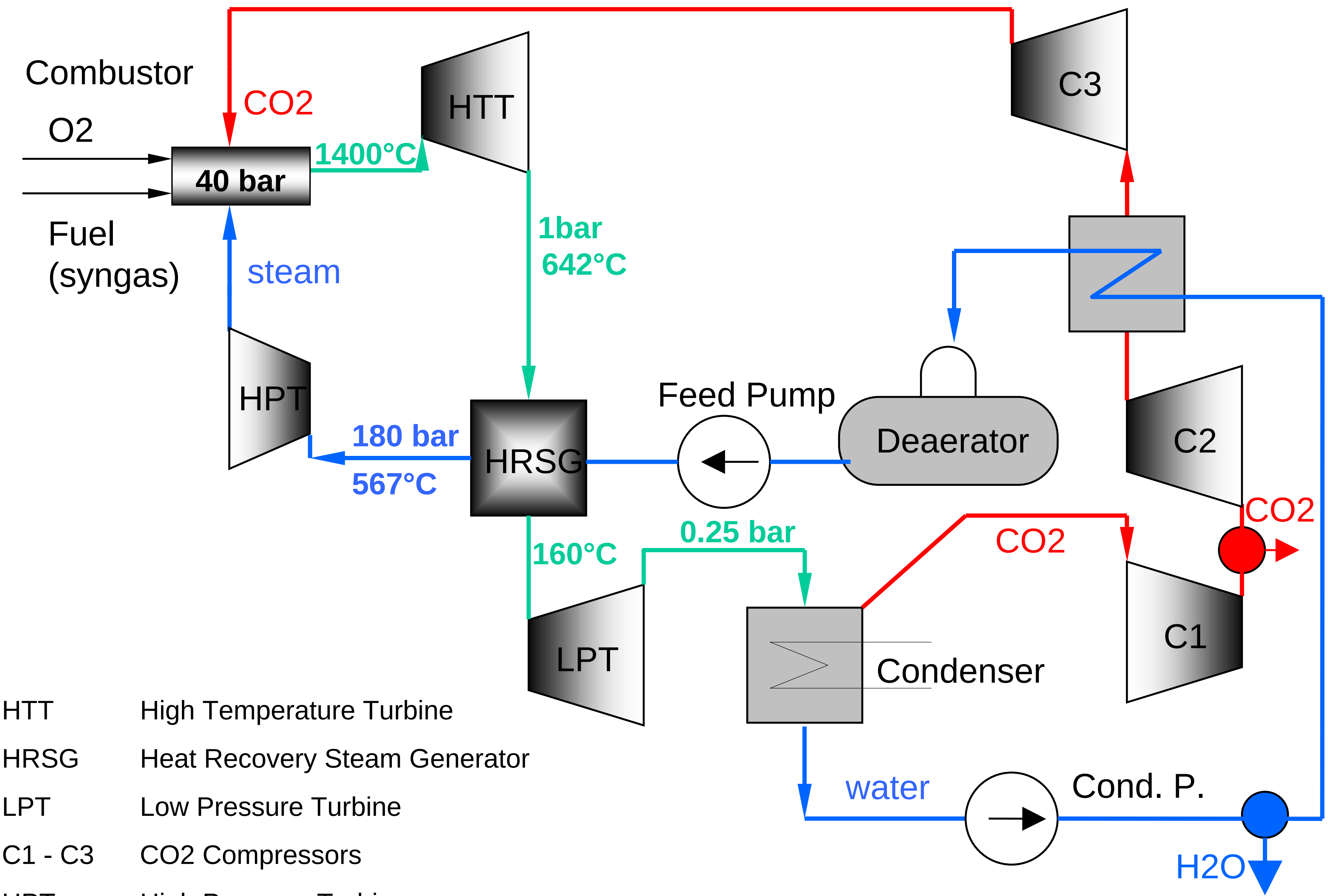
\- Additional high costs of oxygen production

+ 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**
  - **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)**
  - **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 (syngas, gas from gasification processes, ...)**
- **2002: conceptual layout of turbomachinery relevant components of prototype Graz Cycle power plant**

Cycle Scheme



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

Main Cycle Data

- Fuel: syngas from coal gasification:
  50 % H_2, 40 % CO, 10 % CO_2
- Complete stoichiometric combustion
- Combustion pressure in the order of the maximum pressure found in aircraft engines: 40 bar
- Turbine inlet temperature in the range of high power stationary gas turbines: 1400° C
- Turbine isentropic efficiency: 92 % (HPT 90 %)
- Compressor isentropic efficiency: 90 %
- HP turbine: 180 bar / 567° C
- Condenser: 0.25 bar / 15° C at exit
- HRSG: hot inlet temperature: 642° C
  ΔT_{cold}: 18° C, ΔT_{hot}: 75° C
- CO_2 provided at 1bar

Balance of Graz Cycle

Turbines				
Name	HPT	HTT	LPT	Total
Power [MW]	9.3	91	10.7	111

Compressors and Pumps						
Name	C1	C2	C3	Cond.P.	Feed P.	Total
Power [MW]	5.5	4	8.9	0.01	0.4	18.8

Total heat input: 143.4 MW

η **= (111-18.8)/143.4**

Thermal efficiency: 64.3 %

Additional Losses and Expenses

- Including generator / mechanical losses: η = 98 %

  Net cycle efficiency: 63.0 %

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

  Efficiency: 57.5 %

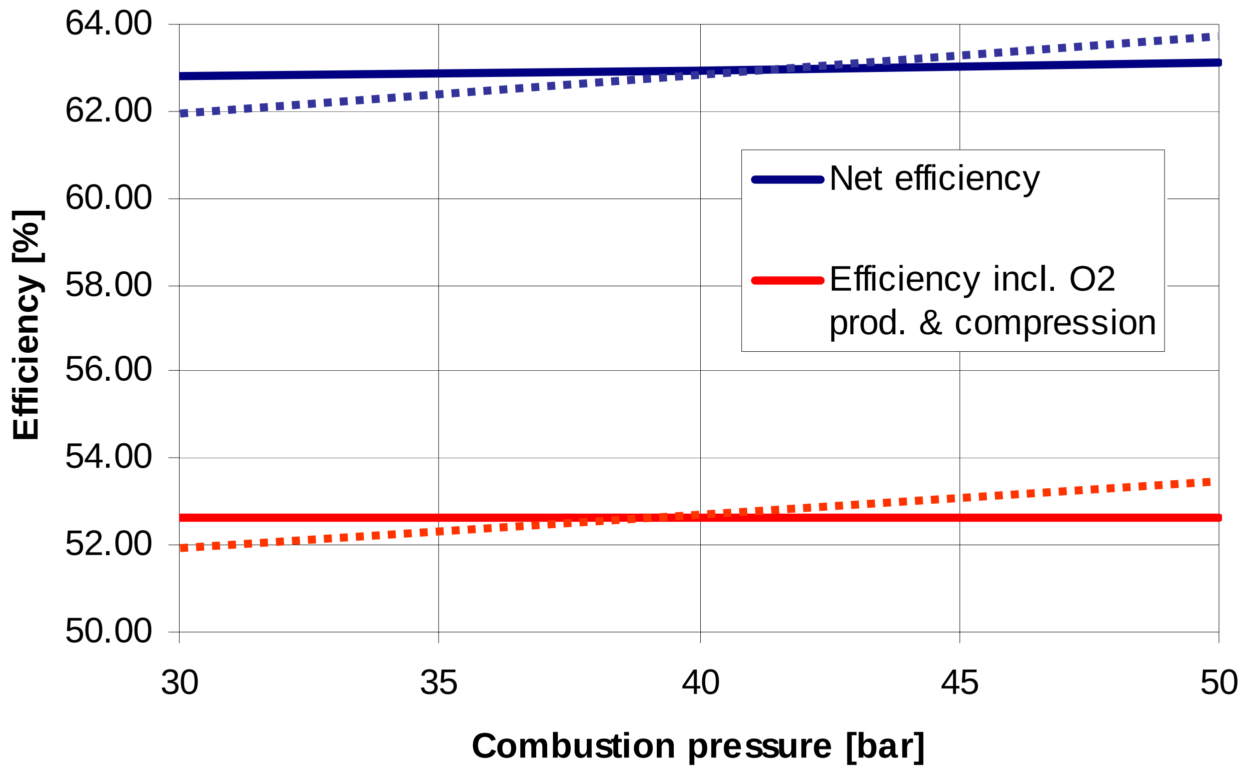
- Oxygen compression (1 to 40 bar, inter-cooled, η = 85 %): 0.107 kWh/kg (3.4 MW)

  Efficiency: 55.0 %

- Compression of separated CO2 for liquefaction (1 to 100 bar, inter-cooled, η = 85 %): 0.03 kWh/kg (3.3 MW)

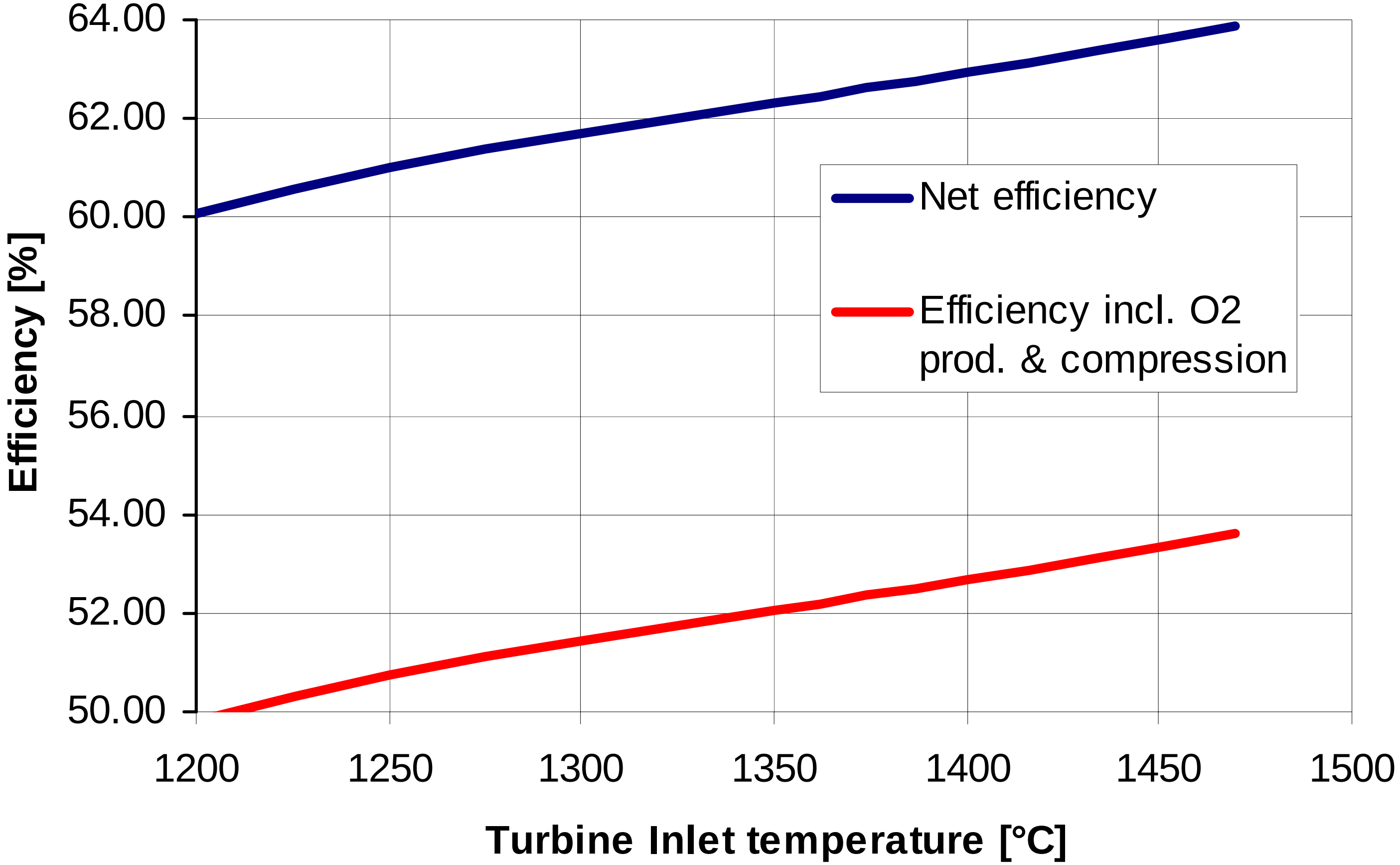
  Efficiency: 52.7 %

Efficiency vs. Combustion Pressure



- **Nearly constant efficiency if inlet temperature of HPT is varied (from 680° C to 500° C), especially if O2 compression is considered**
- **2 % (1.5 %) - points increase in the range of 30 - 50 bar, if HPT inlet temperature is fixed at 567° C**

Efficiency vs. HTT Inlet Temperature



- **Strongest influence on cycle efficiency**
- **Variation of 4 % -points for a TIT range of 1200° C - 1470° C**

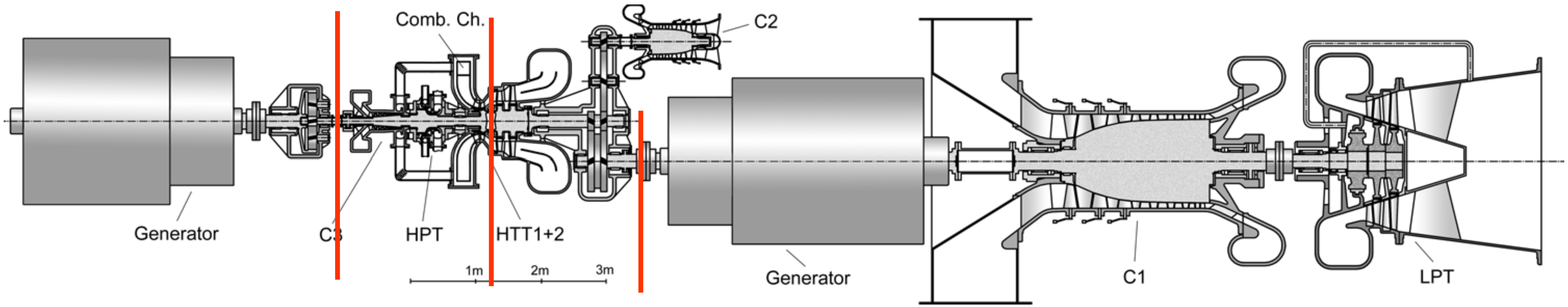
Lay-out of Components

- **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 1/4 H_2O and 3/4 CO_2
    cooling with steam
- **Non-critical components**
  - **Low pressure turbine LPT**
  - **High pressure turbine HPT**
  - **CO_2 compressors**
  - **Heat exchangers**

General Arrangement of Turbomachines

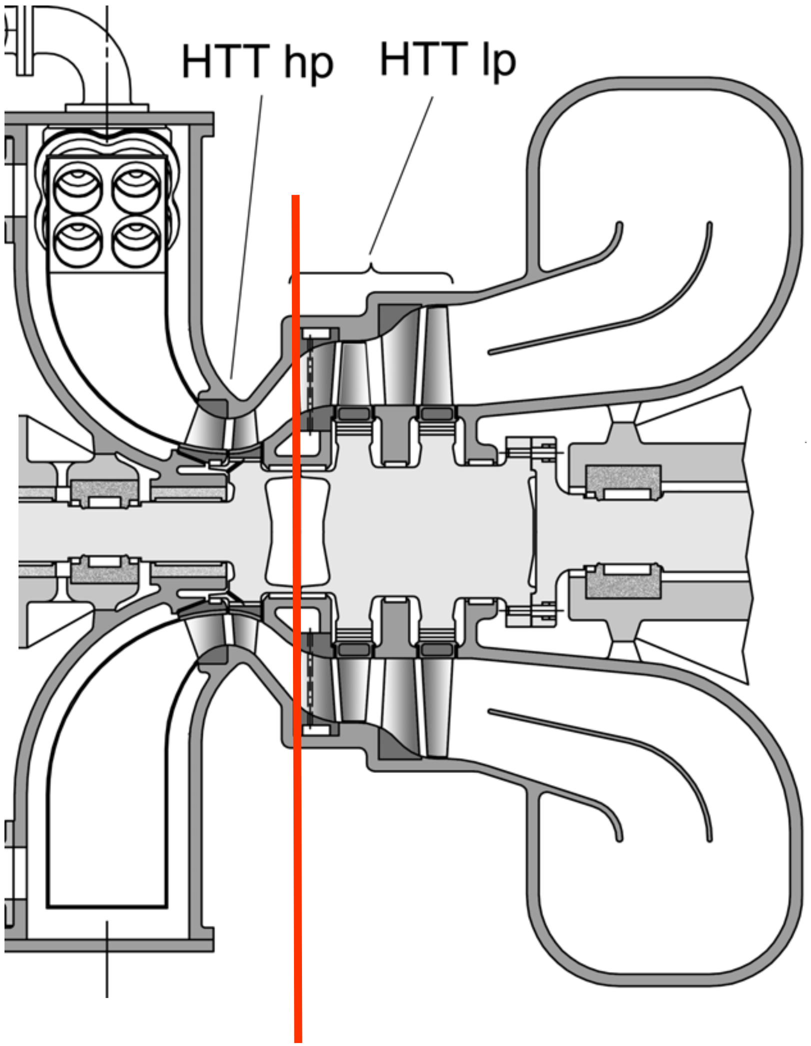
- First design deliberations show reasonable dimensions of the turbomachinery for a 92 MW plant
- Turbo set with 3 different speeds
- 20 000 rpm: HTT first stage + HPT + C3 compressor
- 12 000 rpm: HTT second/third stage + C2 compressor
- 3 000 rpm: LPT + C1 compressor

20 000 rpm



12 000 rpm **3 000 rpm**

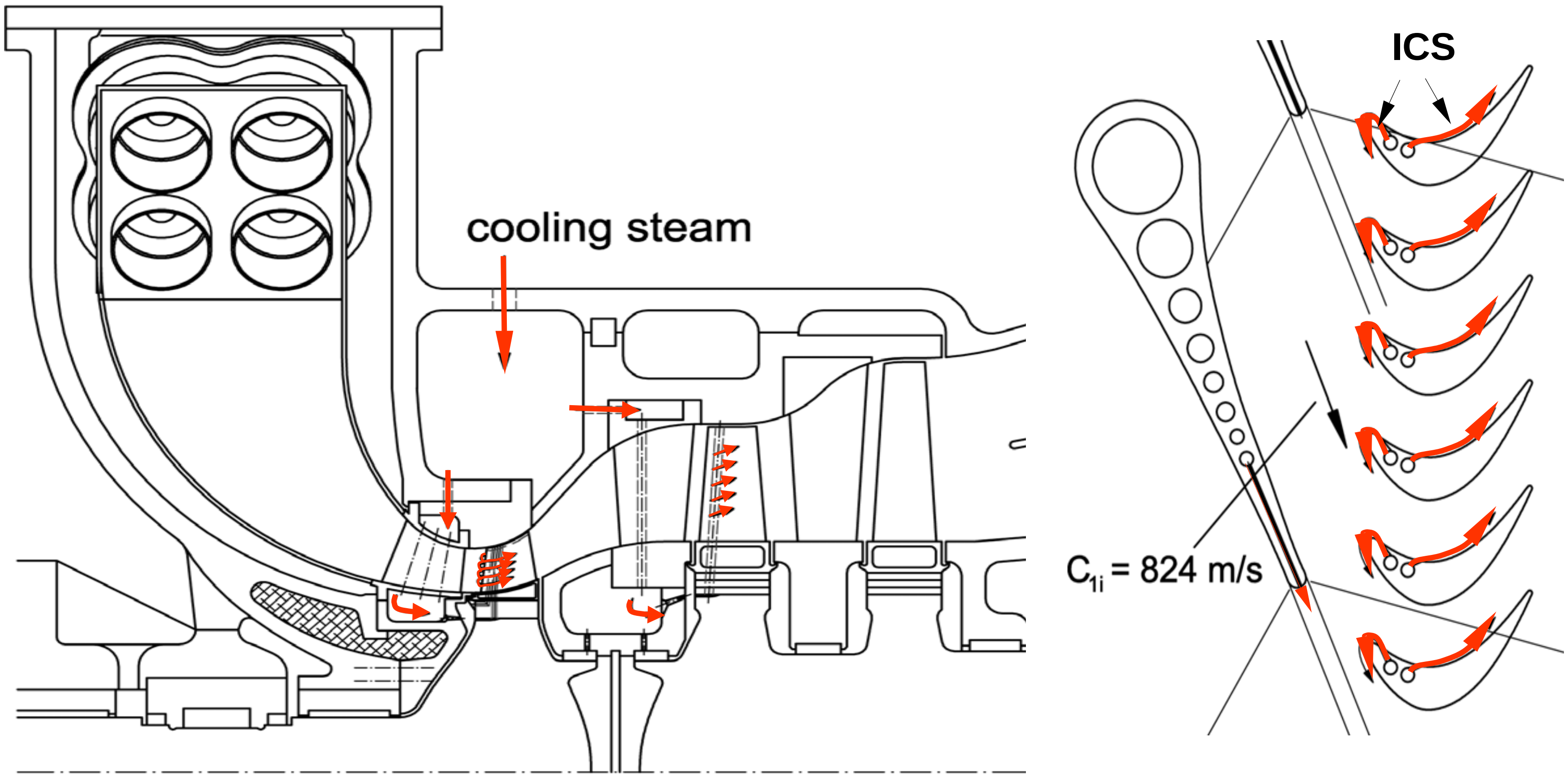
High Temperature Turbine HTT



20 000 rpm 12 000 rpm

- Pressure drop: 40 bar - 1 bar
- Comparison of R, cp between CO_2/H_2O mix and air-turbine exhaust gas :
  -11 % R, +23 % cp => same enthalpy drop
  higher temperatures for same pressure ratio -> higher cooling effort!
  smaller volumes for same flow conditions (p, T)
- High rotational speeds to keep number of stages low
- Split into two overhang shafts with 20 000 and 12 000 rpm to obtain optimal speeds

HTT Cooling

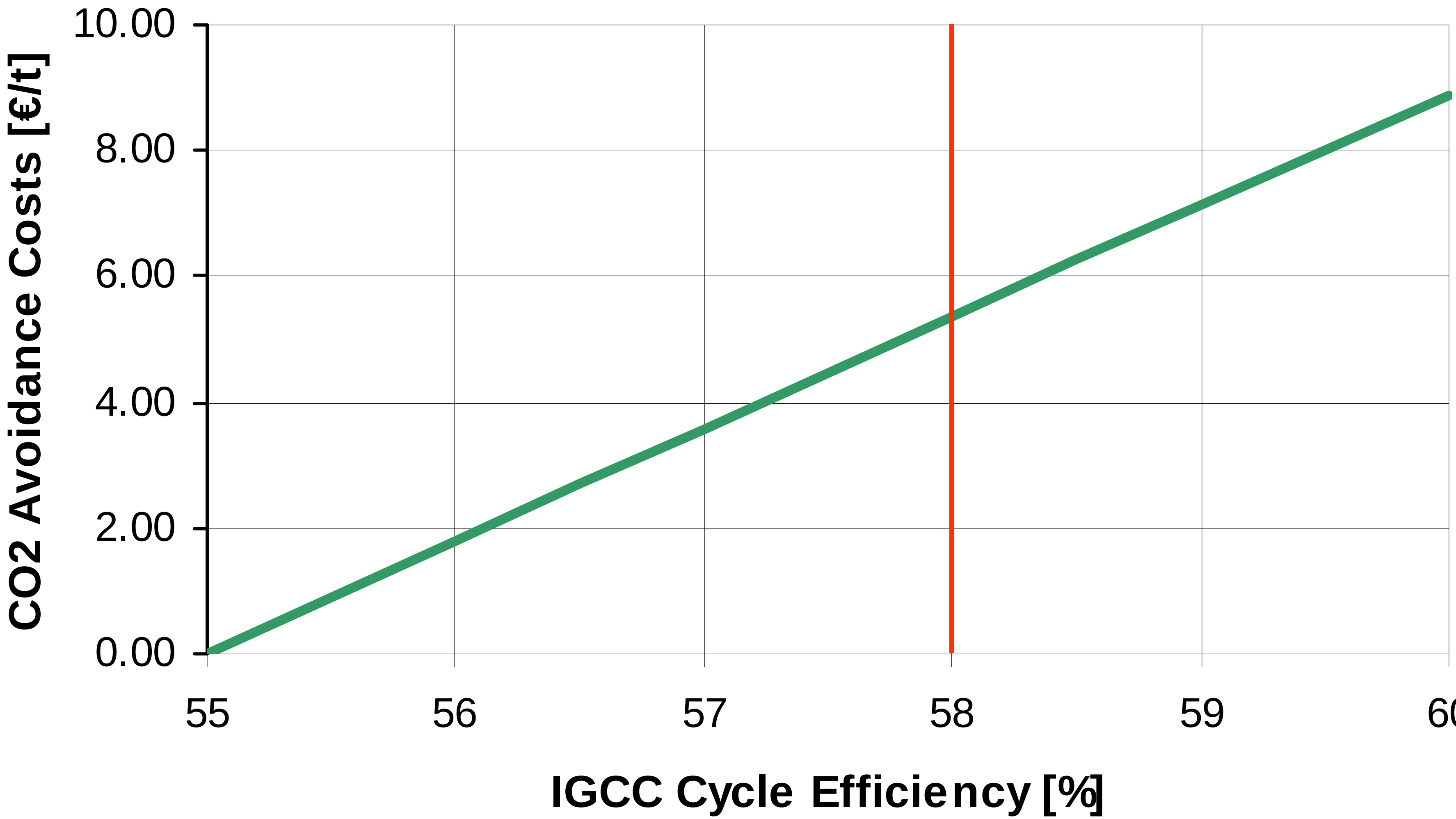


- Cooling of 1st and 2nd stage blading
- Steam with favorable cooling properties from HPT exit at 40 bar available
- Innovative Cooling System ICS using underexpanded jets: 2 radial holes and 2 slit rows

Economical Aspects

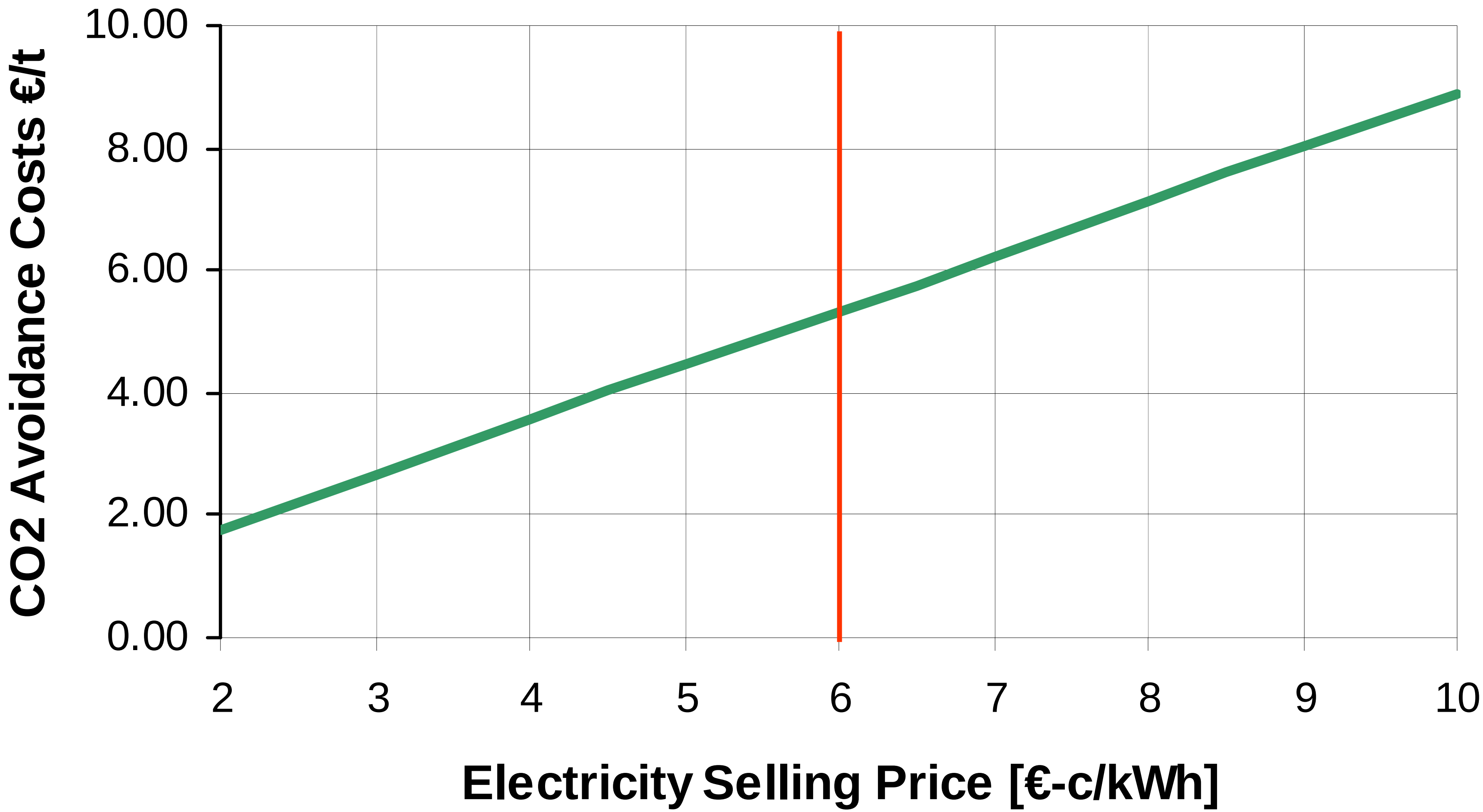
- Comparison with a Combined Cycle Power Plant fired with syngas from coal gasification (IGCCPP) with same power output, η = 58 % (excluding gasification)
- Electricity selling price: 6 €-c/kWh
- Graz Cycle with zero emission and 55 % net efficiency (excluding CO_2 compression)
- Assumption of the same capital costs (similar erection costs, no costs for new developments, no costs for ASU), assumption of the same O&M costs
- CO_2 avoidance costs (3 % - points efficiency):
  5.3 €/t CO_2
- Assuming a CO_2 tax of 30 €/t CO_2
  additional costs of 1.4 €-c/kWh could be covered,
  i.e. additional investment: 1500 €/kW (15 years x 7000 hrs)

Variation of Cycle Efficiency



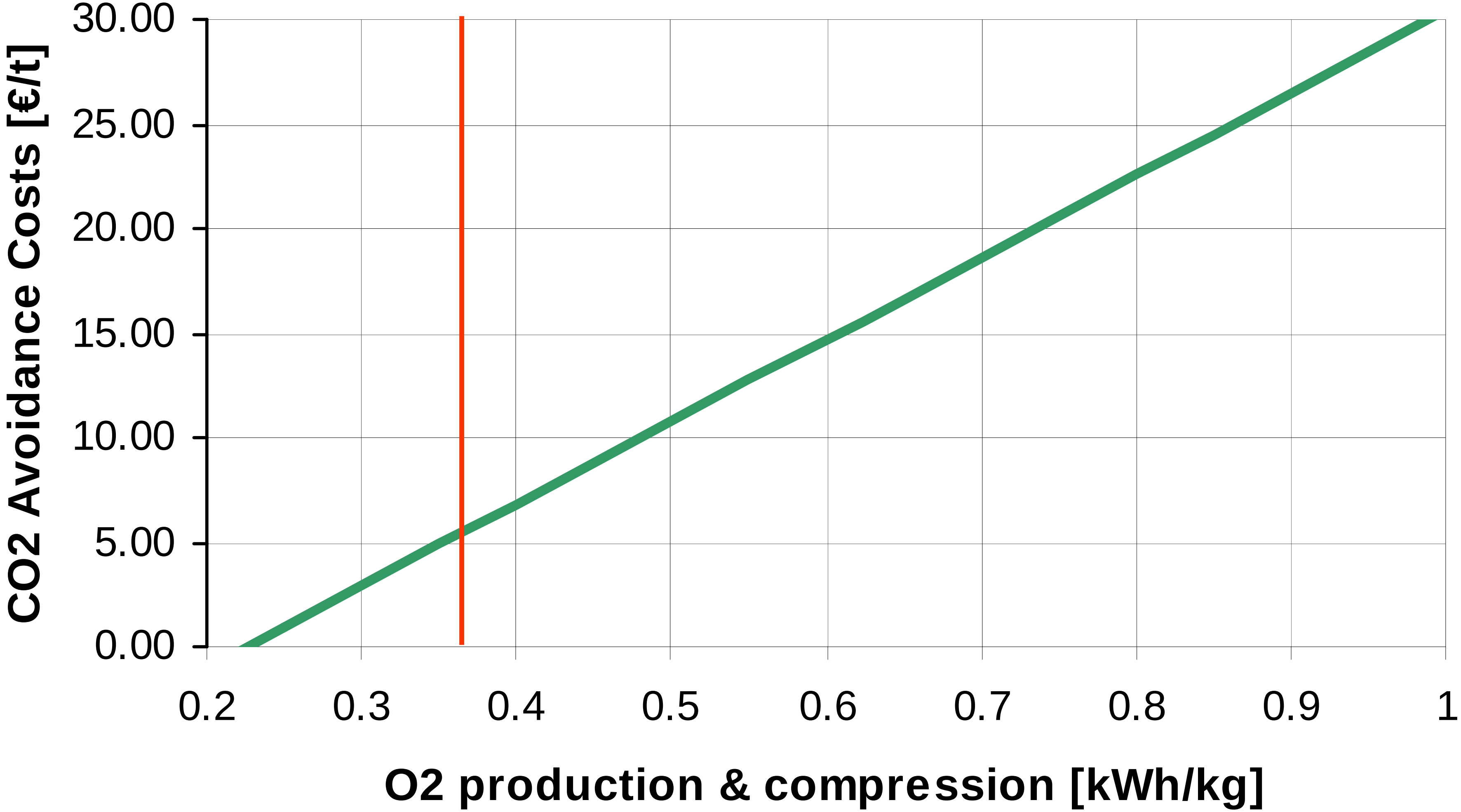
Sensitivity Analysis - II

Variation of Electricity Selling Price



Sensitivity Analysis - III

Variation of O2 Effort



Summary

- Presentation of the Graz Cycle as "zero-emission gas turbine cycle" with oxy-fuel combustion and CO_2 retention
- Thermodynamic layout promises efficiencies up to 63 % (55 % if expenses of O_2 supply are considered)
- Possible arrangement of turbomachines running at 20 000, 12 000 and 3 000 rpm is presented which allows short flow paths in the hot sections
- Innovative design for the two critical components, combustion chamber and High Temperature Turbine, is suggested
- First economic considerations show competitiveness to state-of-the-art combined cycle power plants for a future CO_2 tax

Activities in the future

- Detailed design of HRSG with industrial partner
- More detailed cost estimations with industrial partners
- More in-depth design of HTT and Combustion Chamber
- Ultimate goal: erection of a demonstration plant