



# **ENCAP SP6 – Novel pre-combustion and oxy-fuel concepts**

Presentation at the ENCAP - CASTOR Training Seminar

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# ENCAP SP6 Objectives



- “Novel Pre-combustion Capture Concepts”
- Investigate prospective emerging pre-combustion capture technologies with
  - High potentiality for capture cost reduction
  - High capture rate
- Oxy-fuel combustion cycles
  - Natural gas
- Pre-combustion capture cycles
  - Natural gas
  - Hard coal

# ENCAP SP6 partners



- ALSTOM Power Centrales (France) (SP lead)
- ALSTOM Ltd (Switzerland)
- Air Liquide SA (France)
- ALSTOM POWER LTD – Technology Centre (UK)
- Siemens AG (Germany)
- Institut Français du Pétrole, IFP (France)
- SINTEF Energy Research (Norway)
- The Norwegian University of Science and Technology, NTNU (Norway)
- University of Ulster (UK)
- Universität Paderborn (Germany)

# Contents

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- Objectives
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## ■ CONCLUSIONS



# WP6.1

“Methodology for modelling and screening of optional concepts”

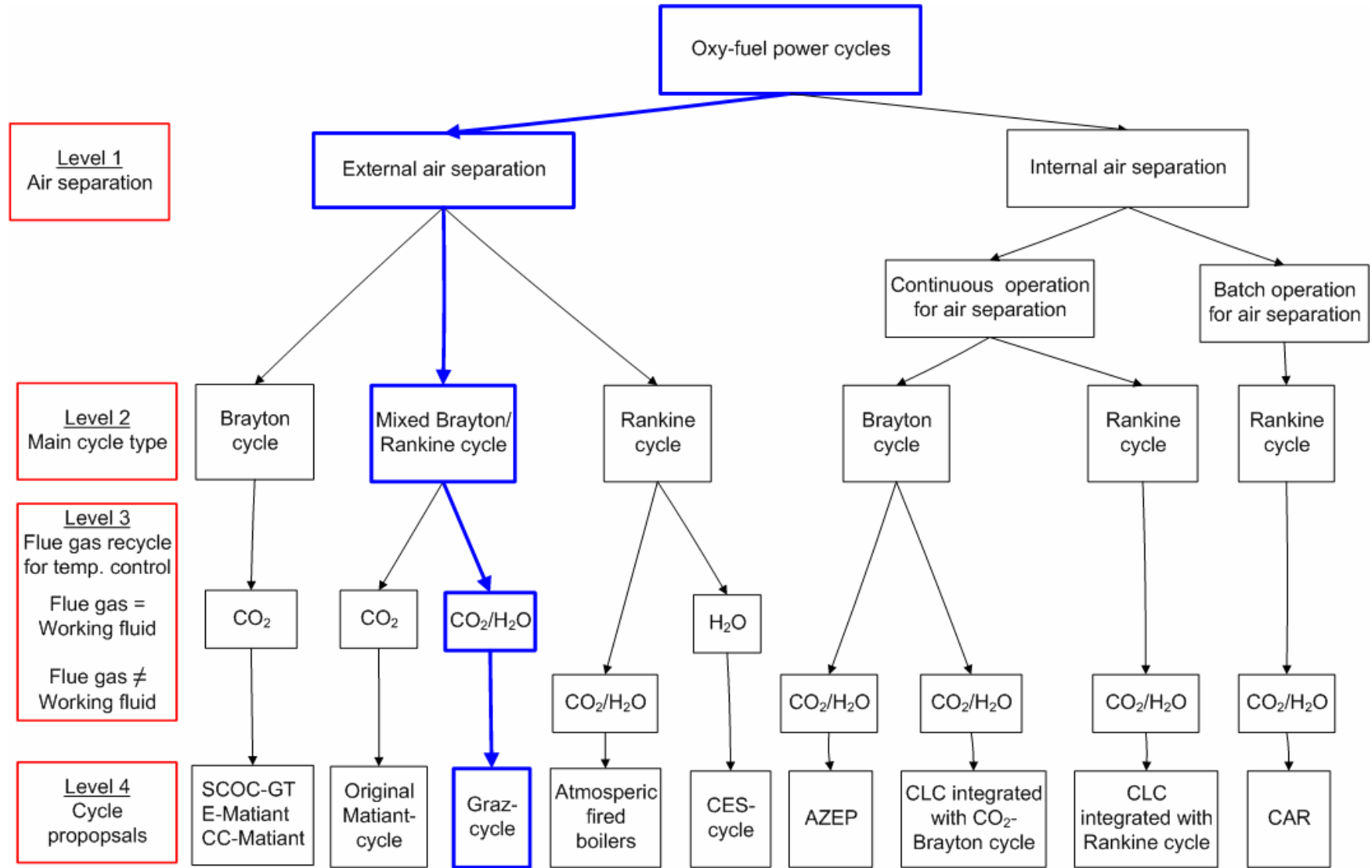
- Identification and selection of promising novel cycle options
  - Reduced costs and/or
  - Higher capture efficiency
  - Results (heat and mass balances) to WP6.2 and WP6.4
  - Cycle simulation work finished and published in deliverable D6.1.3)
  
- Common framework of the modelling basis
  - All cycles evaluated on the same basis
  - External parameters from SP1 (e.g., fuel specifications, cooling water, reference cases)
  - Generic cooled gas turbine
    - Representing state-of-the-art gas turbine technology
    - Used in all cycles including a cooled gas turbine

# WP6.1

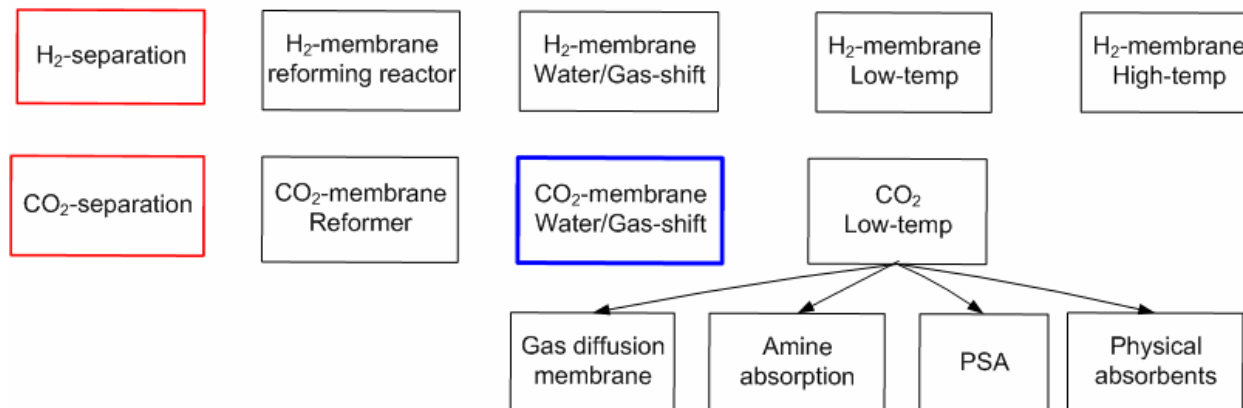
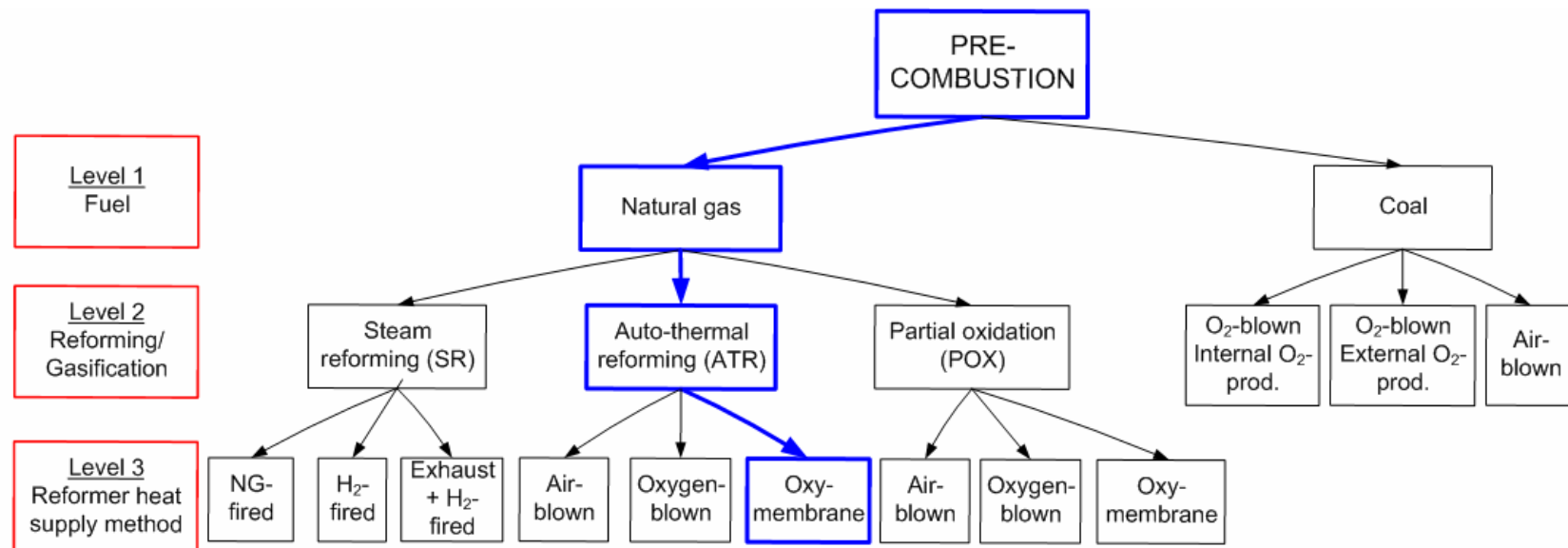
“Methodology for modelling and screening of optional concepts”

- Cycle classification: all cycles are classified into a common structure:
  - Oxy-fuel combustion (natural gas)
  - Pre-combustion capture (natural gas and coal)

# WP6.1 Oxy-fuel classification



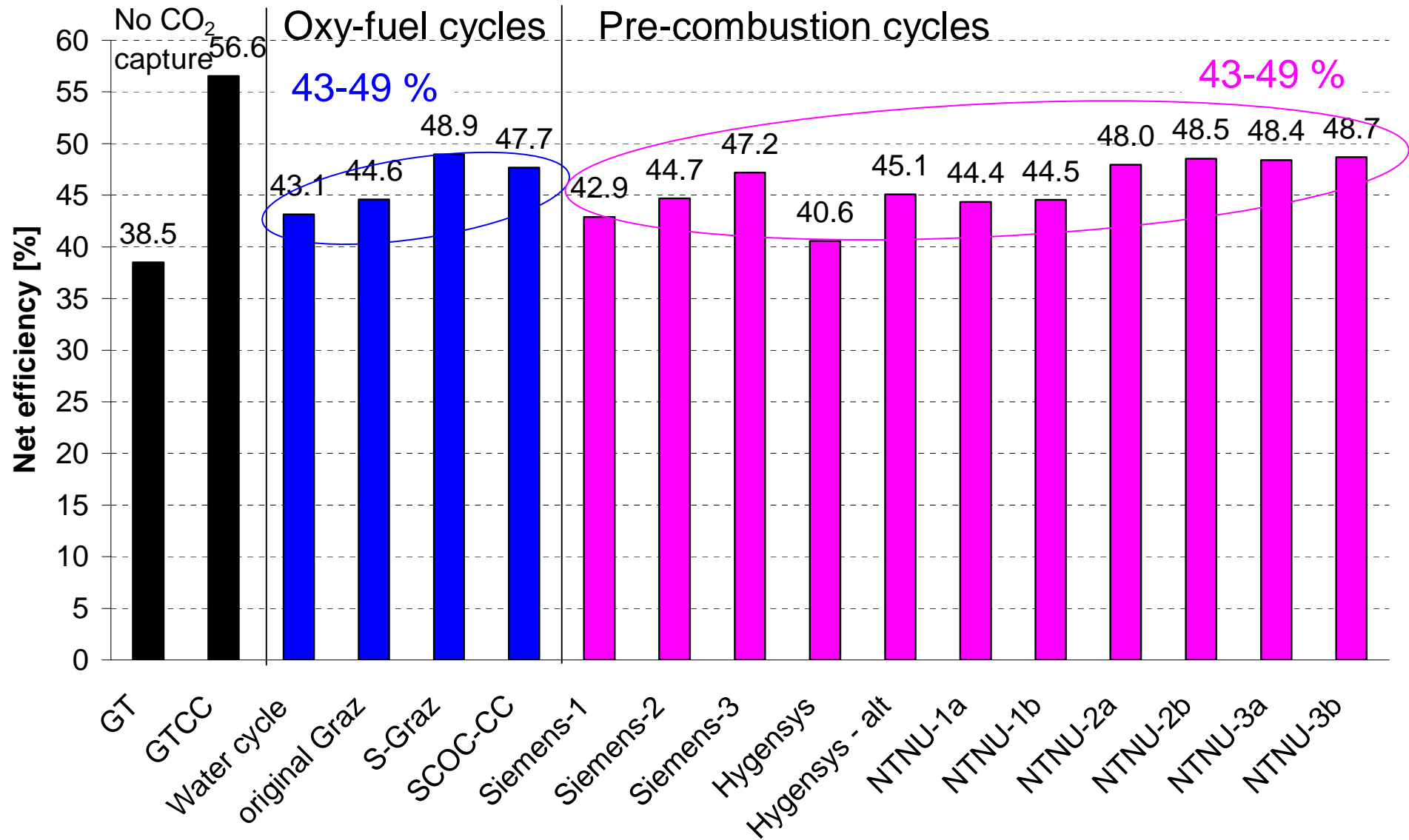
# WP6.1 Pre-combustion classification



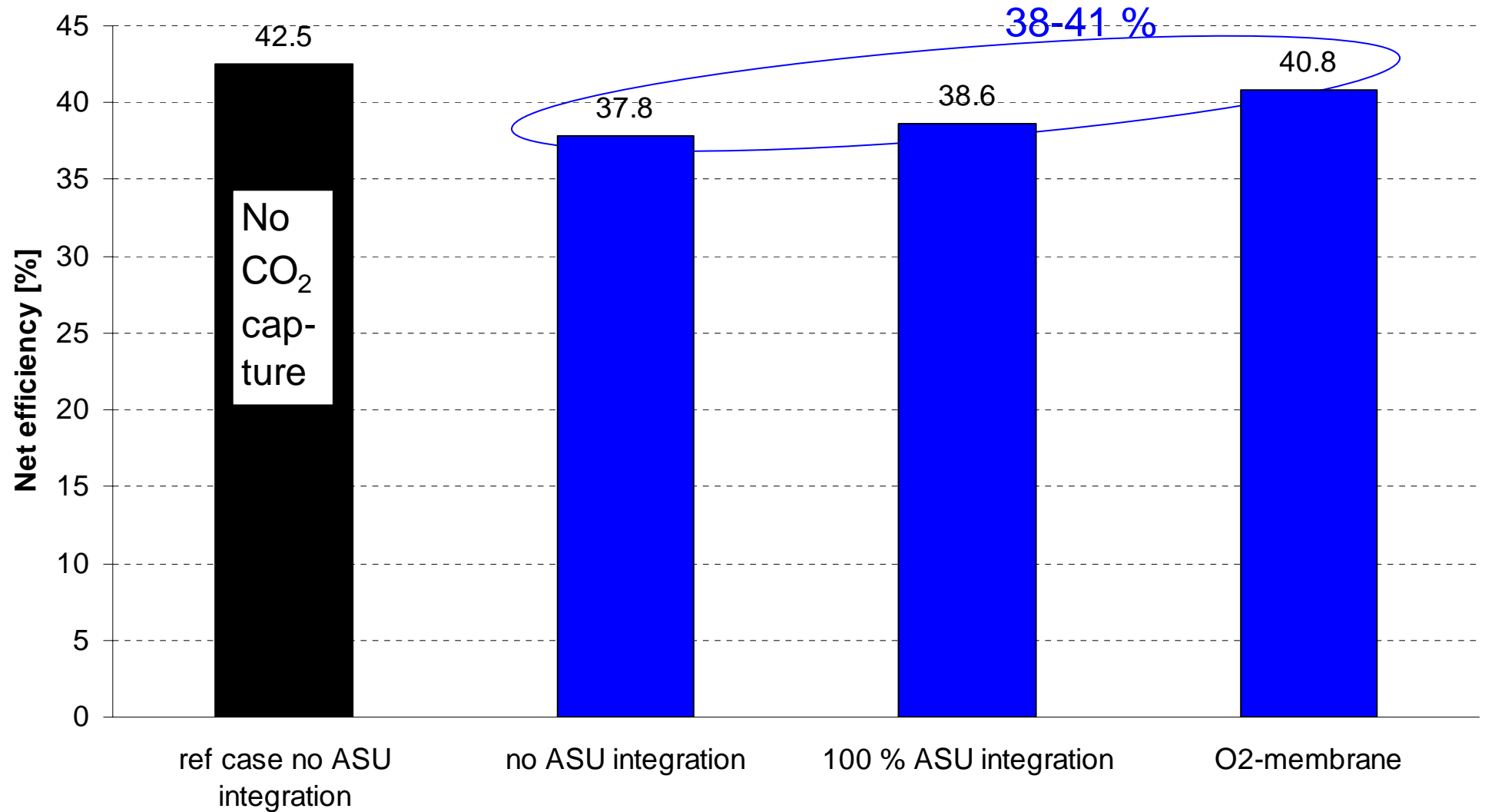
# WP6.1 Results

- 17 cycles
  
- Natural gas
  - Oxy-fuel combustion
  - Pre-combustion capture
  
- Coal
  - Pre-combustion capture (IGCC)
  
- Basis for component studies and economic analysis ⇒ benchmarking

# WP6.1 Results – Natural gas



# WP6.1 Results – Coal/IGCC



# WP6.2

“Modelling, design and operational analysis”

- WP6.2 – “Modelling, design and operational analysis”
  - Novel or modified cycle components
  - Feasibility studies of key components
    - Turbomachinery and combustors
    - Heat exchangers
    - Novel components (e.g., membranes, membrane reactors)
  - Key technical areas: combustion, heat transfer, materials
  - Identify small-scale experimental investigations
  - Results to WP6.4 (economic evaluation)
  - First evaluation report D-6.2.1 submitted end of February 2006

# WP6.2

“Modelling, design and operational analysis”

## Methodology

- For each cycle
  - For each component
    - Composition and mass flows of inlet and outlet streams
    - Inlet and outlet pressures and temperatures
    - Power input or output and component efficiencies
  - Collection of expert opinions on each component, considering available technology, best design practices, state of the art in materials, existing experience and other relevant issues
  - Technical and economic traffic lights given to each component
    - **Green**: available technology, current engineering practice
    - **Yellow**: not current engineering practice but not new science
    - **Red**: completely new development needed or very high cost

# WP6.2 Example: Water Cycle

## 4 - Integrated Brayton-Rankine cycle - Water Cycle

Component	Inlet streams	Mass flow (kg/s)	Inlet pressure (bar)	Inlet temperature (°C)	Power (MW)	Polytropic efficiency	Isentropic efficiency	Outlet streams	Mass flow (kg/s)	Outlet pressure (bar)	Outlet temperature (°C)	Technical Comments	Economic Comments
C1	S8 Methane & Ethane	4.92	70.00	10.00	0.25	80.78	80.93	S9 Methane and Ethane	4.92	97.55	38	High exit pressure. From Air Liquide we understand compressor is commercially available.	
C2	S10 Oxygen	19.24	75.00	15.00	0.57		80.00	S11 Oxygen	19.24	97.55	42.91	High exit pressure. From Air Liquide we understand compressor is commercially available.	
T1	S13 Steam 94.38% + CO2 5.06% etc.	113.54	88.00	619.56	67.21		90.00	S14 Steam 94.38% + CO2 5.06% etc.	113.54	9.07	293.82	High inlet temperature but about OK for today. Corrosion danger to be checked. Unknown effect of CO2 and H2O in these concentrations. The exit temperature is 120 C above the dew point temperature.	
T2	S17 am 67.11% + CO2 11.62% etc. 1425 °C	161.44	8.80	1254.00	331.16	87.25	92.29	S18 Steam 89.11% + CO2 9.81%	186.64	0.07	389.66	Very high pressure ratio = 138. Steam cooling. Combustor exit temperature is 1425 C but turbine inlet temperature is 1254 C, after mixing of the cooling fluid. Fluid composition very different from that of gas and steam turbines. Properties as in Common Framework. The inlet temperature to the condenser is 37 C. This turbine is	M.I: Inlet pressure and temperature similar to modern gas turbine, but a completely new design is required because of very different fluid
	S27 Steam 184.41 °C	21.73	8.80										
R1	S7 H2O, S9 Fuel, S11 Oxygen	S7 89.38, S9 4.92 and S11 19.24	97.55	S7 @ 302.01, S9 @ 38.0 and S11 @ 42.91				S13	113.54	88.00	619.56	High pressure combustor (82bar) which require dextensive development. It is proposed by APIUK that O2 is mixed with part of H2O (S7) before fuel is added to achieve the desired combustion temperature and emissions. CES (Clean Energy Systems) is currently testing this type of combustor (Kimberlina, 5MWel). Combustor was demonstrated for 20 MWel-10MWel, 1649 C and 107 bar.	
R2	S14 (84% H2O, 5% CO2 etc.), S15 (Methane, Ethane), S16 (O2), S25 (H2O)	S14 113.54, S15 9.75, S16 38.15, S25 26.23	S14 9.07, S15 70.00, S16 9.07, S25 8.89	S14 293.82, S15 10.0, S16 15.0 & S25 104.79				S17 (87% H2O, 12% CO2), S26 H2O	S17 161.44, S26 26.23	8.80	S17 1425, S26 184.41	O2 should be mixed with part of the exhaust (S14) before fuel is added. Optimization required to achieve combustion stability and low emissions	
H4	S21 90% H2O, 10% CO2	186.6	0.07	36.9	329			S22 32% H2O, 62% CO2	50.3	0.07	19.0	initial evaluation of design approaches and materials in progress - no basic obstacles expected Very low heat transfer coefficient due to inert gases. Exit pressure very low.	Large size due to low heat transfer coefficient
	S32 water	7969.8	2.50	15.0				S23 water	136.3	0.06	19.0		
	S2 water	114.6	1.21	19.0				S33 water	7969.8	2.48	25.0		
H1	S20 gas (89 mol.% H2O, 9.8 mol.% CO2)	186.6	0.07	140.7	39			S3	114.6	1.20	99.8	Exit gas below dew point temperature (36.97 C)	Similar to HRSG design but very low pressure => very large volumes => large size equipment
	S6 water	89.4	98.54	104.8				S21	186.6	0.07	36.9		
H3	S19 gas (89 mol.% H2O, 9.8 mol.% CO2)	186.3	0.07	388.7	81			S7 H2O	89.4	97.55	302.0		Similar to HRSG design but very low pressure => very large volumes => large size equipment

Steam + CO<sub>2</sub> turbine - high pressure ratio

High pressure combustor – extensive development

Low heat transfer coefficient, large size equipment, leading to high cost

# WP6.2 Example: Steam Graz Cycle

6 - Integrated Brayton-Rankine cycle - Steam Graz Cycle													
Component	Inlet streams	Mass flow (kg/s)	Inlet pressure (bar)	Inlet temperature (°C)	Power (MW)	Polytropic efficiency	Isentropic efficiency	Outlet streams	Mass flow (kg/s)	Outlet pressure (bar)	Outlet temperature (°C)	Technical Comments	Economic Comments
C1	S35 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	194.21	1.00	114.8	137.05	-	-	S36 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	194.21	16.00	515.3	Compressor for recycled CO <sub>2</sub> (10 %)-steam (89 %). Inlet volume flowrate 380 m <sup>3</sup> /s. Corrosion has to be taken into account. Molecular weight 29.7 kg/kmol.	
C2	S37 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	194.21	15.84	387.0	66.87	-	-	S38 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	194.21	41.24	575.81	Compressor for recycled CO <sub>2</sub> (10 %)-steam (89 %). Inlet volume flowrate 37 m <sup>3</sup> /s. Corrosion has to be taken into account. Molecular weight 29.7 kg/kmol.	
C3	S43 (saturated gas, 53.9 vol.% CO <sub>2</sub> , 46.2 vol.% H <sub>2</sub> O)	48.97	0.05	19.0	7.37	-	-	S44 (gas, 53.9 vol.% CO <sub>2</sub> , 46.2 vol.% H <sub>2</sub> O)	48.97	0.24	155.17	Compressor for excess CO <sub>2</sub> (4 %)-steam (96 %). Inlet volume flowrate 662 m <sup>3</sup> /s. Corrosion has to be taken into account. Molecular weight 33.0 kg/kmol.	
C4	S47 (saturated gas, 79.9 vol.% CO <sub>2</sub> , 11.4 vol.% H <sub>2</sub> O)	40.27	0.23	22.0	4.99	-	-	S48 (gas, 79.9 vol.% CO <sub>2</sub> , 11.4 vol.% H <sub>2</sub> O)	40.27	1.00	154.41	Compressor for excess CO <sub>2</sub> (80 %)-steam (11 %). Inlet volume flowrate 106 m <sup>3</sup> /s. Corrosion has to be taken into account. Molecular weight 40.2 kg/kmol.	
T1	S19 (steam)	110.65	167.40	537.2	39.88	-	-	S20 (steam)	110.65	41.24	329.64	Standard high pressure steam turbine.	
T2	S27 (gas, 11.7 vol.% CO <sub>2</sub> , 87.0 vol.% H <sub>2</sub> O), S23 (steam)	S27 326.5 kg/s, S23 54.6 kg/s	S27 40.0 bar, S23 41.2 bar	S27 1425 C, S23 262.2 C	541.63	86.92	90.6	S28 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	381.10	1.19	569.5	Cooled gas turbine for CO <sub>2</sub> (exit 10 %)-steam (exit 89 %). Open-loop cooling with superheated steam. TIT after mixing of hot gas-cooling fluid = 1248.8 C. Pressure ratio 24. Corrosion has to be taken into account. High power output. Exit molecular weight 28.7 kg/kmol.	Inlet pressure and temperature similar to modern gas turbine, but a completely new design is required because of very different fluid composition.
T3	S40 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	169.36	1.01	212.6	62.7	-	-	S41 (wet gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O)	169.36	0.06	32.54	Low pressure uncooled turbine for CO <sub>2</sub> (10 %)-steam (89 %). Exit gas below dew point temperature (52.61 C), vapor fraction 57.1 %. Pressure ratio 10. Corrosion has to be taken into account. Molecular weight 28.7 kg/kmol.	
R1	S38 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S24 (steam), S25 (natural gas), S26 (gas, 95 vol.% O <sub>2</sub> , 2 vol.% Ar)	S38 164.2 kg/s, S24 40.3 kg/s, S25 14.67 kg/s, S26 27.4 kg/s	S38 41.2 bar, S24 41.2 bar, S25 10 C, S26 15 C	S38 575.0 C, S24 298.0 C, S25 10 C, S26 15 C	-	-	-	S27 (gas, 11.7 vol.% CO <sub>2</sub> , 87.0 vol.% H <sub>2</sub> O)	326.54	40.00	1425	Combustion chamber for natural gas and oxygen rich stream. CO <sub>2</sub> -steam and steam added for temperature control.	
H1	S49 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S5 (water)	S49 17.6 kg/s, S5 114.9 kg/s	S49 1.01 bar, S5 1.21 bar	S49 212.6 C, S5 19.5 C	-	-	-	S50 (saturated gas, 87.5 vol.% CO <sub>2</sub> , 2.9 vol.% H <sub>2</sub> O), S52 (saturated liquid, 0.06 vol.% CO <sub>2</sub> , 99.94 vol.% H <sub>2</sub> O), S6 (water)	S50 4 kg/s, S52 13.6 kg/s, S6 114.9 kg/s	S50 1.0 bar, S52 1.0 bar, S6 1.20 bar	S50 23.5 C, S52 23.5 C, S6 99.8 C	High-pressure condenser for CO <sub>2</sub> -steam. Some steam condensers. Corrosion is a challenge in the section where condensation takes place. Condensation with inert gases present must be taken into account. Compare with the SCOCGT and SCOC-CC condensers.	Maybe green for economy? Compare with condenser in SCOC-GT and SCOC-CC.
H3	S34 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S9 (water)	S34 194.2 kg/s, S9 111.9 kg/s	S34 1.01 bar, S9 103.3 bar	S34 212.6 C, S9 184.8 C	-	-	-	S29 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S10 (water)	S29 194.2 kg/s, S10 111.9 kg/s	S29 1.00 bar, S10 197.2 bar	S29 114.8 C, S10 173.2 C	Economizer (cooling of CO <sub>2</sub> -steam before recycle compression).	
H4	S31 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S10 (water)	S31 381.1 kg/s, S10 111.9 kg/s	S31 1.15 bar, S10 197.2 bar	S31 374.1 C, S10 173.2 C	-	-	-	S32 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S11 (water)	S32 381.1 kg/s, S11 111.9 kg/s	S32 1.15 bar, S11 191.3 bar	S32 213.2 C, S11 207.0 C	HRSG economizer. Standard HRSG technology, but with somewhat different fluid composition compared to air based system.	
H5	S30 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S12 (water)	S30 381.1 kg/s, S12 122.7 kg/s	S30 1.15 bar, S12 191.3 bar	S30 194.2 C, S12 362.0 C	-	-	-	S31 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S13 (steam)	S31 381.1 kg/s, S13 122.7 kg/s	S31 1.15 bar, S13 191.3 bar	S31 374.1 C, S13 362.0 C	HRSG evaporator. Standard HRSG technology, but with somewhat different fluid composition compared to air based system.	
H6	S36 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S16 (steam)	S36 194.2 kg/s, S16 110.7 kg/s	S36 16.0 bar, S16 191.3 bar	S36 515.3 C, S16 362.0 C	-	-	-	S37 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S17 (steam)	S37 194.2 kg/s, S17 110.1 kg/s	S37 16.0 bar, S17 185.6 bar	S37 387.0 C, S17 484.1 C	Superheater (intercooling for compression of recycled CO <sub>2</sub> -steam).	
H7	S29 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S17 (steam)	S29 381.1 kg/s, S17 110.7 kg/s	S29 1.19 bar, S17 185.6 bar	S29 568.5 C, S17 484.1 C	-	-	-	S30 (gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S18 (steam)	S30 381.1 kg/s, S18 110.7 kg/s	S30 1.15 bar, S18 180.0 bar	S30 491.2 C, S18 543.5 C	HRSG superheater. Standard HRSG technology, but with somewhat different fluid composition compared to air based system.	
H8	S41 (wet gas, 9.8 vol.% CO <sub>2</sub> , 89.1 vol.% H <sub>2</sub> O), S54 (water)	S41 169.4 kg/s, S54 4872.6 kg/s	S41 0.055 bar, S54 2.50 bar	S41 32.54 C, S54 15.0 C	-	-	-	S43 (saturated gas, 53.9 vol.% CO <sub>2</sub> , 46.2 vol.% H <sub>2</sub> O), S42 (saturated liquid, 0.02 vol.% CO <sub>2</sub> , 99.98 vol.% H <sub>2</sub> O), S55 (water)	S43 49.0 kg/s, S42 120.4 kg/s, S55 4872.6 kg/s	S43 0.0545 bar, S42 185.6 bar, S55 2.48 bar	S43 19.0 C, S42 19.0 C, S55 25.0 C	Low-pressure condenser for CO <sub>2</sub> -steam. Some steam condensers. Corrosion is a challenge in the section where condensation takes place. Condensation with inert gases present must be taken into account. Compare with the Water cycle condenser.	Very low heat transfer coefficient due to inert gases. Exit pressure very low.

CO<sub>2</sub> and steam turbine: risk of corrosion

CO<sub>2</sub> and steam turbine: risk of corrosion, very low exit temperature

Very low pressure condenser for CO<sub>2</sub> and steam, risk of corrosion, very low heat transfer coefficient

# WP6.2 Example: Semi-closed oxy-fuel CC

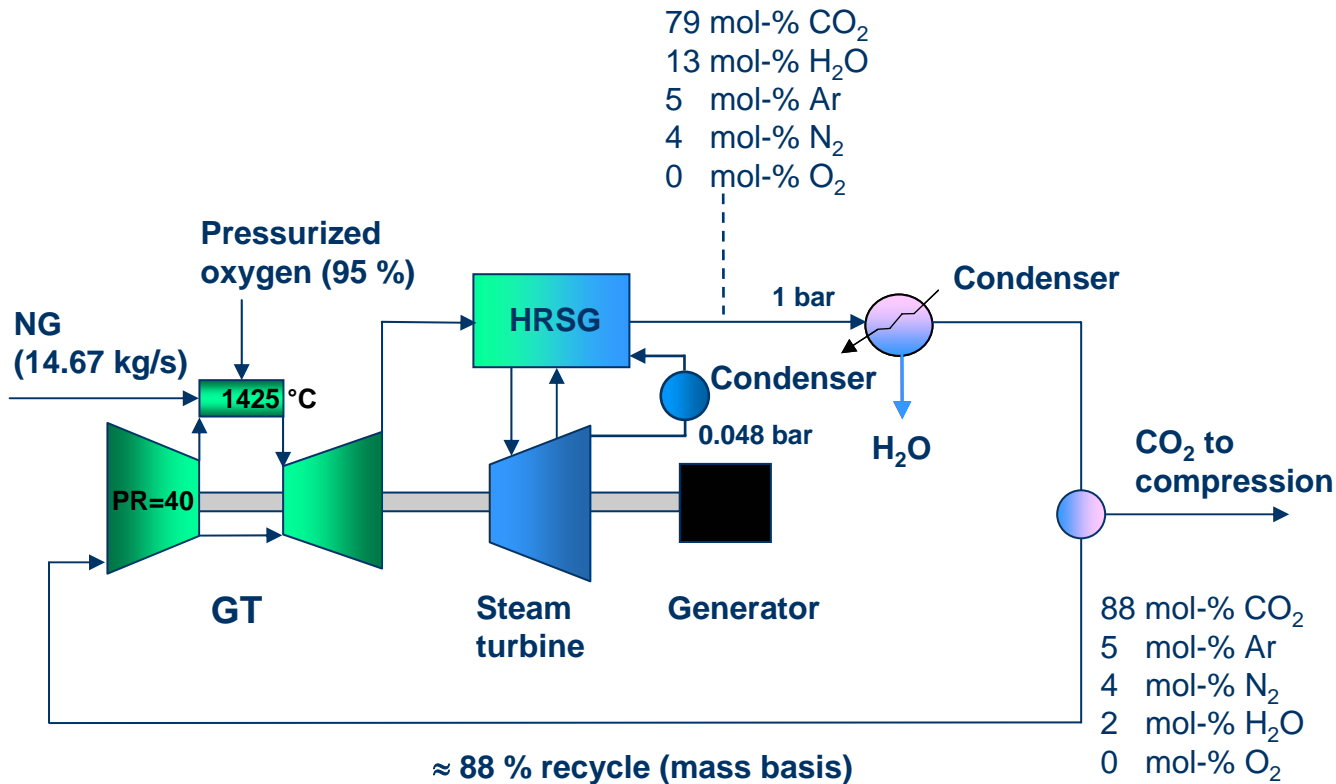
CO<sub>2</sub> (88%) and steam compressor

CO<sub>2</sub> (79%) and steam turbine

**No major technical or economic barriers!**

8 - Semi-closed oxygen combustion combined cycle - SCOC-CC													
Component	Inlet streams	Mass flow (kg/s)	Inlet pressure (bar)	Inlet temperature (°C)	Power (MW)	Polytropic efficiency	Isentropic efficiency	Outlet streams	Mass flow (kg/s)	Outlet pressure (bar)	Outlet temperature (°C)	Technical Comments	Economic Comments
C1	S1 (CO <sub>2</sub> 88.17% + N <sub>2</sub> 4.29% + Ar 5.35% + 2.18% steam)	536.14	1.01	19.00	193.9	91.5	88.37	S2 (CO <sub>2</sub> 88.17% + N <sub>2</sub> 4.29% + Ar 5.35%)	536.14	40.53	393.74	The compressor is similar to a gas turbine compressor, but the fluid is a mixture of CO <sub>2</sub> and steam for which the molecular weight is higher than for air, thus a new design is required.	New design required
T1	S8 (CO <sub>2</sub> 78.71% + Steam 12.68%)	608.2	39.31	1231.49	468.96	86.37	89.75	S9 (CO <sub>2</sub> 78.71% + Steam 12.68%)	608.2	1.06	629.11	The fluid is a mixture of CO <sub>2</sub> and steam for which the molecular weight is higher than for air, thus a new design is required. To be studied as a gas turbine. Potential steam/CO <sub>2</sub> mixture effects on materials would need to be investigated (acidic mixture - aggressive environment for materials)	New design required
T2	S31 (Steam)	82.83	116.25	556.24	29.81		90.00	S32 (Steam)	82.83	32.05	362.71	Standard steam turbine	
T3	S36 (Steam)	82.83	28.95	559.14	46.39		92.00	S37 (Steam)	82.83	3.96	282.39	Standard steam turbine	
T4	S38 (Steam)	98.90	3.96	287.54	65.37		88.00	S39 (Steam)	98.90	0.05	32.15	Standard steam turbine	
R1	S3 (CO <sub>2</sub> ) S4 (fuel) S5 (O <sub>2</sub> )	S3 411.23 S4 14.67 S5 57.39	S3 40.53 S4 70.00 S5 40.53	S3 393.74 S4 10.0 S5 15.0				S6 (CO <sub>2</sub> 76%, H <sub>2</sub> O 15%)	483.29	39.31	1425.00	The O <sub>2</sub> needs to be mixed with part of the CO <sub>2</sub> to give the design combustor exit temperature. The CO <sub>2</sub> can be used for combustor cooling.	New design required
H1	S23 (13% H <sub>2</sub> O, 79% CO <sub>2</sub> )	608.2	1.02	86.7	110.1			S24 water	29.5	1.01	19.0	The condenser pressure is 1 bar (in the Water cycle, the pressure is 0.07 bar). Corrosion is a challenge where condensation takes place. Condensation with inert gases present must be taken into account.	
						S25 (2% H <sub>2</sub> O, 88% CO <sub>2</sub> )	578.7	1.01	19.0				
	S28 water	2632.6	2.50	15		S29 water	2632.6	2.48	25.0				
H2-H16												Standard HRSG technology, but with somewhat different fluid composition compared to air-based system	

# WP6.2 Example: Semi-closed oxy-fuel CC



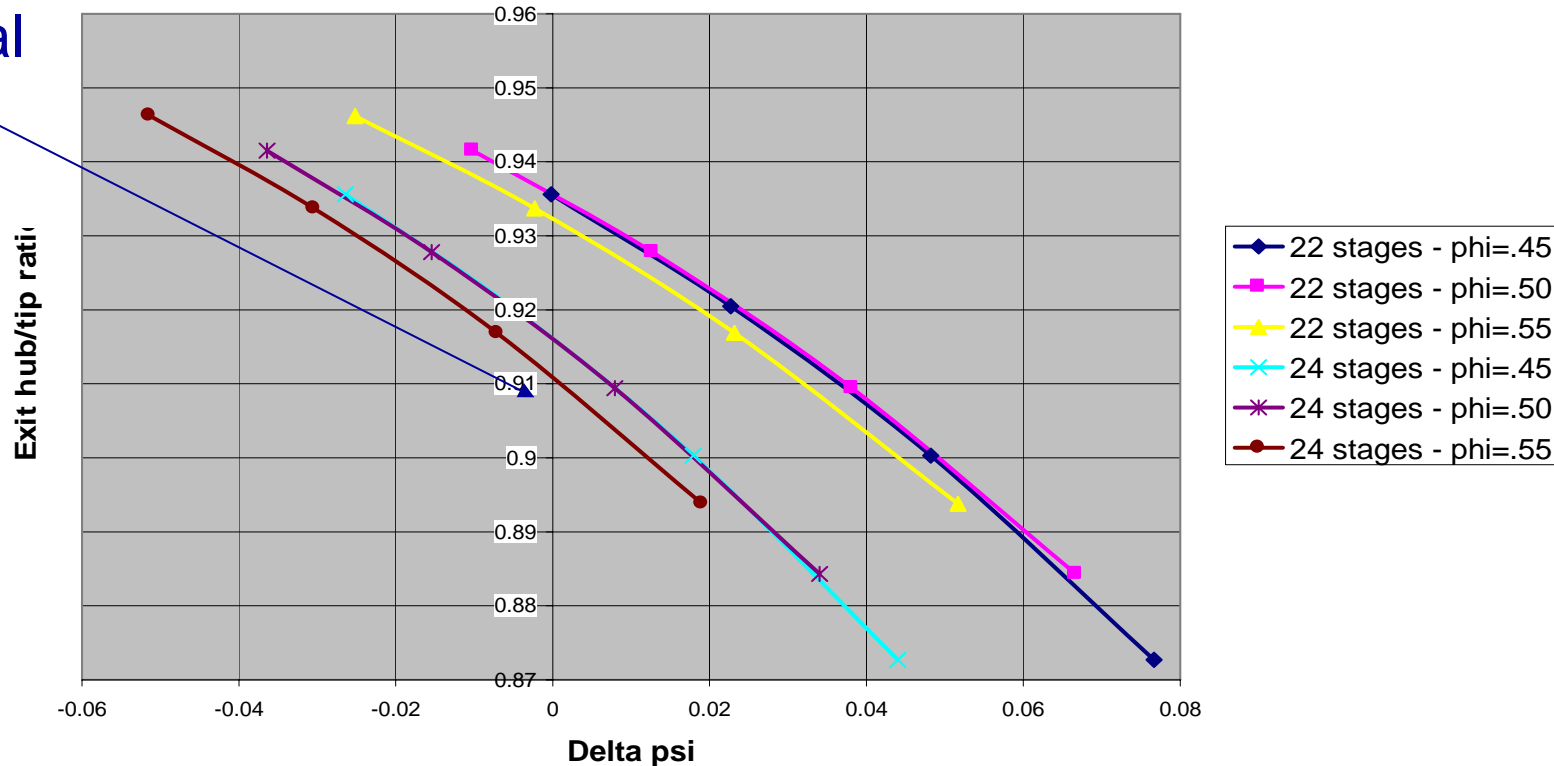
- Combined cycle with exhaust gas recirculation
- Combustion with oxygen
- 2-p HRSG, reheat
- Net efficiency **47.7 %**
- Net power 325 MW
- **99.9 %** CO<sub>2</sub> capture efficiency
- CO<sub>2</sub> emission 0.6 g CO<sub>2</sub>/kWh<sub>e</sub>
- ASU 0.30 kWh/kg O<sub>2</sub>
- Critical components
  - Turbomachinery for CO<sub>2</sub>/H<sub>2</sub>O
  - Near-stoichiometric combustion

# WP6.2 Example: Semi-closed oxy-fuel CC

## CO<sub>2</sub> and steam compressor

Change in loading coefficient for PR=40 against exit hub/tip ratio

Ideal operational region

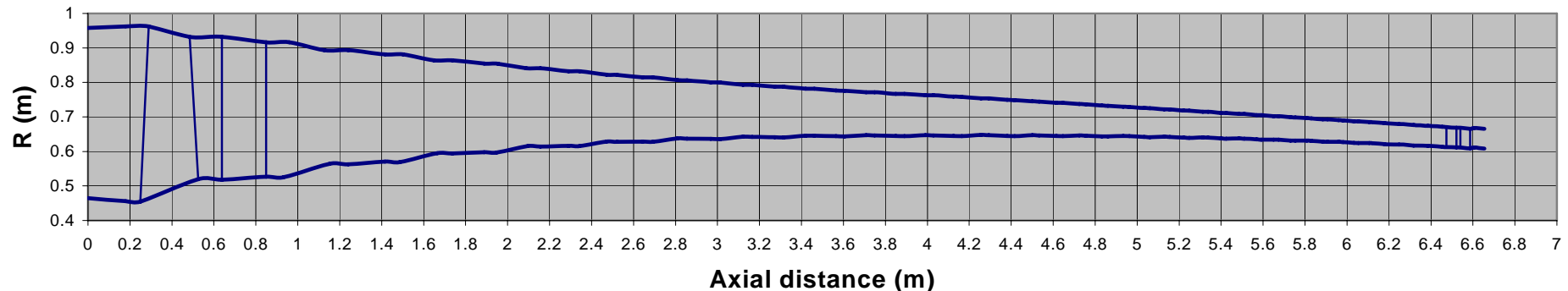


A compromise configuration for good surge margin and low sensitivity to clearance losses resulted in 24 stages

# WP6.2 Example: Semi-closed oxy-fuel CC

## CO<sub>2</sub> and steam compressor

Annulus of initial compressor concept



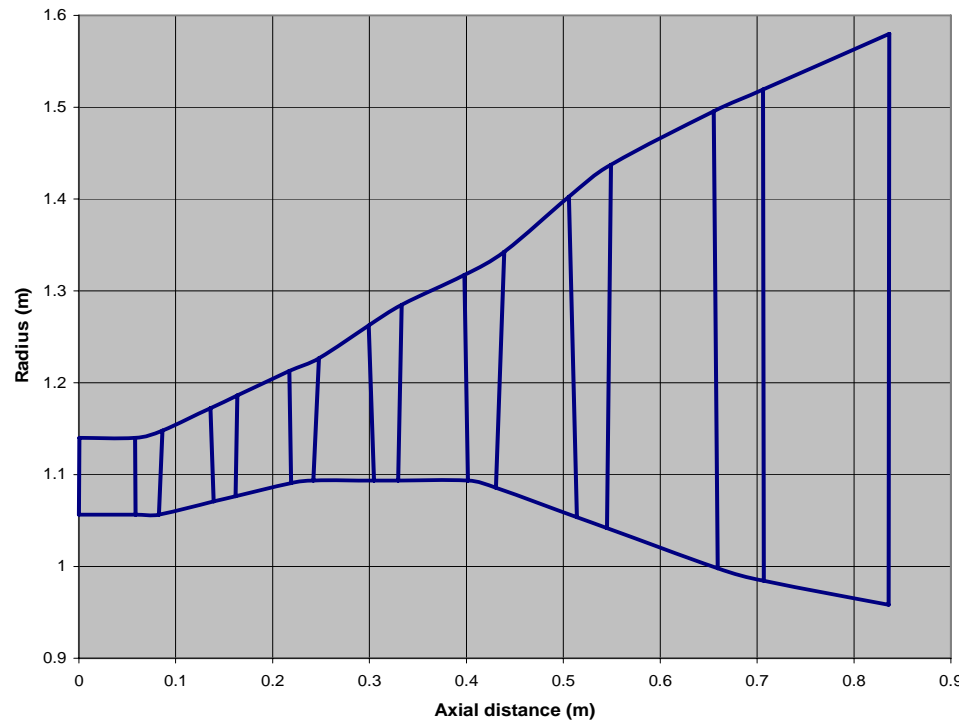
## Conclusions

- The working fluid of the compressor necessitates the design of a radically different compressor from those currently in use in 50 Hz industrial gas turbines
- Working fluid results in the need for more stages at lower exit radius, the impact of the longer rotor on rotor dynamics should be investigated
- If the compressor parameters are not significantly changed, high efficiencies consistent with cycle calculations should be obtained

# WP6.2 Example: Semi-closed oxy-fuel CC

## CO<sub>2</sub> and steam compressor

Annulus of initial turbine concept



Four stages, high hub/tip ratio at first stage

## Conclusions

- Due to working fluid, a new turbine is required
- Implications of CO<sub>2</sub> as the cooling gas should be assessed
- First stage should be optimised with respect to tip clearance and cooling flows

# WP6.4

“Methodology for modelling and screening of optional concepts”

- Performed by the University of Ulster (UK)
  - Input from the other WPs
  
- On going work
  - Precise information about module costs (boiler island, piping, turbine, heat exchangers) is currently collected from the partners.
  - Implementation of economic analysis using the ECLIPSE toolbox.
  
- Expected results
  - Economic analysis is expected for the end of **July 2006**
  - Followed by a sensitivity analysis that is to be completed at the end of **December 2006**
  - CO<sub>2</sub> avoidance cost including transportation and storage at the end of **February 2007**

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## ■ ENCAP SP6

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## ■ WORK PACKAGES

- WP6.1 (Cycle analysis)
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- WP6.4 (Economic Evaluation)

## ■ CONCLUSIONS



## Conclusions 1(2)

- The semi-closed oxygen combustion combined cycle (SCOC-CC) is one of the most promising cycle
  - Efficiency (47.7 %) almost as high as for the S-Graz cycle (the cycle with the highest efficiency, 48.9 %)
  - Optimisation could improve the efficiency by up to 0.5 %-points
  - The SCOC-CC is the least complex of the oxy-fuel cycles

## Conclusions 2(2)

- General disadvantages of oxy-fuel cycles
  - Large fraction of non-condensable gases in the stream sent to the CO<sub>2</sub> compression train (10 mol-%)
  - The energy required for purification has not been considered
  - The S-Graz cycle and the Water cycle have very low condenser pressures ( $\Rightarrow$  large, expensive heat exchangers)

**Thank you for your attention!**