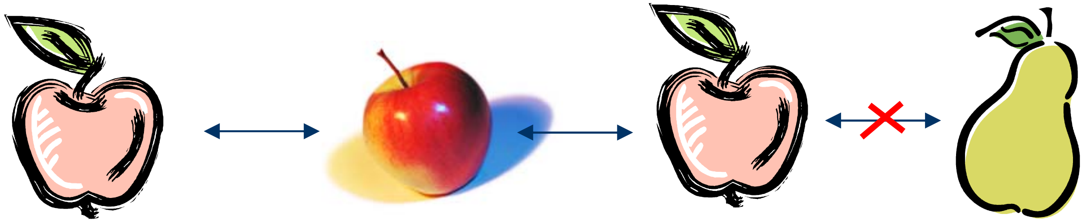


Benchmarking of power cycles with CO_2 capture

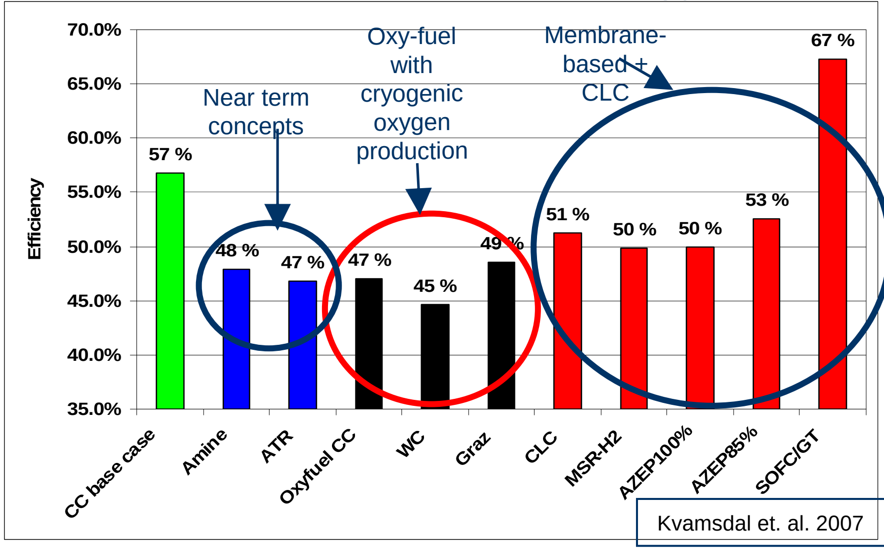
The impact of the chosen framework

4th Trondheim Conference on CO_2 Capture, Transport and Storage

Kristin Jordal, SINTEF Energy Research

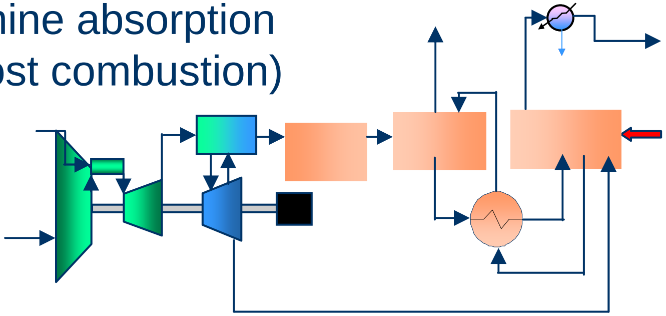
The benchmarking activity at SINTEF/NTNU within BIG CO2

- Nine different power cycles with CO_2 capture evaluated
- Fuel is natural gas
- Reference case is a gas turbine combined cycle of 386 MW and a thermal efficiency of **56.7%**
- The work has been presented at GHGT-7 and in *Energy*

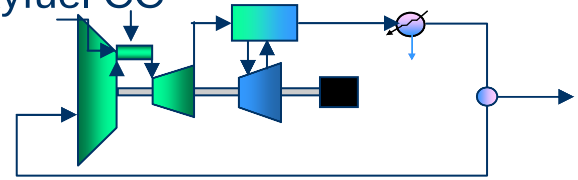


Kvamsdal et. al. 2007

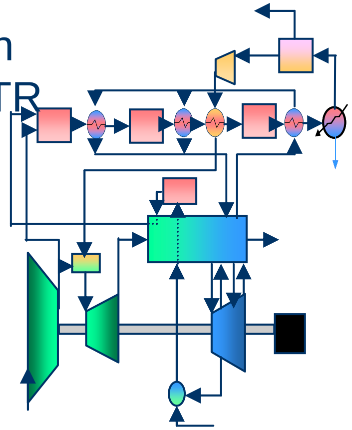
Amine absorption (post combustion)



Oxyfuel CC



Pre-combustion capture with ATR

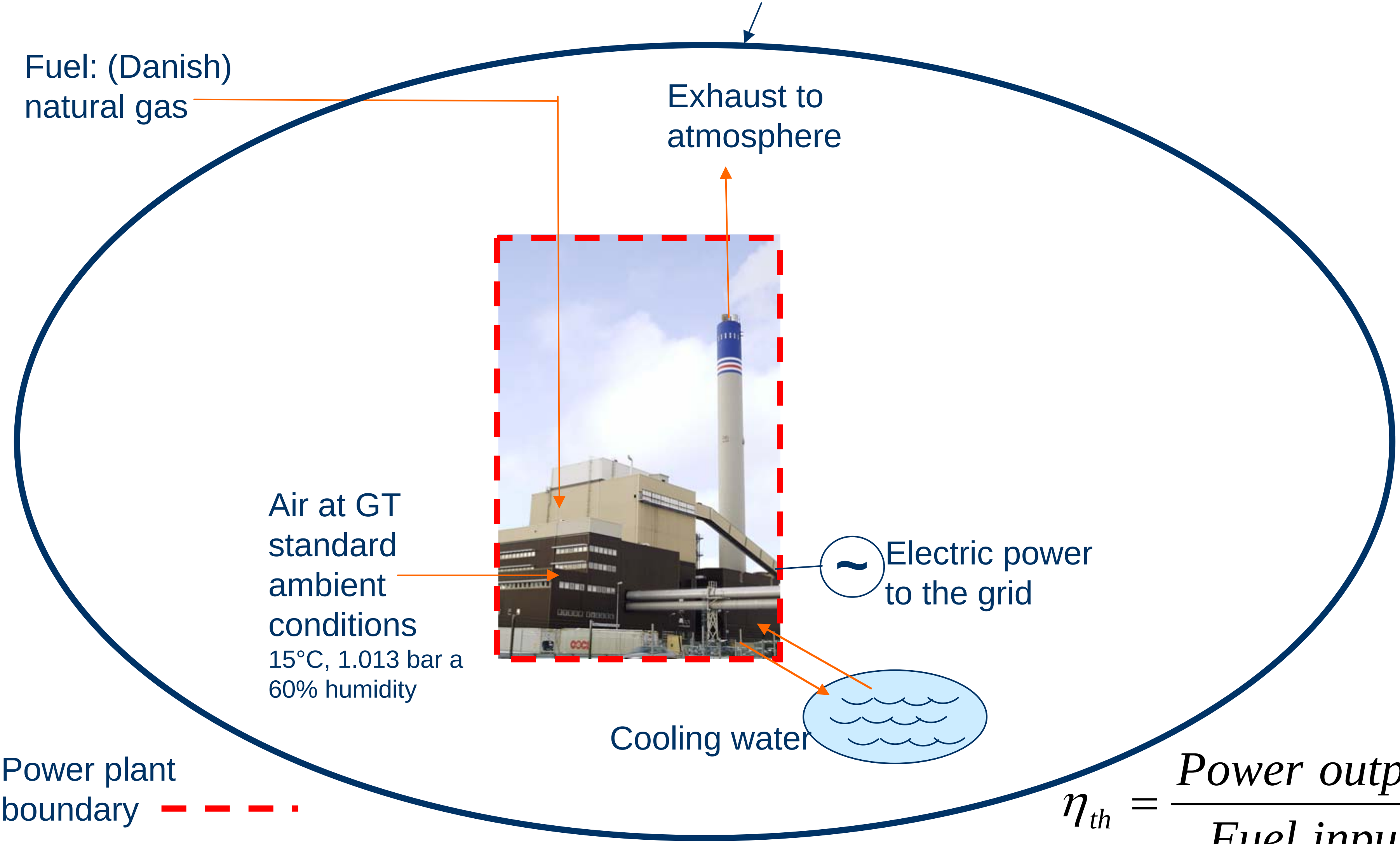


About quantitative benchmarking

- The methodology for general thermodynamic studies of different power cycles is well established - it is known what process conditions give a high thermal efficiency
- CO_2 capture and compression is a new element to be included in power cycles
- Benchmarking of different power cycles with CO_2 capture against a reference case without capture has become an acknowledged method to evaluate the impact of CO_2 capture on power cycle efficiency (and cost)

- The boundary for a power plant with CO_2 capture is more complex than that of a standard power plant

”My” power plant boundary 10 years ago…



Ambient boundary

Fuel: (Danish)
natural gas

Exhaust to
atmosphere

Air at GT
standard
ambient
conditions
15°C, 1.013 bar a
60% humidity

~ Electric power
to the grid

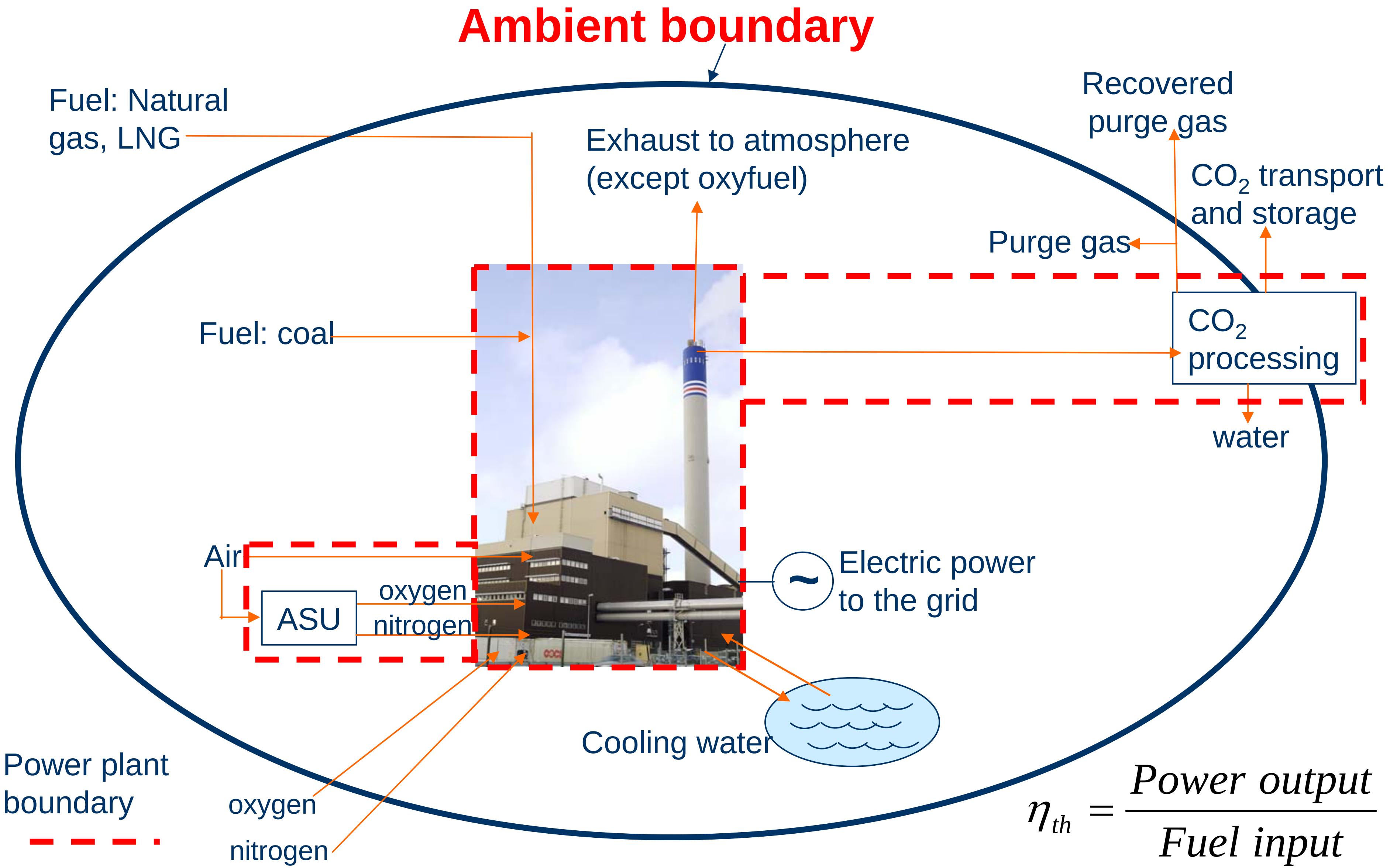
Cooling water

Power plant
boundary

$$\eta_{th} = \frac{Power\ output}{Fuel\ input}$$

Picture of Västhamnsverket in Helsingborg, Sweden

The power plant boundary with CO_2 capture



Ambient boundary

Fuel: Natural gas, LNG

Exhaust to atmosphere (except oxyfuel)

Recovered purge gas

CO_2 transport and storage

Purge gas

Fuel: coal

CO_2 processing

water

Air

ASU

oxygen

nitrogen

Electric power to the grid

Cooling water

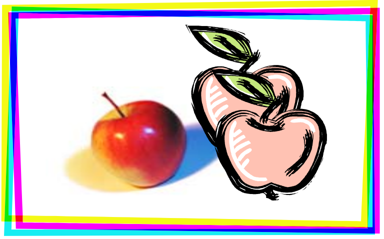
Power plant boundary

oxygen

nitrogen

$$\eta_{th} = \frac{Power\ output}{Fuel\ input}$$

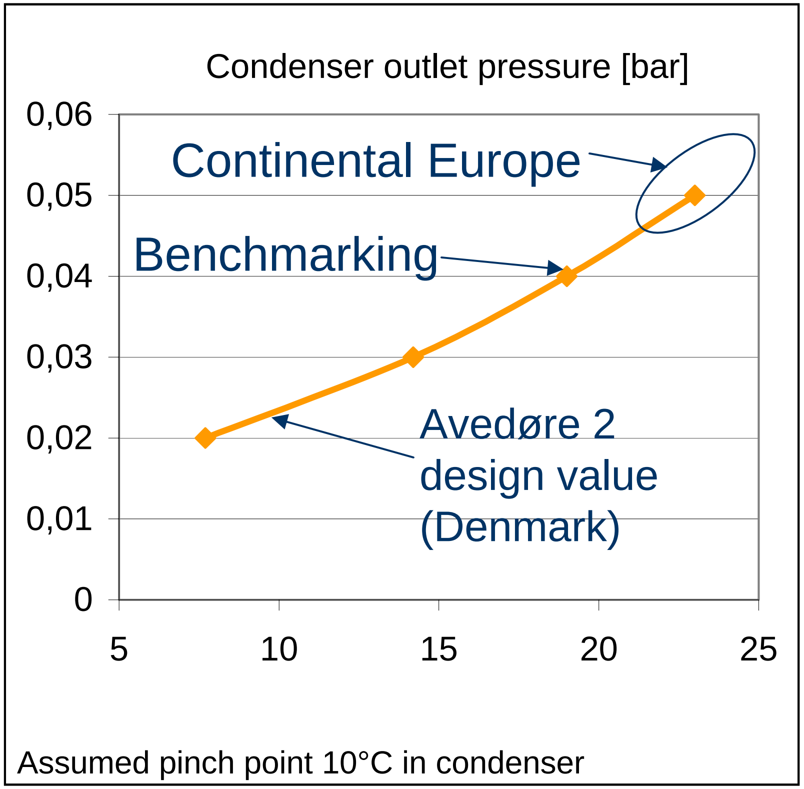
Framework selection



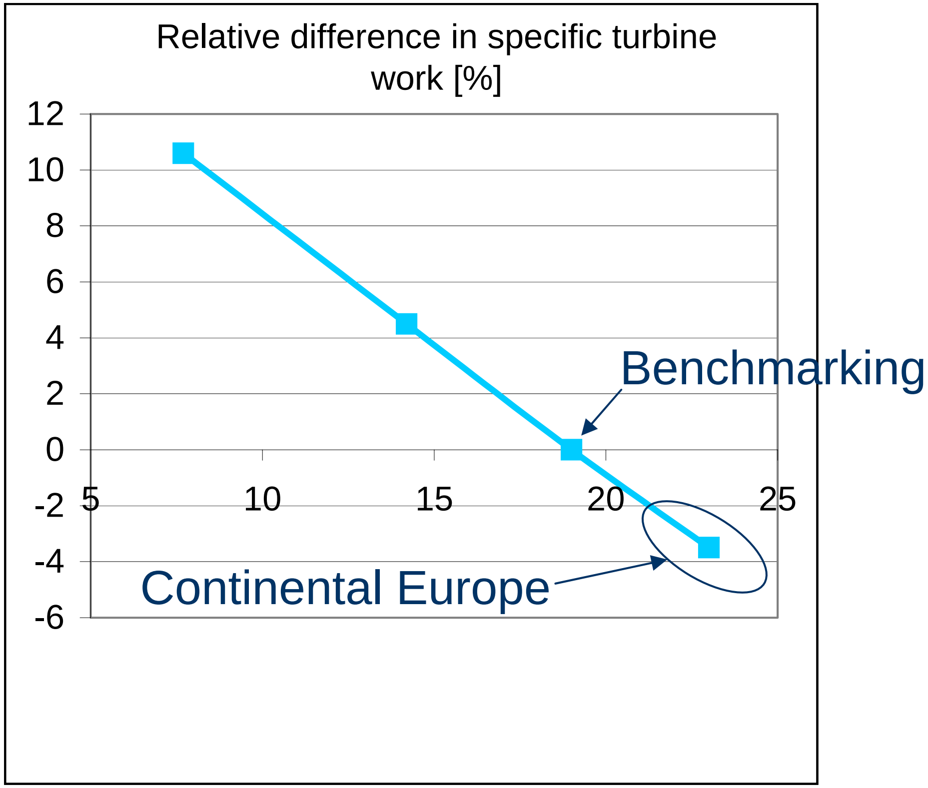
- Standard boundary conditions or site specific?
  - ”Standard” boundary conditions, as far as possible, make the results more of general interest
  - Site-specific boundary conditions give a more true picture for a selected site or geographic area
    - Ambient temperature
    - Cooling water temerature

      } Norwegian conditions favourable!
    - Natural gas delivery conditions (LNG or gas?)
    - CO_2 final pressure
    - Oxygen production on site?
- What technology level do we want to reflect?
  - Current (known) technology status – previous SINTEF benchmarking
  - Estimated future technology, when CO_2 capture is likely to be generally adopted for new power plants – topic in this presentation
    - Purpose is to present an idea of what could be the development potential of some different capture technologies

Site-specific conditions: impact of cooling water temperature (=condenser pressure)



Assumed pinch point 10°C in condenser



- Relative gain from reduced cooling water temperature (right picture) based on LP turbine in combined cycle only.
- Value reduced when considering the entire turbine train with multiple steam extractions.

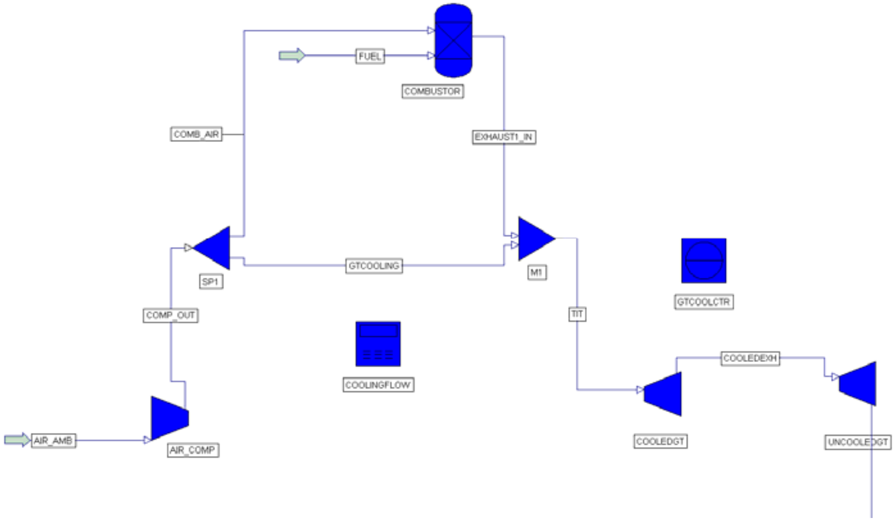
Example of framework selection: Future technology levels

Parameter	Previous benchmarking	~5-10 years (?)	~15-20 years(?)
GT combustor outlet temperature [°C]	**1328**	**1428**	**1528**
GT max blade temperature (rough estimate)	900	940	980
Max steam temperature [°C]	560	600 (done today already)	700 (goal of R&D programs), 656 max in this work
HP/IP steam turbine inlet pressure [bar]	111/27	Result of optimisation	Result of optimisation (HP supercritical?)
Amine re-boiler steam requirement [kJ/kg CO_2]	3.4 (low figure!)	2.8	1.5 (unrealistic for temp-swing only)

Each new technology level requires a new reference case without CO_2 capture!

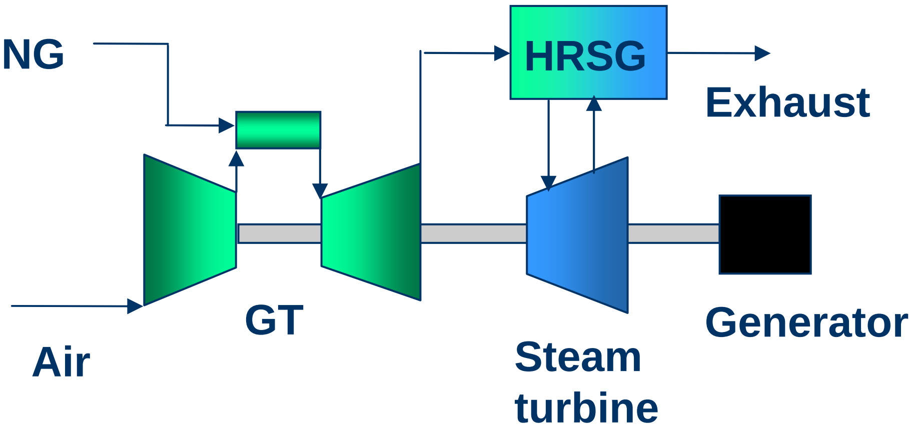
Establishing new reference cases (1): Gas turbine modelling, ”future technology”

- A realistic generic gas turbine required when increasing the combustion temperature
- Temperature increase possible due to increased materials temperature and better blade cooling
- Pressure ratio adapted for anticipated exhaust temperature



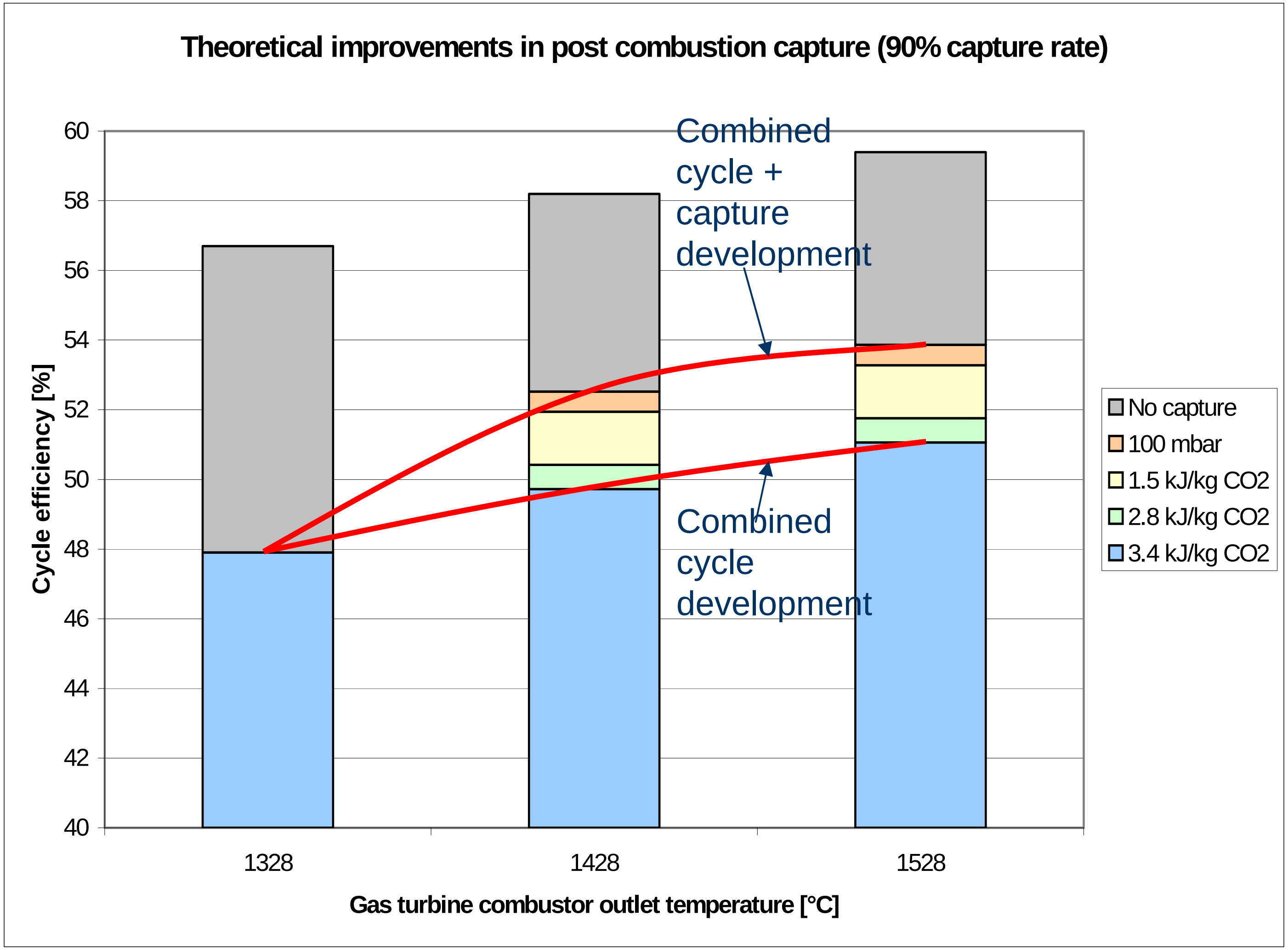
Establishing new reference cases (2): Combined cycle modelling

- For each new gas turbine, a new reference combined cycle must be established
- We cannot compare a CO_2 capture cycle based on advanced power plant data against a reference cycle reflecting older technology
- Efficiency optimisation in this case was done in GTPRO



T_g [°C]	P_{el} [MW]	Efficiency [%]	Steam data [bar/°C/°C]
1328	386	56.7	111/560/560
1428	411	57.9	111/560/560
1428	414	58.2	140/580/580
1528	436	58.8	111/560/560
1528	440	59.4	180/600/600

Post combustion capture – development possibilities



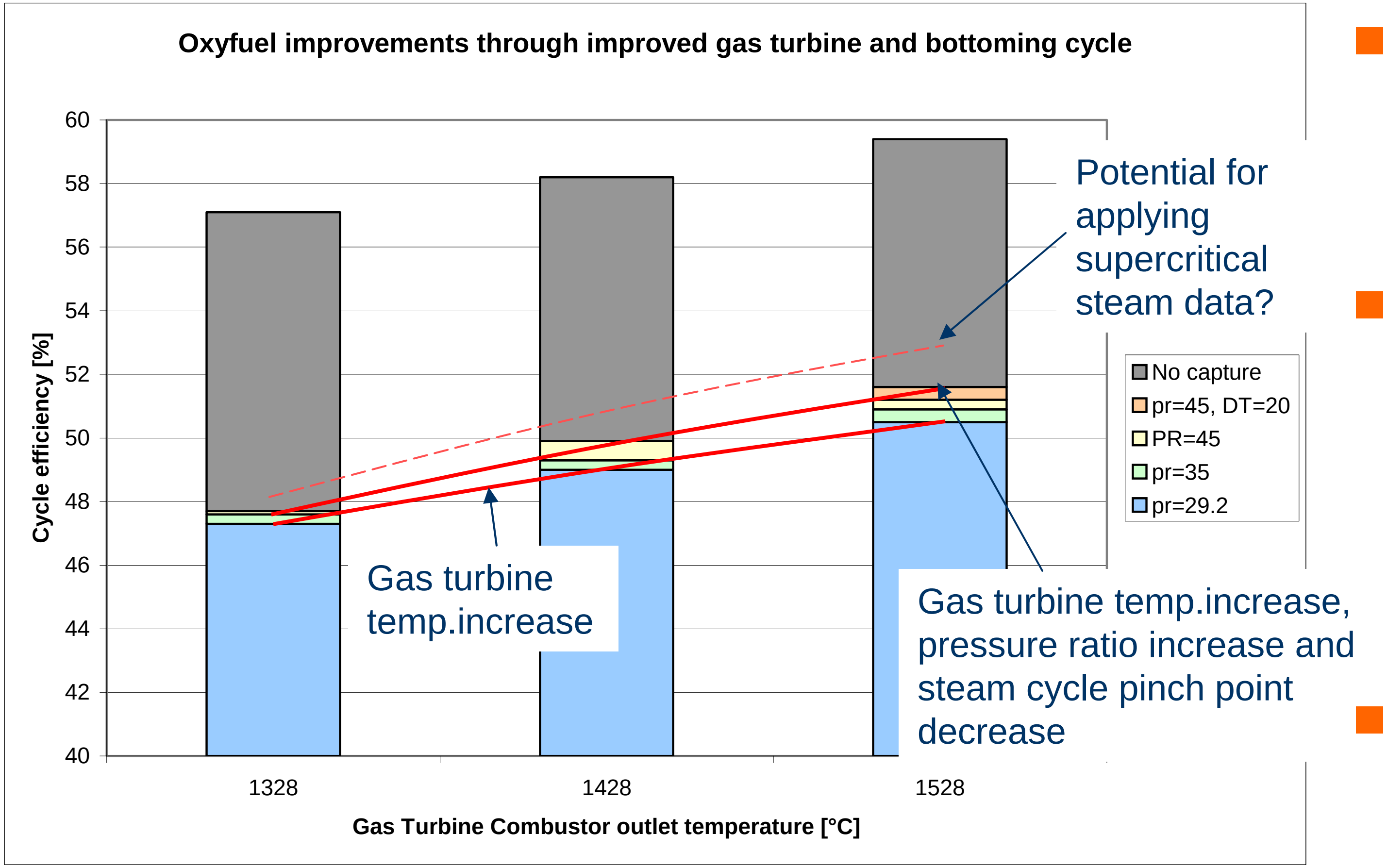
Combined cycle + capture development

Combined cycle development

N.B.! Upper limit values are extremely optimistic!

Should be regarded as an extreme limit for the potential for this thechnology

Oxyfuel CC development possibilities



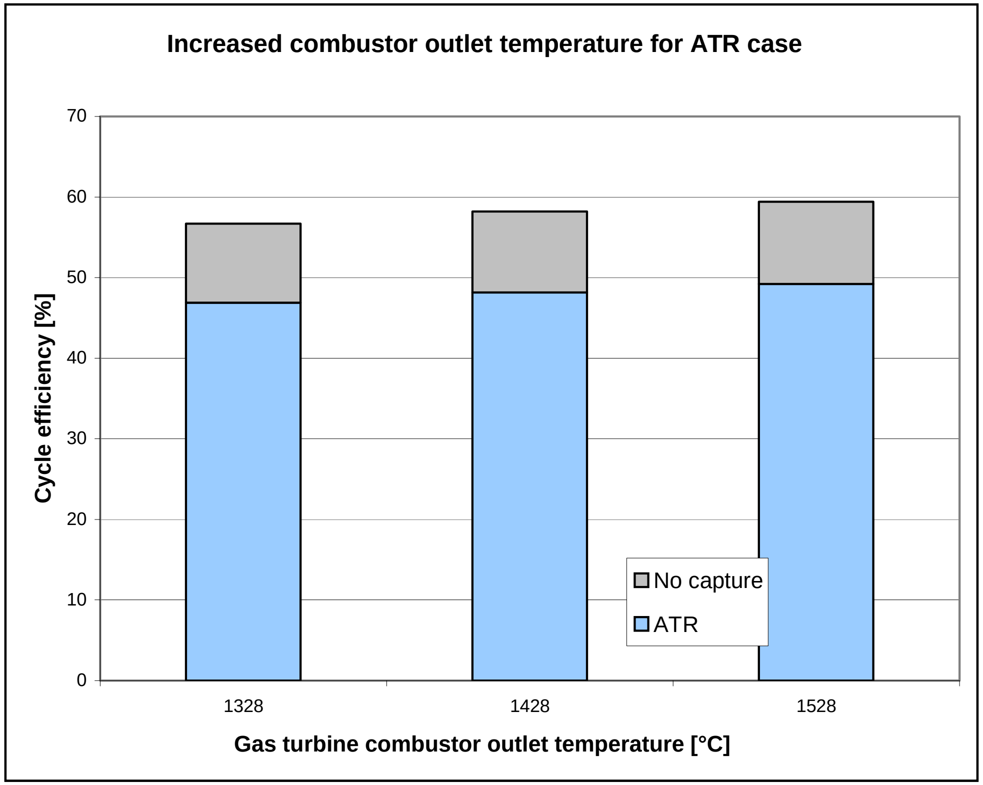
Potential for applying supercritical steam data?

Gas turbine temp.increase

Gas turbine temp.increase, pressure ratio increase and steam cycle pinch point decrease

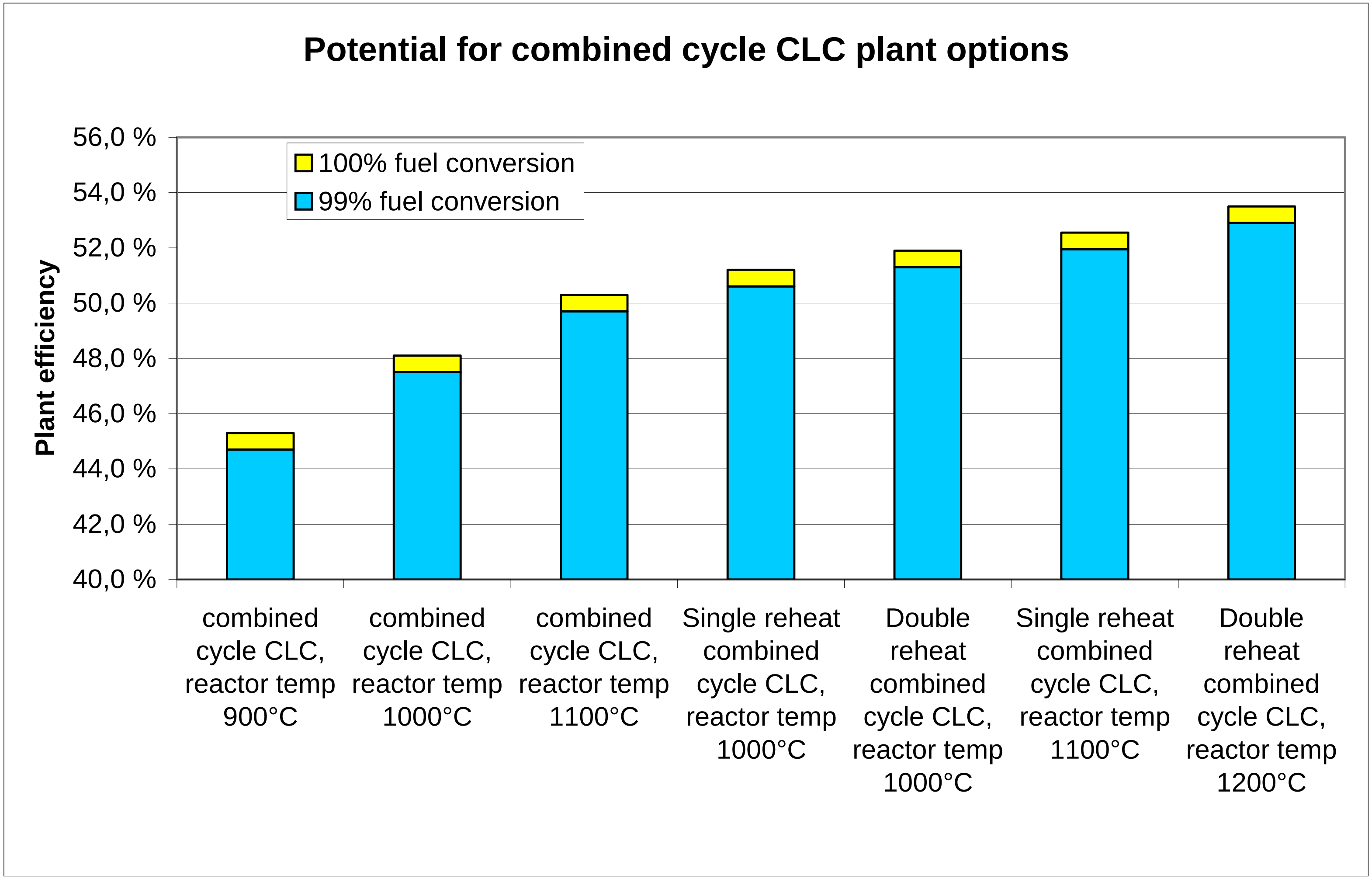
- Capture is more integrated in the oxyfuel CC than in the post combustion cycle.
- More difficult to push performance parameters towards the ”extreme” in a computational exercise
- Oxyfuel CC penalised by consistent framework for steam bottoming cycle???

Pre-combustion with ATR



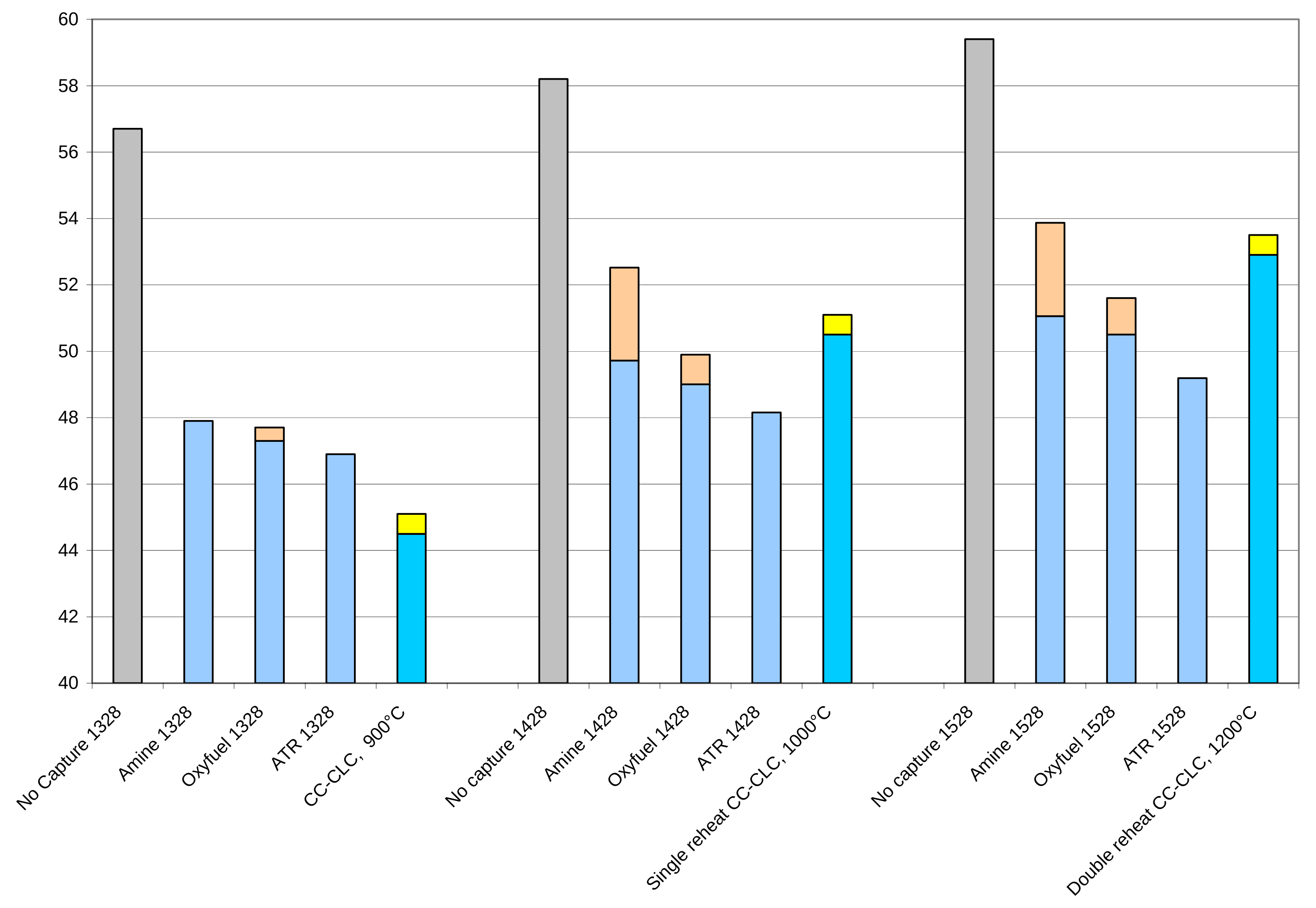
- CO_2 capture in pre-combustion with ATR even further integrated than in oxyfuel CC
- No benefit (in current process layout) from increasing GT pressure ratio
- Not possible (in current process layout) to use improved steam data from reference CC
- Only technology improvement with positive impact on performance is increased combustor outlet temperature

Chemical Looping potential



Source: Naqvi R., 2006, "Analysis of Natural Gas-Fired Power Cycles with Chemical Looping Combustion for CO2 capture", Doctoral Theses at NTNU, 2006:138.

Summary, future development potential



Conclding remarks, future development potential

- When considering future development potential, the same boundary conditions were applied as in previous benchmarking
- New reference combined cycles were established to reflect the anticipated technology development
- Post combustion capture has a low degree of integration with the power plant, and it is easy to produce theoretical results with increased cycle efficiency, beyond a realistic limit
- It appears from this work that the more integrated the CO_2 capture into the cycle, the more difficult it could actually be to improve cycle efficiency beyond combustor outlet temperature improvements
  - The development potential with evolving technology should be useful to consider for a manufacturer before deciding to pursue the development of a certain technology

Concluding remark: impact of chosen framework for CO_2 capture studies

- Main issue: be careful when presenting results and/or when interpreting results that are presented to you!
  - Is the framework for the study consistent?
  - What is included in the efficiency calculation?
  - What are the boundary conditions? (site specific? ISO standard?)
  - What is the technology level? Is it realistic? Outdated?
  - What is the reference case without CO_2 capture? Does it have the same framework as the case(s) with CO_2 capture?

Thank you for your attention!

BIG CO2 benchmarking: Stream input data (boundary conditions)

Fuel feed stream		
Composition		
N2	[mole%]	0,9
CO2	[mole%]	0,7
C1	[mole%]	82
C2	[mole%]	9,4
C3	[mole%]	4,7
C4	[mole%]	1,6
C5+	[mole%]	0,7
Properties		
Pressure	[bar a]	50
Temperature	[°C]	15
Molecular weight	[g/mol]	20,05
Density	[kg/Sm3]	0,851
Conditions		
lower heating value	[kJ/Sm3]	40448
lower heating value	[kJ/kg]	47594
Air feed streem		
Composition		
N2	[mole%]	77,3
CO2	[mole%]	0,03
H2O	[mole%]	1,01
Ar	[mole%]	0,92
O2	[mole%]	20,74
Properties		
Pressure	[bar a]	1,013
Temperature	[°C]	15

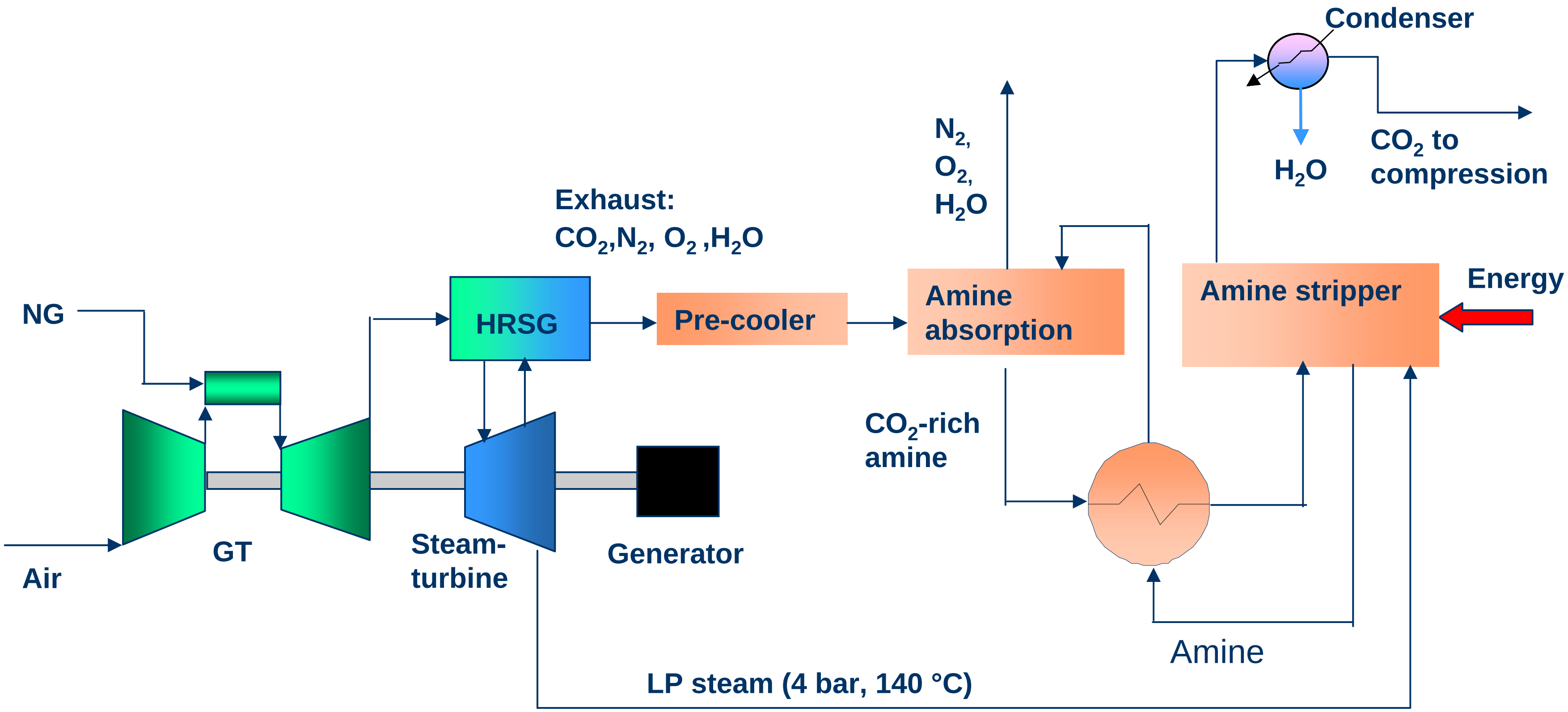
Oxygen feed streem		
Composition		
O2	[mole%]	95
N2	[mole%]	2
Ar	[mole%]	3
Properties		
Pressure	[bar a]	2,38
Temperature	[°C]	15
Conditions		
Energy production requirement	kJ/kg O2	812
CO2 outlet		
Composition		
CO2 concentration	[mole%]	88,6-99,8
Properties		
Pressure	[bar a]	200
Temperature	[°C]	30

BIG CO2 benchmarking: Computational assumptions (inside the power plant)

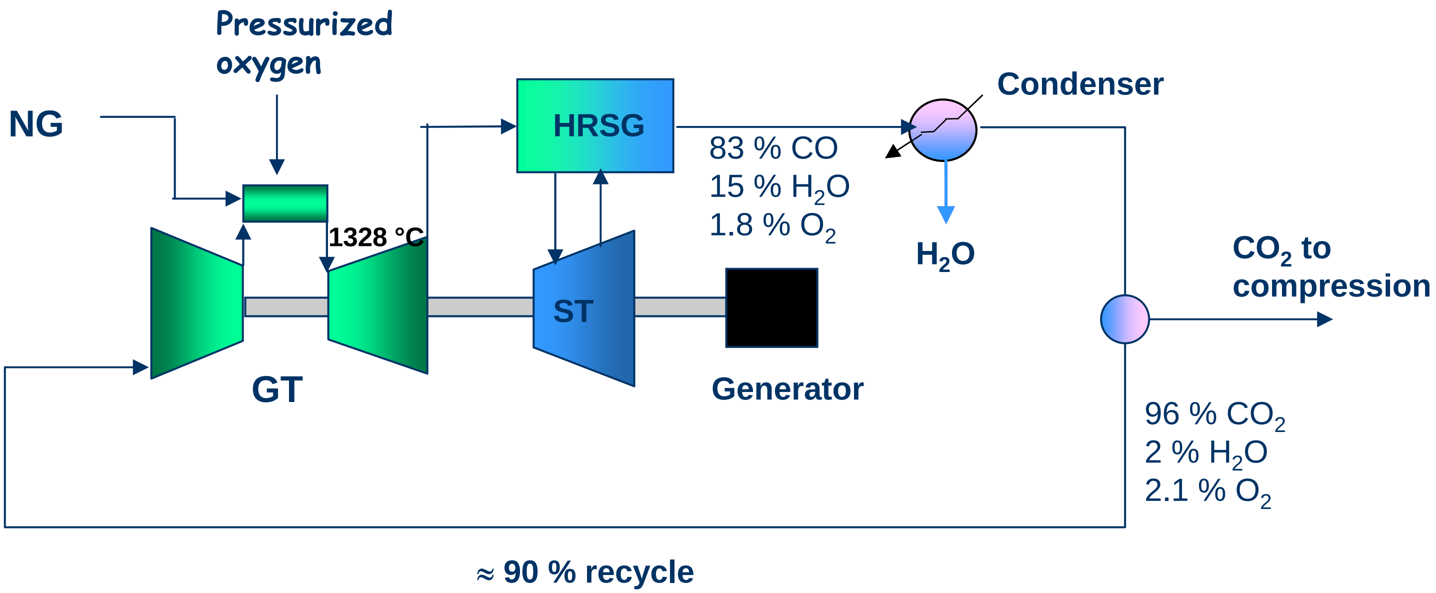
Heat exchangers		
Pressure drop	[%]	3
ΔT_{min} gas/gas	[°C]	30
ΔT_{min} gas/liquid	[°C]	20
HRSG ΔT steam out/exhaust in	[°C]	20
HRSG pinch point	[°C]	10
CO2 compression intercooler temeprature	[°C]	30
Gas side pressure drop through HRSG	[mbar]	40
Reactors		
GT Combustor and reactor pressure drop	[%]	5
Duct burner pressure drop	[%]	1
Combustor outlet temperature (max)	[°C]	1328
Reactor outlet temperature, CLC and AZEP	[°C]	1200
Turbomachinery efficiencies		
Main GT Compressor polytropic efficiency	[%]	91
Main GT Uncooled turbine polytropic efficiency	[%]	91
Small compressor polytropic efficiency	[%]	87
Small turbine polytropic efficiency	[%]	87
CO2 compression isentropic efficiency stage 1	[%]	85
CO2 compression isentropic efficiency stage 2	[%]	80
CO2 compression isentropic efficiency stage 3	[%]	75
CO2 compression isentropic efficiency stage 4	[%]	75
SOFC/GT cycle compressor polytropic efficiency	[%]	87,5
SOFC/GT cycle turbine polytropic efficiency	[%]	87,5
AZEP and SOFC/GT recirc compressor polytropic efficiency	[%]	50
HP steam turbine isentropic efficiency	[%]	92
IP steam turbine isentropic efficiency	[%]	92
LP steam turbine isentropic efficiency	[%]	89
Pump efficiency (incl. motor drive)	[%]	75
Note: Small compressor/turbine refers to H2O/CO2 recircualtion compressor, ATR and MSR-H2 fuel compressors, MSR-H2, CLC and AZEP CO2/steam turbines		

Steam power cycle		
Max steam temperature, pure steam cycle	[°C]	560
HP steam turbine inlet pressure	[bar a]	111
IP steam turbine inlet pressure	[bar a]	27
LP steam turbine inlet pressure	[bar a]	4
Max temperature WC HP turbine	[°C]	900
Deaerator pressure	[bar a]	1,2
Condenser pressure, pure steam cycle	[bar a]	0,04
Condenser pressure, Water Cycle	[bar a]	0,045
Condenser pressure, Graz cycle	[bar a]	0,046
Condenser pressure, Oxyfuel CC	[bar a]	1,01
Cooling water inlet temperature	[°C]	8
Cooling water outlet temperature	[°C]	18
CO2-capture-specific cycle units		
CO2 absorption recovery rate, ATR and post combustion	[%]	90
CO2 stripper outlet pressure, ATR and post combustion	[bar a]	1,01
Amine re-boiler steam requirement	[MJ/kg CO2]	3,4
Pressure drop in absorption column	[mbar]	150
Methane conversion MSR-H2	[%]	99,8
Shift reaction conversion MSR-H2	[%]	99
H2 separation MSR-H2	[%]	99,6
CLC degree of carrier oxidation	[%]	100
CLC degree of carrier reduction	[%]	70
CLC degree of fuel utilisation	[%]	100
Auxiliaries		
Generator mechanical efficiency	[%]	98
O2 and CO2 compression mechanical drive efficiency	[%]	95
Auxiliary power requirements (of net plant output)	[%]	1

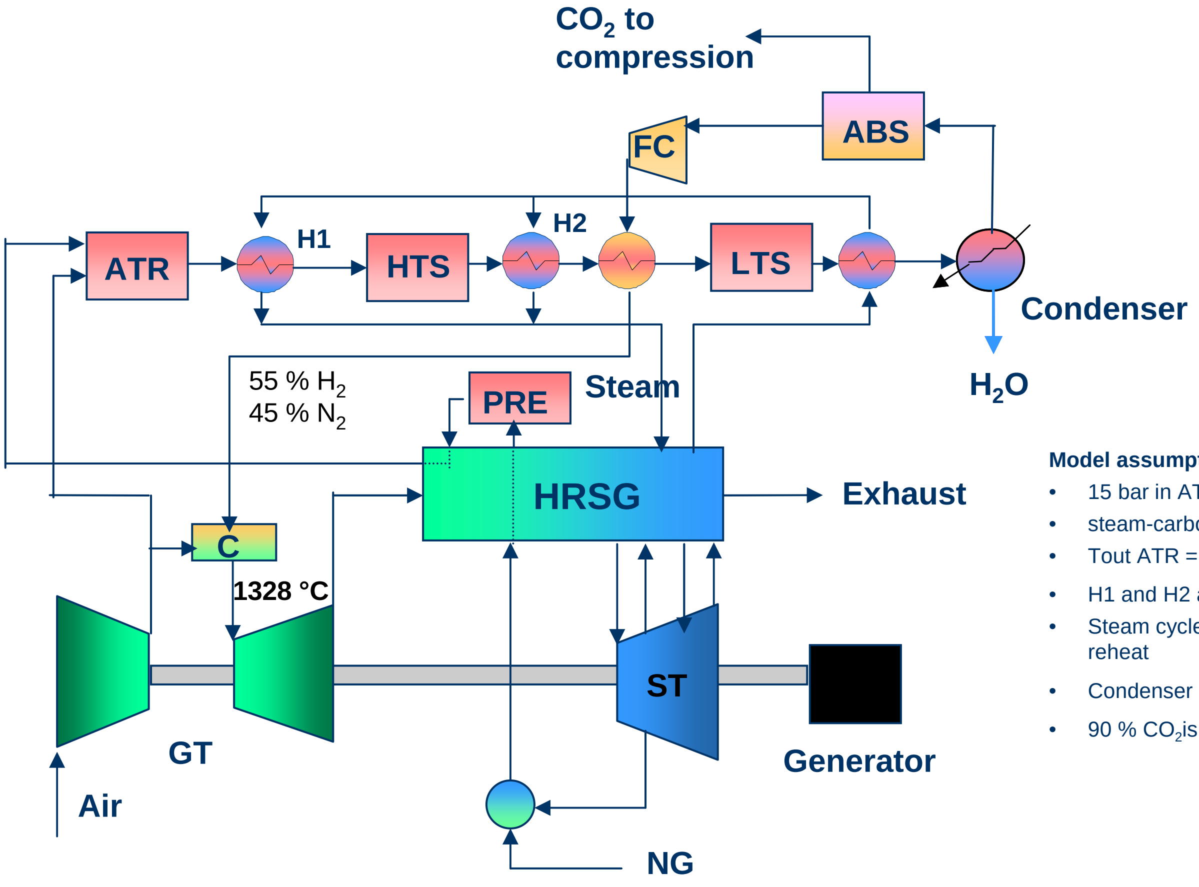
Konsept 1a: Eksosgassrensing med amin



Oxy-fuel CC


Pressurized oxygen
NG
HRSG
Condenser
83 % CO
15 % H_2O
1.8 % O_2
1328 °C
H_2O
CO_2 to compression
ST
GT
Generator
96 % CO_2
2 % H_2O
2.1 % O_2
≈ 90 % recycle

Konsept 2a: Reformering av hydrokarboner vha autotermisk reaktor (ATR)



Model assumptions:

- 15 bar in ATR
- steam-carbon ratio = 2
- Tout ATR = 900 °C
- H1 and H2 are boilers
- Steam cycle: 3 pressure levels (4, 27 og 111 bar) and reheat
- Condenser heat used in the absorption stripper
- 90 % $CO_2$is removed by absorption