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Institute for
Thermal Turbomaschinery
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FIRST GENERATION GRAZ CYCLE POWER PLANT FOR NEAR-TERM DEPLOYMENT

(ASME Paper GT2011-45135)

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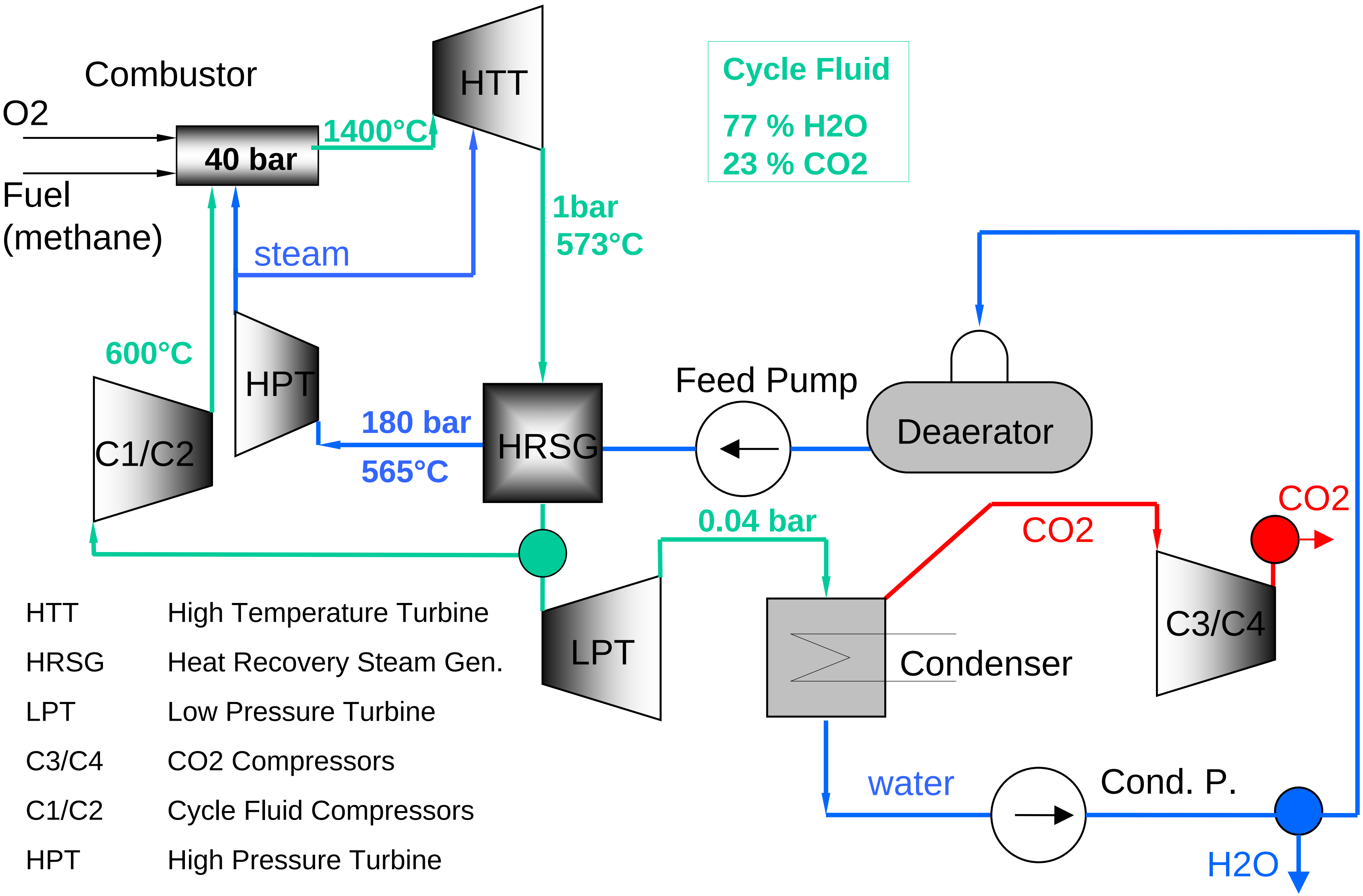
Introduction

- To curb global warming and to maintain a certain CO2 level in atmosphere **Carbon Capture and Storage (CCS)** has an important bridging function till renewables can take over
- Among CCS technologies **Oxy-Fuel Cycles** with internal combustion with pure oxygen are very promising
- A working fluid consisting mainly of **CO2** and **H2O** allows an easy separation by **condensation**
- Graz University of Technology has worked since 1995 on the **Graz Cycle**, an oxy-fuel cycle of highest efficiency, presenting thermodynamic studies and turbomachinery layout

Graz Cycle (ASME 2005)



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

Graz Cycle Power Balance ASME 2005

- Electrical cycle efficiency for methane firing:

  Efficiency: 64.6 % (same for syngas firing)

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

  Oxygen compression (2.38 to 40 bar, inter-cooled): 325 kJ/kg

  Efficiency: 54.8 %

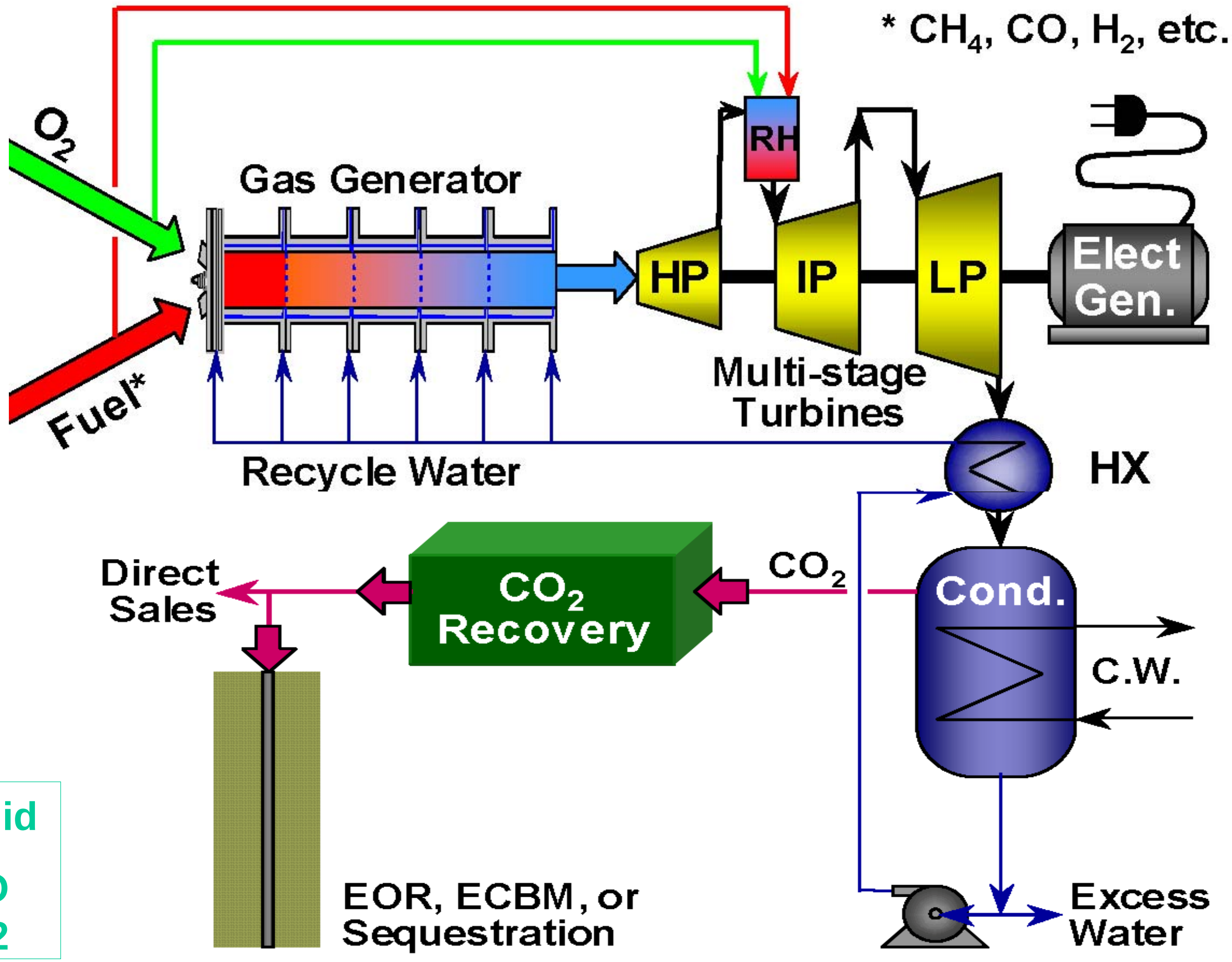
- Compression of separated CO2 for liquefaction (1 to 100 bar, inter-cooled): 270 kJ/kg (3.7 MW)

  Efficiency: 52.7 %

Objective: Towards a Near-Term Plant

- **Significant development effort and further research is needed**
- **Quick alternative: use of commercially available plant equipment for a near-term demonstration plant -> example of Clean Energy Systems, Inc. (CES)**
- **CES: prototype oxyfuel power plant in California since 2005**

CES Cycle (ASME 2010)

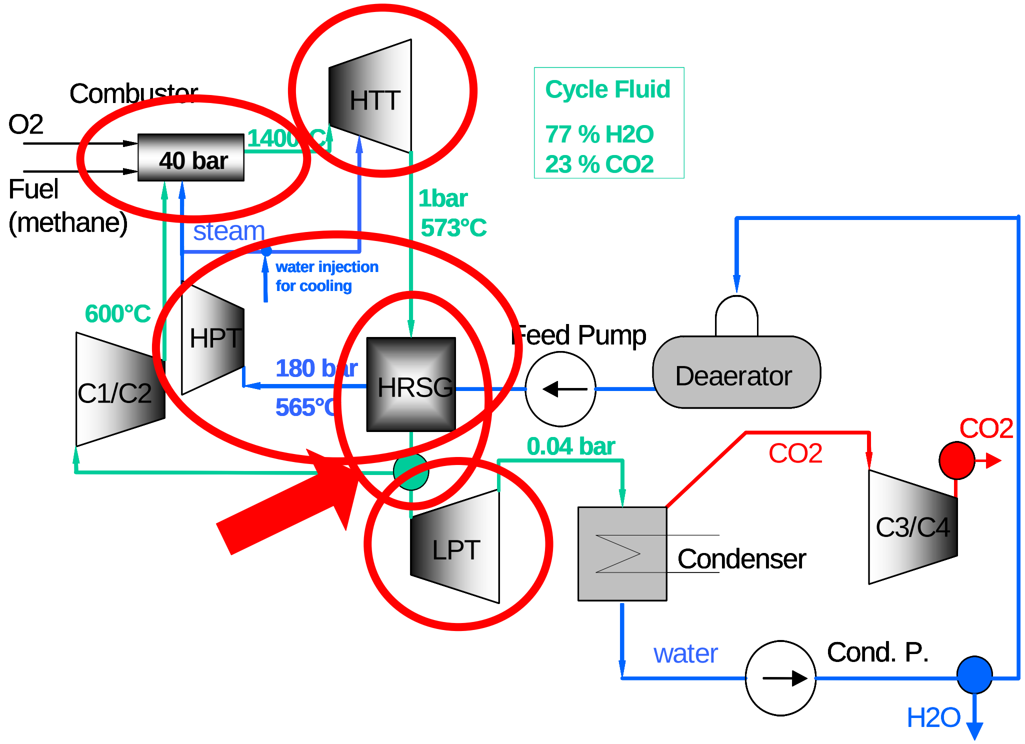


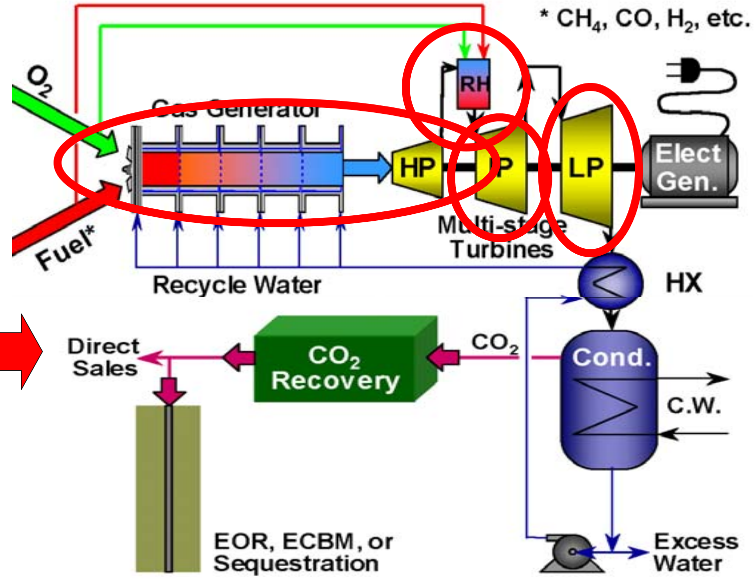
Cycle Fluid

79 % H2O
21 % CO2

taken from
GT2010-23001

Cycle Comparison

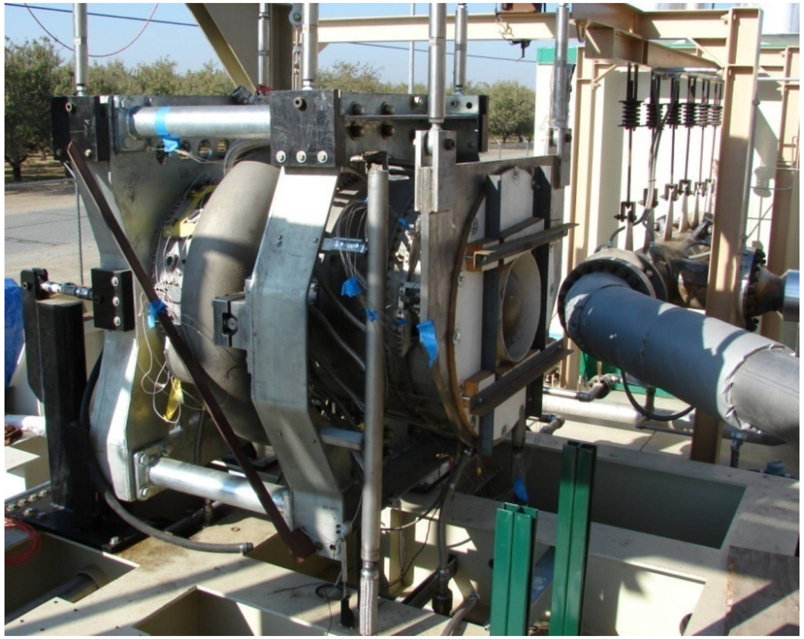




- **Main difference: recycle compressor in the Graz Cycle which is technically more challenging but leads to higher efficiency**
- **Main components have similar engineering specifications**
- **Both cycles can benefit from related R&D done for each cycle**

CES developments

- Considerable experience with GG of 20 and 170 MWth
- Kimberlina Power Plant (KPP), CA: 20 MWth GG + a small steam turbine -> fully proven proof-of-concept
- Current implementation of a re-engineered GE J79 turbine as a high-temperature turbine expander:
  - removal of 17-stage axial compressor
  - thrust bearing system added
  - inflow through a volute manifold
  - approximately 32 MW (shaft) power output
  - additional single-stage turbine providing 11 MW
- Further work for a next generation oxy-turbine based on Siemens SGT-900 (funded by DOE)



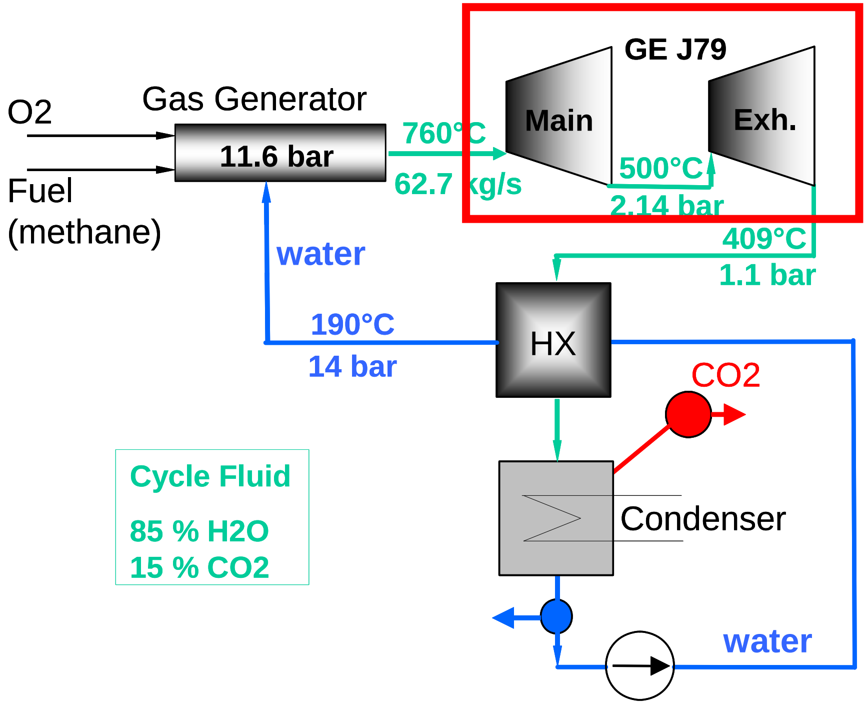
taken from GT2010-23001

Objective

- **Question:**
  What can be achieved, technically as well as economically, if J79 is installed in a first-generation Graz Cycle Plant?
- **Presentation of a first generation Graz Cycle plant with a simplified flow scheme and modest cycle data based on the J79 turbine expander**
- **Discussion of power data and efficiencies for a pilot plant**
- **An economic analysis for niche market application**

GE J79 in KPP

- **Combination of J79 main and exhaust turbine will be employed in KPP as an IP turbine.**
- **Working fluid will be provided by the 170 MWth CES GG**
- **Similar power output at inlet conditions of 760°C/11.6 bar, compared with 927°C / 12.3 bar originally.**
- **No need for blade cooling**

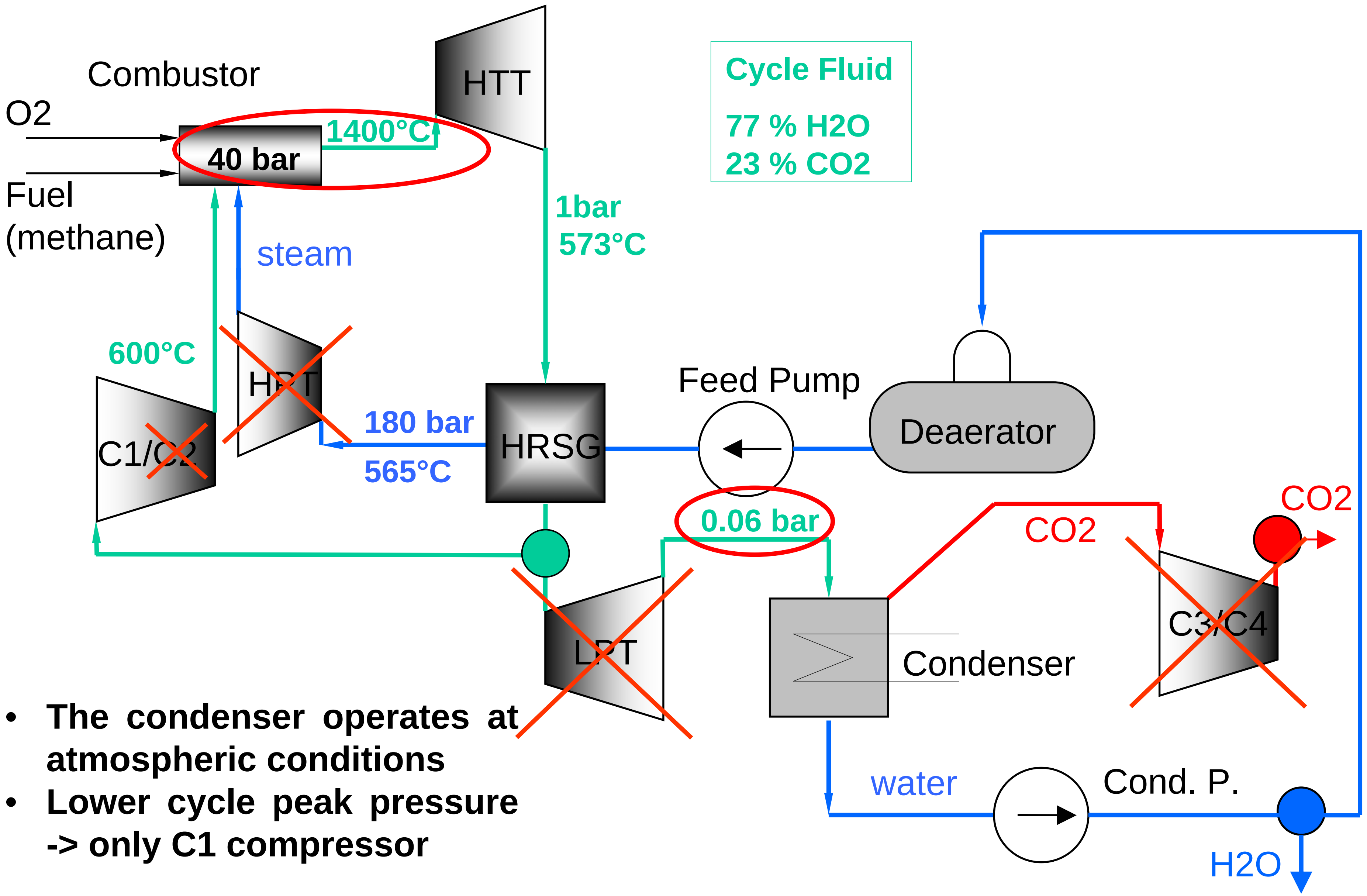


Fuel for First-Generation GC Plant

- **At a suitable location where revenues using CO_2 for enhanced oil recovery (EOR) can be obtained**
- **Benefits using a mixture of NG (5%) and available Reservoir Gas (RG) that has up to 85% CO_2 content**
- **Heating value: HHV of about 265 Btu/scf (5.75 MJ/kg/ LHV 5.25 MJ/kg)**

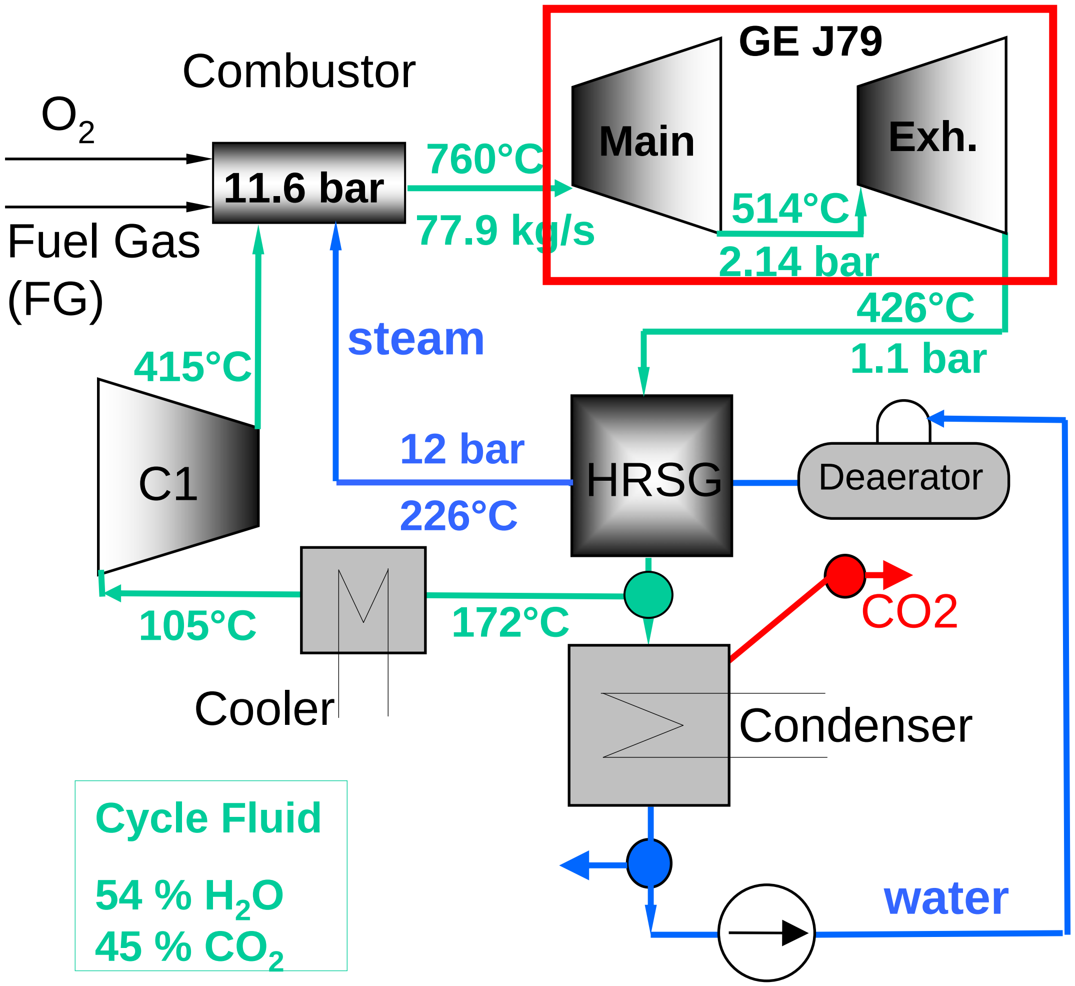
GAS SPEC mol-%	Res Gas	Pipeline NG	Fuel Gas
CH4	7.50%	93.9 %	11.8 %
C2H6	2.50%	3.20%	2.54%
C3H8	1.50%	0.70%	1.46%
C4+	2.00%	0.30%	1.92%
N2	1.50%	0.90%	1.47%
CO2	85.0 %	1.00%	80.8 %
HHV (Btu/scf)	224	1033	265

First-Generation Graz-Cycle Plant - I



- **The condenser operates at atmospheric conditions**
- **Lower cycle peak pressure -> only C1 compressor**

First-Generation Graz-Cycle Plant - II



- **Relatively low steam superheating**
- **Cooling before C1 increases overall efficiency**

Turbine Operating Conditions

Operating Parameters	i) CES-J79: NG	ii) GC-B-J79: FG	iii) GC-AD-J79: FG
Mass flow [kg/s]	**62.7**	**77.9**	**74.1**
Inlet pressure [bar]	**11.6**	**11.6**	**12.3**
Inlet temperature [°C]	**760**	**760**	**815**
Speed [rpm]	**7460**	**7460**	**6890**
Main Turbine [MW]	32.4	32.6	33.0
Exhaust Turbine [MW]	10.8	10.9	10.7
% Composition (H_2O/CO_2)	85/15	54/45	51/48
Inlet Volume [m^3/s]	23.4	23.3	21.5
Intermediary Vol. [m^3/s]	95.0	96.1	93.9
Exit Vol. [m^3/s]	163	166	162.7
Spec. Enthalpy drop [kJ/kg]	710	576	607
Main Turbine Exit Temp. [°C]	500	514	552
Exh. Turbine Exit Temp. [°C]	409	426	463

Power Balance

CES Cycle	Fuel Gas is as shown in Table 1 column 3	GC-B-J79 (760°C/ 11.6 bar)	GC-AD-J79 (815°C/ 12.3 bar)
170 MWth	Total Heat Input (HHV) [MW]	65.3	62.6
43.2 MW	Total Turbine Power [MW]	43.5	43.6
	Compressor Power [MW]	23.5	22.5
43.2 MW	Net shaft power [MW]	20.0	21.1
	Thermal cycle efficiency [%] (1)	**30.6**	**33.7**
	Auxiliary Losses [MW] (2)	0.6	0.6
	Electrical cycle efficiency [%] (3)	**29.2**	**32.2**
	Power for ASU [MW] (4) **(0.34 kWh/kg)**	5.9	5.7
	Net Power Output [MW_e]	**13.2**	**14.5**
	Net Efficiency (HHV) [%](5)	**20.2**	**23.2**
	Net Efficiency (LHV) [%](5)	22.2	25.4

Economics

- Deployment of a Basic Graz Cycle plant in a niche market with revenue from multiple product streams: Permian Basin or onshore along the Gulf Coast with enhanced oil recovery (EOR)
- Opportunity for using CO2 as well as N2 as injectant gas into the same or two adjacent oil zones at different depths
- Costs are appropriate for the Gulf Coast area as of 3Q-2010

Capital Investment Costs

Graz Cycle - Basic Reservoir Gas with 5% NG	
INVESTMENT SUMMARY	**$mill.**
Power Plant Capital Cost	41.54
Air Separation Unit Cost	44.05
Total CO2 Plant Capital Cost	**85.6** $mill.
Development Costs	2.77
Pre-FEED + Contingency	1.08
Interest During Construction	4.49
Govt. Grant Support	0.00
TOTAL PROJECT COST	93.9 $mill.

- **Base case scenario without plant compression equipment, but selling of injectant gas**
- **Specific power plant costs: US-$ 3147/kW (13.2 MWe net power)**
- **ASU: 414 tpd O2 -> US-$46.5/ tpd**

Plant Output

PLANT CAPACITY SUMMARY	
Power Output	13.2 MWe
Efficiency (HHV) 15,405 Btu/kWh	20.2 %HHV
Availability	92.0 %
Annual Production Hours	8,065 hrs
Annual Electrical Output	0.106 TWh
Annual CO2 Output	0.394 mt/yr
Annual N2 Output	0.454 mt/yr
Annual H2O Output	0.068 mt/yr

- **Combustion process yields 68,000 t/yr (~54,000 US gall/day) of industrial-quality de-ionized water**

Financial Assumptions

FINANCIAL ASSUMPTIONS	
Interest Rate	7.5%
Equity Percent	30%
Debt Term	12 yrs
Project Duration	15 yrs
Construction Duration	1.5 yrs
Business Tax Rate	34.0%
Discount Rate	15.0%

- **70% debt financing**
- **Project duration of 15 years: assumption that adjacent fields will help extend power plant operation beyond the 5 to 8 years typical for tertiary oil recovery floods**

Revenue Assumptions

REVENUE ASSUMPTIONS		
Electricity Tarrif	60.0	\$/MWh
Fuel Gas Cost	3.59	\$/MMBtu
CO2 Sales Price	19.01	\$/tonne
CO2 Credit Price	0.00	\$/tonne
Oxygen Cost	0.00	\$/tonne
N2 Sales Price	14.93	\$/tonne
H2O Sales Price	0.00	\$/tonne

- **Fuel cost: \$3.59 /MMBtu (HHV) based on \$4.50 /MMBtu (HHV) for NG**
- **Electricity tariff: typical market spread \$55 to \$95 /MWh**
- **CO2 sales price: \$1.00 /Mcf (\$19.0 per tonne) uncompressed**
- **N2 sale is not standard practice, but does occur**
  \$0.50 /Mcf (\$14.9 per tonne) uncompressed has commercial value when oil remains above \$80 /bbl
- **No credits for CO2 retention and possible H2O sale**
- **O2 costs are already considered**

Net Operating Income

ANNUAL RESULTS	$mill.
Electricity Sales	6.39
CO2 Sales	7.48
Emission Credits	0.00
N2 Sales	6.78
Steam Sales	0.00
H2O Sales	0.00
Gross Revenues	**20.65 $mill.**
Oxygen Costs	0.00
Fuel Gas Costs	6.46
O&M Costs	0.83
Operating Costs	**7.29**
Net Operating Income	**13.36 $mill.**

- **Gross revenue is evenly distributed between sales of electricity, CO_2 and N_2**
- **No income from sales of produced steam /water nor emission credits (e.g. NOx, sulfur or CO_2 for zero emission power)**

Financial Summary

Graz Cycle - Basic Reservoir Gas with 5% NG	
FINANCIAL SUMMARY	**Project Analysis**
Startup Date: 2014 - Q2 / Project Life: 15 yrs	
Total Project Investment	93.9 $mill.
Net Annual Operating Income	13.4 $mill.
Investment Return — Unlevered	14.5% IRR
Levered	21.8% IRR

- **Net annual income suggests a payback period of 7 years**
- **IRR is compatible with financial market expectations**
- **Multiple revenue streams reduce sensitivity to cost escalation in one area thereby balancing economic risk**
- **IRR identical for Advanced Graz Cycle despite higher efficiency**

Summary

- To achieve near-term development of a GC oxyfuel plant for CCS utilization of existing hardware is proposed
- Based on CES experience with GE J79 turbine expander a “near-term” Graz Cycle plant is presented
- Efficiencies of 20 to 23 % and power output of 13.2 to 14.5 MW can be expected
- For economic evaluation a unique market location (EOR) where power, CO2 and N2 are needed at volumes comparable with the proposed power plant (multiple revenue streams)
- Economic analysis gives a payback period of 7 yrs and IRR at financial market expectations
- Multiple product streams make the project more robust.
- This strategy can enable proof-of-concept demonstration of oxyfuel technology for CCS at acceptable return on invested capital