ASME ORC 2015
3rd International Seminar on ORC Power Systems
12-14 October 2015, Brussels, Belgium

PERFORMANCE EVALUATION OF NGCC AND COAL-FIRED STEAM POWER PLANTS WITH INTEGRATED CCS AND ORC SYSTEMS

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Introduction

Carbon capture and storage (CCS) is an important tool for the power sector to reduce CO_2 emissions.
CCS alone will account for 19% of the total CO_2 emissions reduction in 2050.
Coal-fired steam and natural gas-fired power plants are expected to contribute to about 65 and 30 % of the total installed power generation capacity equipped with CCS.
CO_2 capture from power plants is both very capital- and energy-intensive.

CO_2 removal causes substantial efficiency penalties to the power plant:

1. Thermal energy, typically at 140 °C, for driving the desorption reaction in the reboiler column.
2. Electrical energy for driving exhaust gas fans and solvent circulation pumps,
3. Electrical energy for compressing and pumping CO_2 to high pressure for transport and storage.

Near-term CO_2 removal system based on chemical solvents are expected to reduce plant efficiency in the order of 8-12 percentage points at 90 % CO_2 capture.

R&D projects are dedicated to the development of more efficient or less expensive capture processes.
Exhaust gas recirculation (EGR) was proposed for NGCC to increase the CO_2 concentration and reduce costs.
Efficiency losses are reduced by about 1% pt and capital costs for the capture unit are reduced by 20-30%.

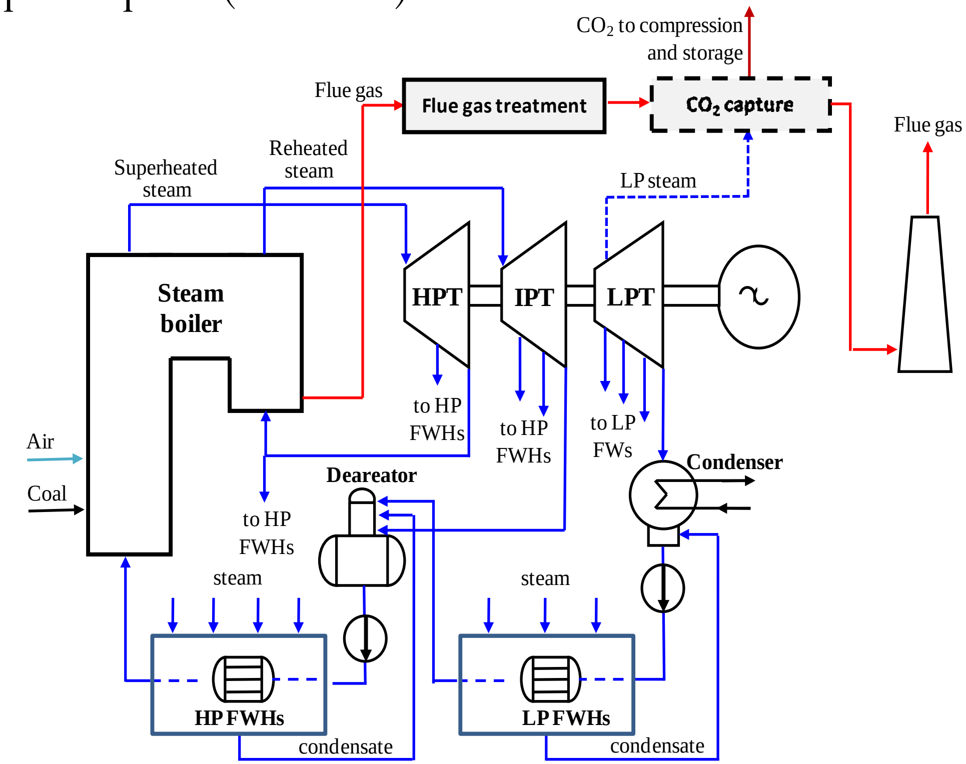
Little attention was given to recovering low temperature heat rejected from capture plants and the auxiliaries.

This paper examines performance impact of recovering low temperature heat with an **Organic Rankine Cycle (ORC)** integrated with a post-combustion CO_2 capture for coal-fired steam plants and natural gas combined cycle.

The study is based on complex simulation models specifically developed through **HYSYS™** and **Gate-Cycle™** commercial softwares.

PC power plant

Large scale **PC (Pulverized coal-fired)** steam power plant (400 MW)

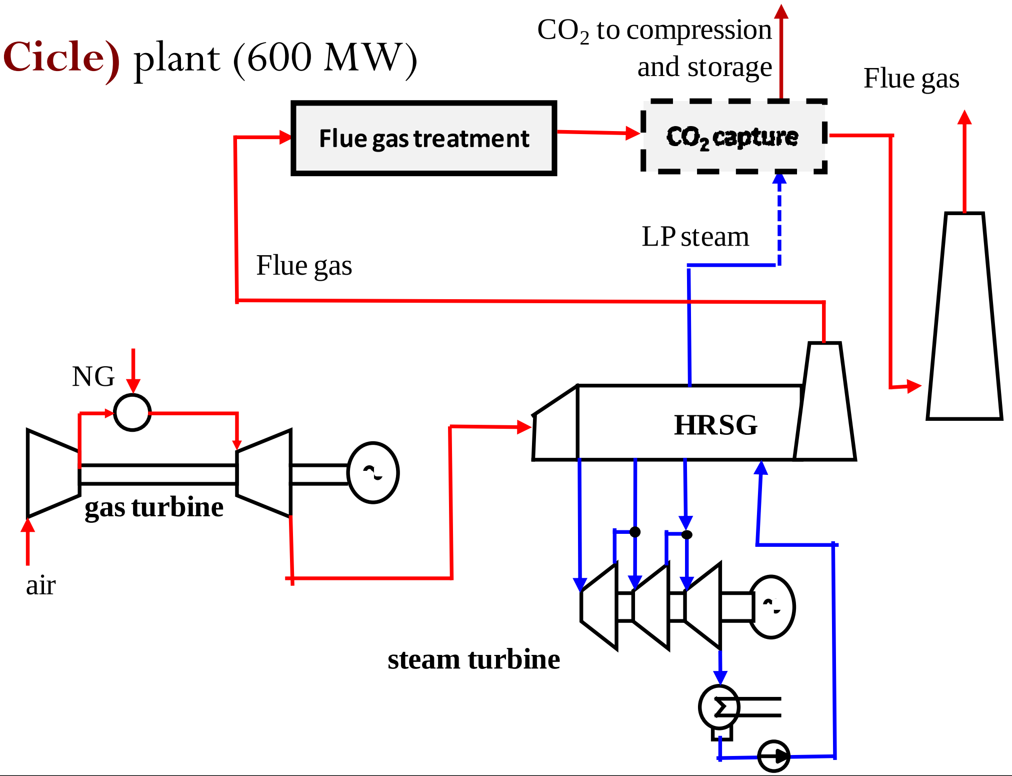


Fuel chemical power input	MW	1000.0
Coal mass flow	kg/s	39.4
Coal lower heating value (LHV)	MJ/kg	25.39
Air mass flow	kg/s	359.8
HP/IP/LP steam temperature	°C	537.9/540.0/322.6
HP/IP/LP steam pressure	MPa	25.0/3.4/0.7
Condenser steam temperature and pressure	°C/kPa	26.7/3.5
High/low pressure heat exchangers minimum ΔT	°C	-1.5/1.5

Natural Gas Combined Cycle

Large scale **NGCC (Natural Gas Combined Cicle)** plant (600 MW)

- Gas turbine
- Triple pressure steam cycle

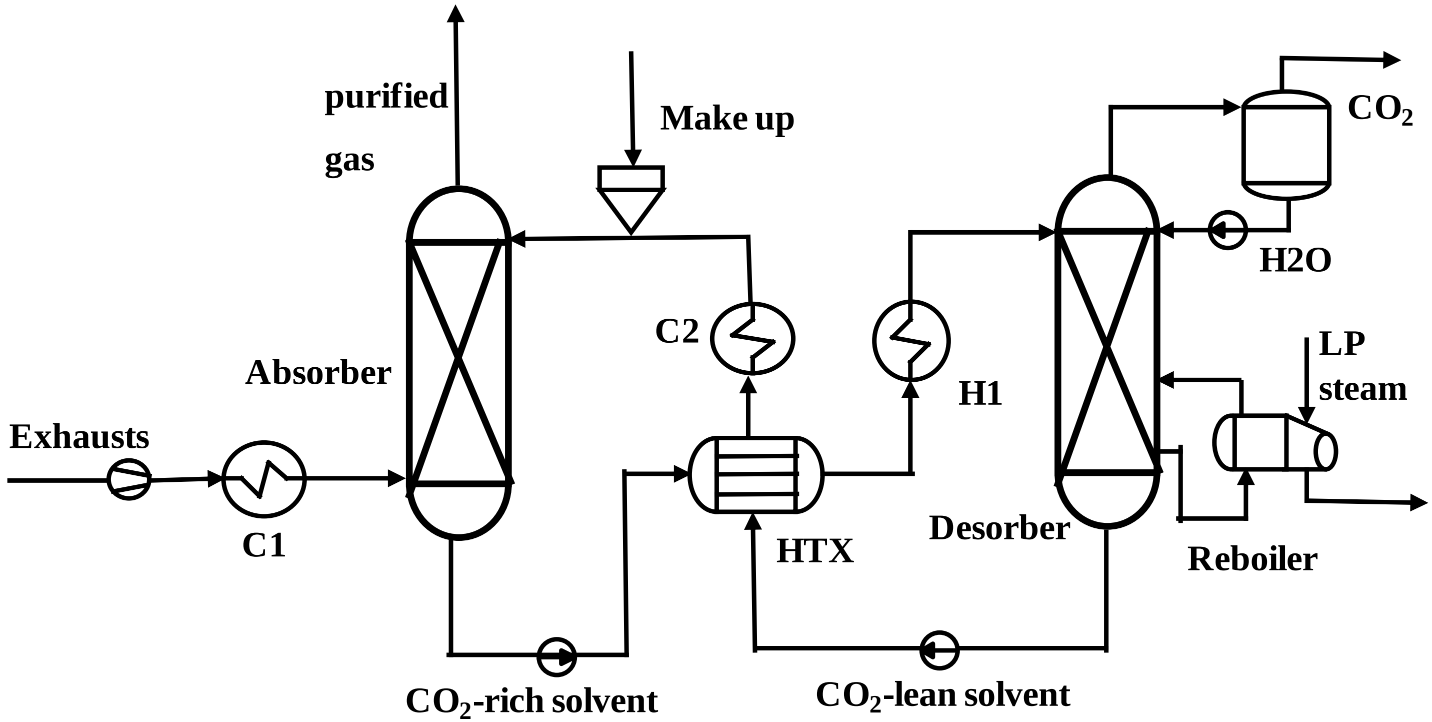


Gas turbine		
Fuel chemical power input	MW	1000.0
Natural gas mass flow	kg/s	20.0
Exhaust mass flow	kg/s	877.4
Exhaust temperature	°C	642.0
Steam cycle		
HP steam temperature/pressure	°C/MPa	565.0/16.3
IP steam temperature/pressure	°C/MPa	565.0/2.4
LP steam temperature/pressure	°C/MPa	311.0/0.45
Condenser pressure	kPa	3.5

CO_2 removal system

Complex configuration with CO_2 removal and compression sections

•Post combustion capture system based on 30 wt-% mixture of MEA and water

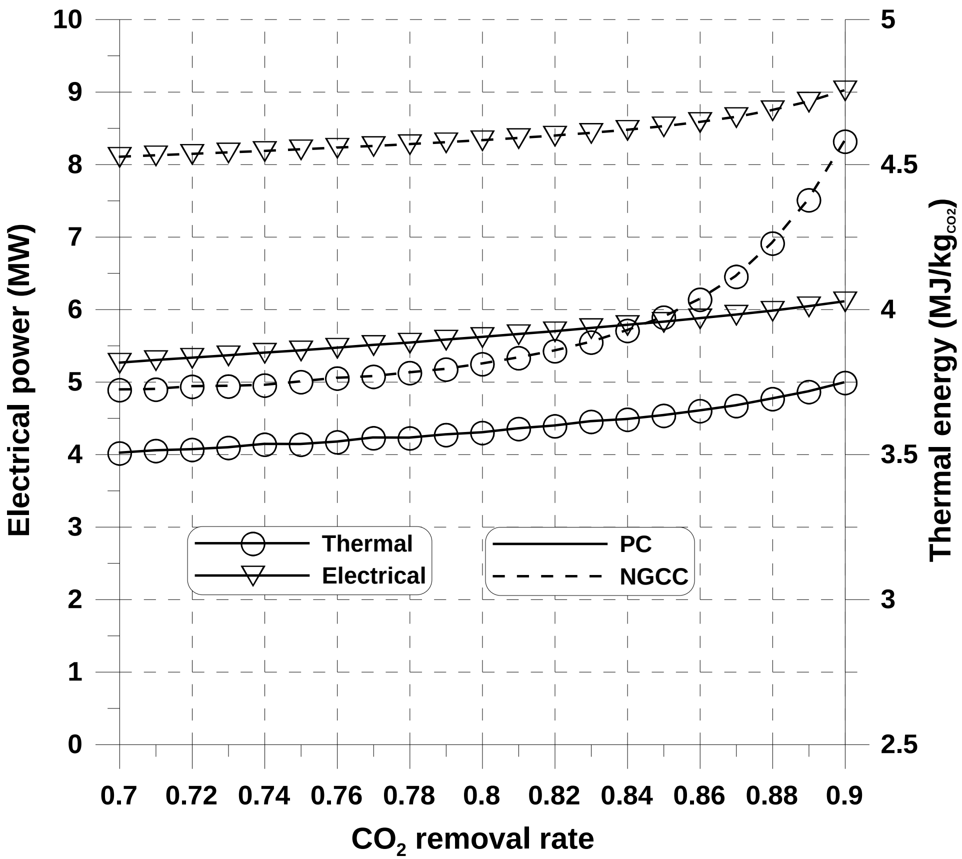


PC and NGCC reference power plants

Reference **PC and NGCC** power plants

		PC	NGCC
Fuel chemical power input	MW	1000.0	1000.0
Flue gas treatment requirements	MW_t	13.3	/
Net power output	MW	420.2	592.0
Net efficiency	%	41.5	59.2
Flue gas mass flow	kg/s	395.5	877.2
CO_2 molar fraction in flue gas	%	15.0	4.1
CO_2 emitted by the plant	kg/s	87.6	55.2
CO_2 specific emissions	g/kWh	735.9	336.0

CO_2 removal rate effects on electrical power and thermal energy requirements



PC

CO_2 removal rate	70%	90%
Electrical power (MW)	5.3	6.1
Thermal energy (MJ/kg$_{CO2}$)	3.50	3.75

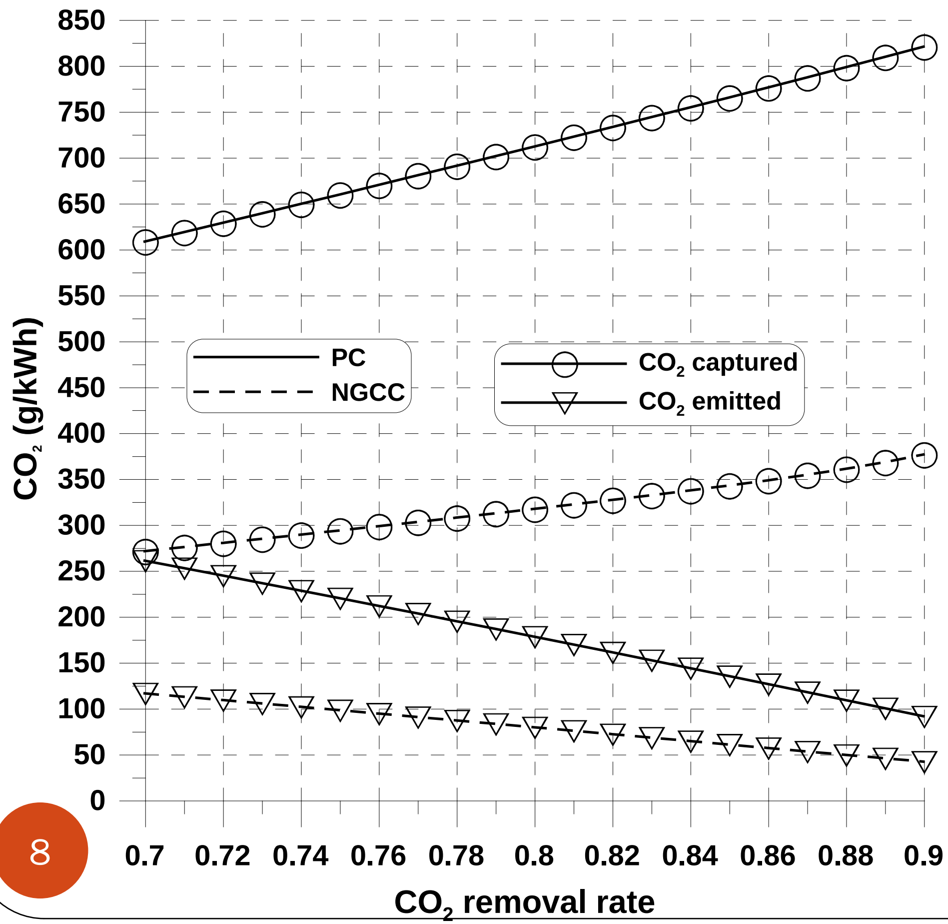
NGCC

CO_2 removal rate	70%	90%
Electrical power (MW)	8.1	9.0
Thermal energy (MJ/kg$_{CO2}$)	3.72	4.58

CO_2 removal rate effects on CO_2 captured and emitted

Reference CO_2 emission :

- **PC** 736 g/kWh
- **NGCC** 336 g/kWh



PC

CO_2 removal rate	70%	90%
CO_2 captured (g/kWh)	608	820
CO_2 emitted (g/kWh)	261	91

NGCC

CO_2 removal rate	70%	90%
CO_2 captured (g/kWh)	271	376
CO_2 emitted (g/kWh)	116	42

CO_2 removal rate effects on power and efficiency

Reference net efficiency:

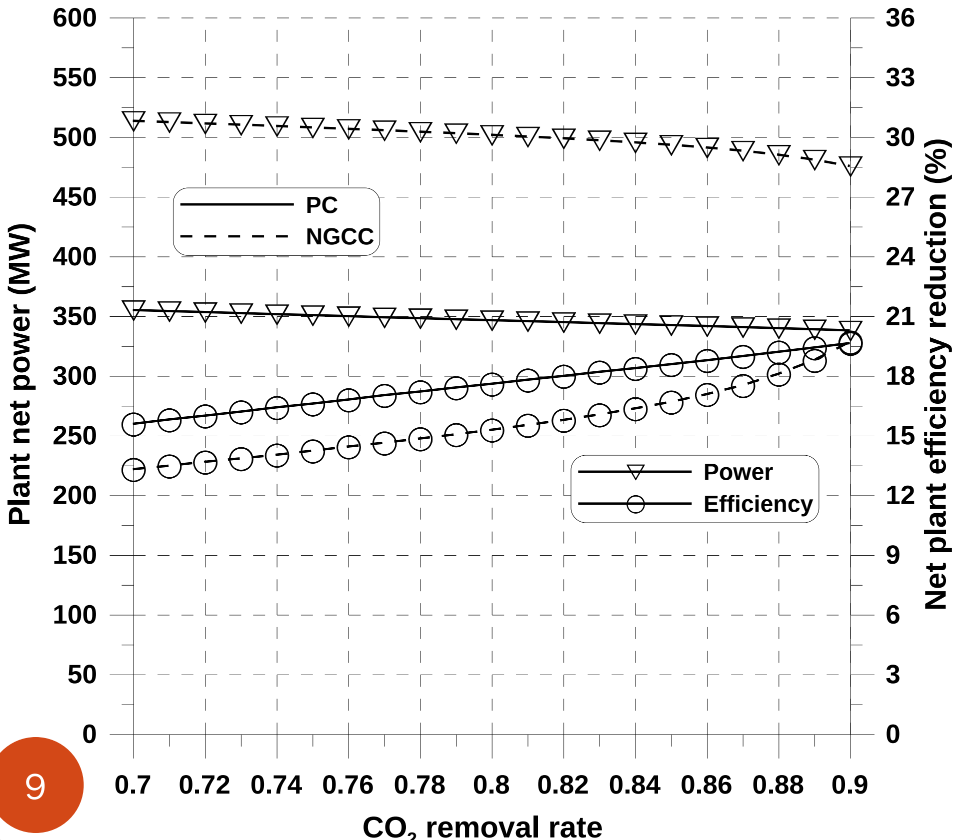
PC 41.3%

NGCC 59.2%

90%CO_2 net efficiency:

PC 33.3%

NGCC 47.5%



Power reduction	
Amine heat requirements	77.2%
Capture system electrical cons.	7.7%
CO_2 compression	15.1%

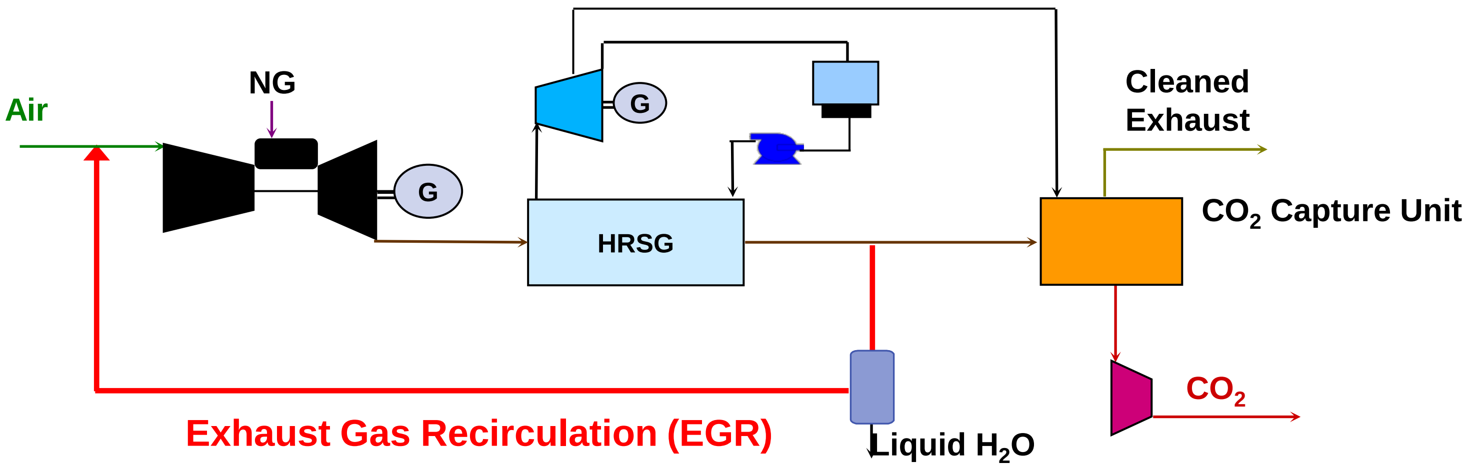
PC

CO_2 removal rate	0%	70%	90%
Net power (MW)	420.2	354.8	337.7
Net efficency decrease (%)	*	15.6	19.6

NGCC

CO_2 removal rate	0%	70%	90%
Net power (MW)	592.0	513.2	475.4
Net efficency decrease (%)	*	13.3	19.7

Exhaust Gas Recirculation (EGR)



Exhaust gas partially extracted at the end of HRSG
Exhaust gas cooled down to near-ambient conditions in an EGR cooler
Exhaust gas recirculated back to the compressor of gas turbine

EGR penalizes compressor performance:

- Higher temperature of air-flue gas mixture
- Higher heat capacity of more humid recirculated gas

EGR improves CO_2 capture efficiency and reduces capture equipment costs:

- Increase of CO_2 concentration in the flue gas
- Reduced size of CO_2 capture unit
- Reduced energy requirements and equipement costs for the amine system

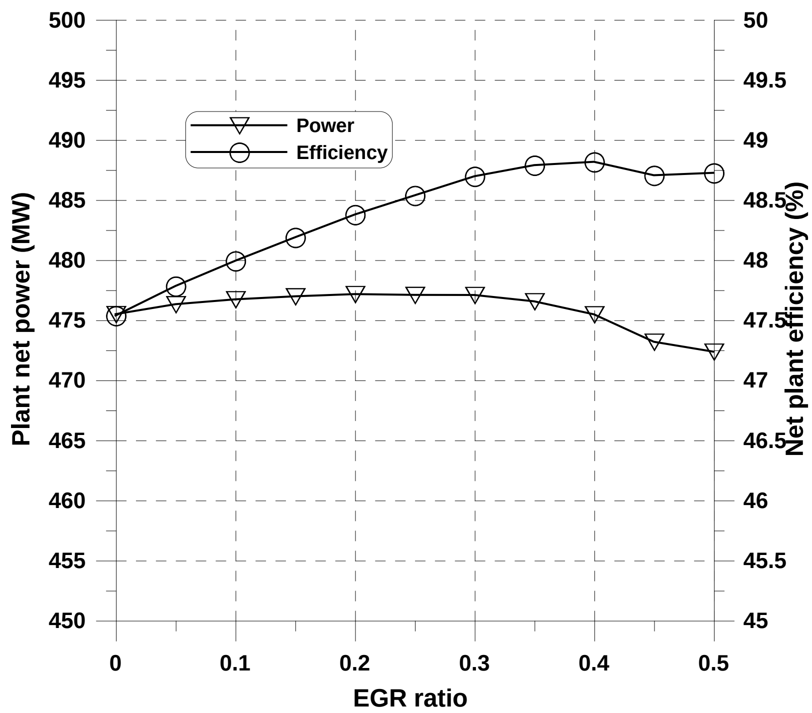
EGR influence on plant power and efficiency

EGR Variables:

EGR ratio (0-0.5)

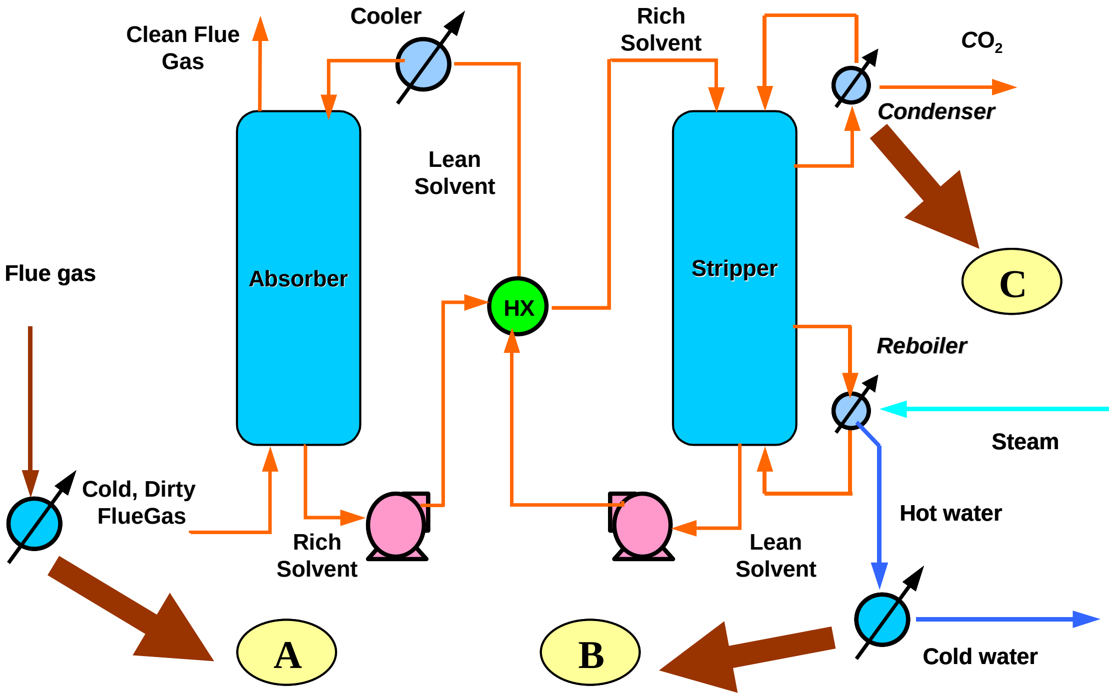
NGCC-CCS with 90% CO_2 capture

EGR cooler outlet temperature =30 °C



Available low temperature sources

Different sources of available low temperature heat from solvent-based CO_2 removal systems



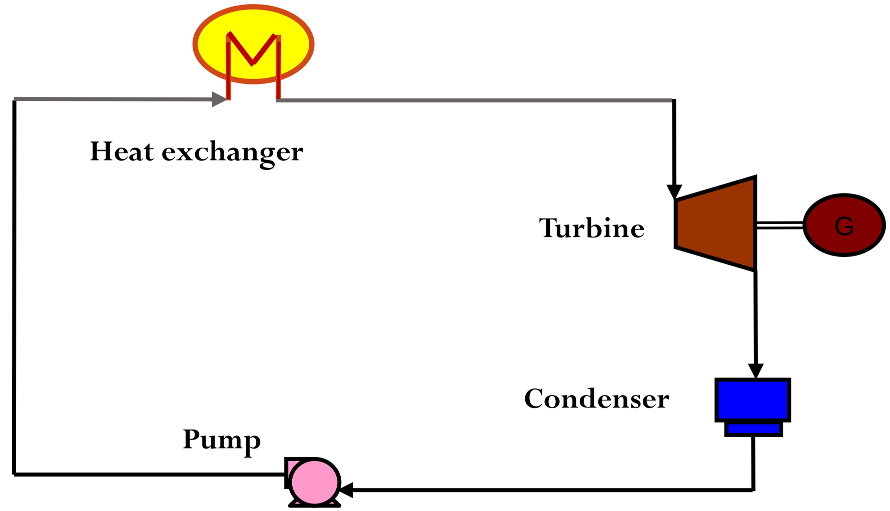
A Exhaust gas cooler

B Amine reboiler condensate cooling

C Stripper condenser

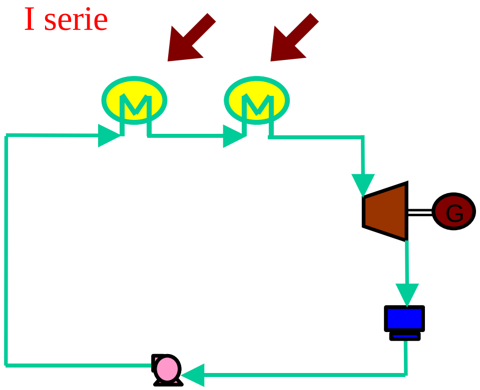
ORC arrangements

Organic Rankine Cycle

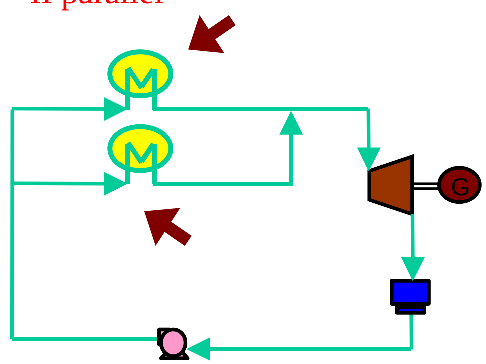


Different ORC arrangements for simultaneous heat recovery in single ORC loop

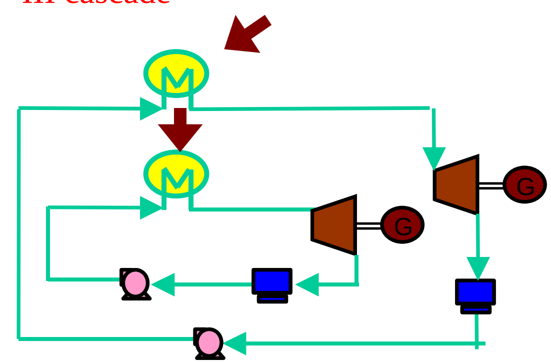
I serie



II parallel



III cascade



ORC fluids

- **Carbon dioxide (CO_2)**
- **N-Butane**
- **Penta-fluoro-propane (R245fa)**

Using CO_2 allows synergies in the fluid handling or safety infrastructure with the CO_2 capture system, low costs for the organic fluid and a better match with the exhaust gas cooling curve

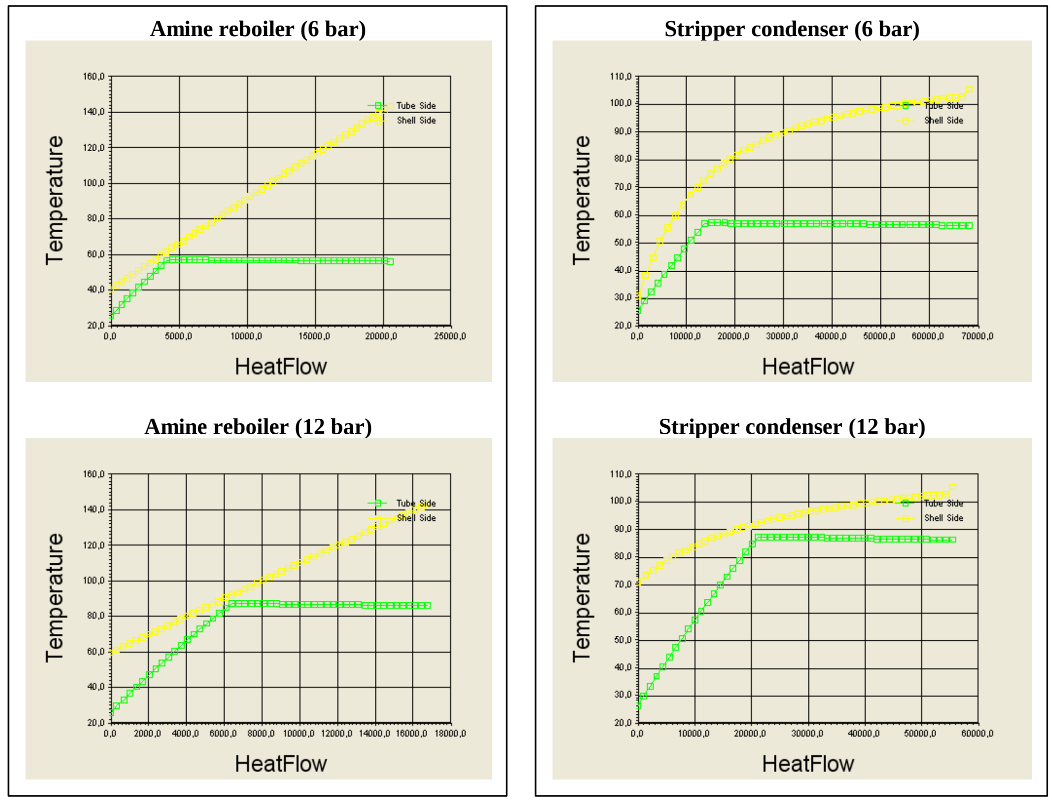
CO_2 shows some disadvantages (a higher pump work) which leads to a low plant performance, due to the supercritical conditions, and potentially higher equipment costs due to the very high operating pressure.

Temperature (°C)	Pressure (bar)	Pressure (bar)	Pressure (bar)
	CO_2	N-Butane	R245fa
10	44.9	1.5	0.8
20	57.3	2.1	1.2
30	72.1	2.8	1.8
40	- *	3.8	2.5
50	-	4.9	3.4
60	-	6.4	4.6
70	-	8.1	6.0
80	-	10.1	7.8
90	-	12.5	10.0
100	-	15.3	12.6

* CO_2 critical point at 73.8 bar and 31 °C

Effects of N-Butane pressure on ORC performance

Parameter	Range
Vapor fraction at the turbine entry	1
Pressure at the turbine entry	6-12 bar
Temperature at the turbine entry	58-88 °C
Pressure at the condenser	2.5 bar
Temperature at the condenser	25°C
Minimum ΔT at the heat exchanger	5°C



N-Butane

Pressure (bar)	Temperature (°C)
4	42.2
6	57.6
8	69.6
10	79.4
12	88.0
14	95.5

Waste Heat Recovery (WHR)

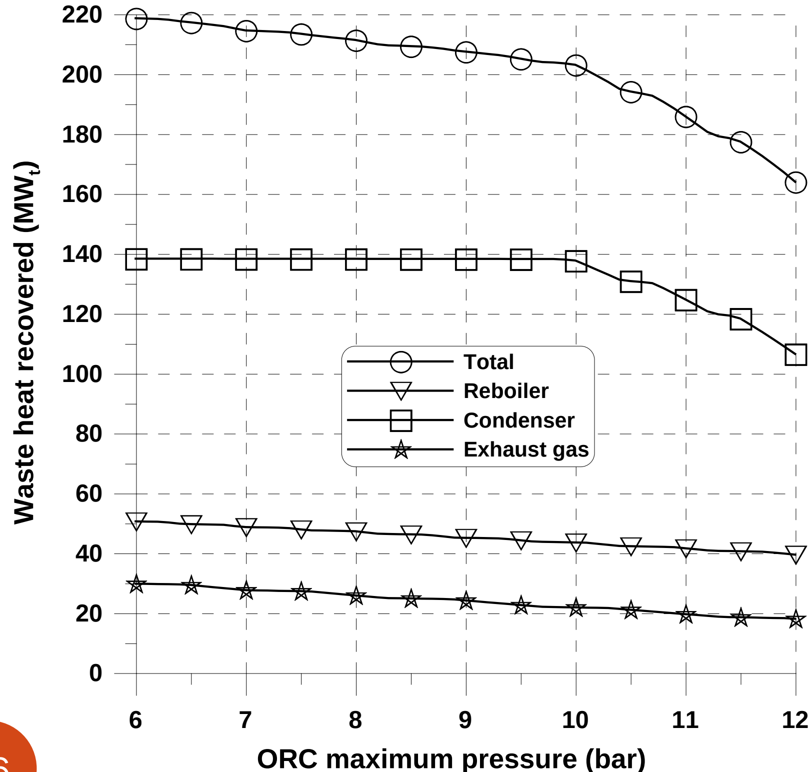
An increase of ORC maximum pressure reduces waste heat recovery

WHR from condenser is the highest one and constant up to 10 bar.

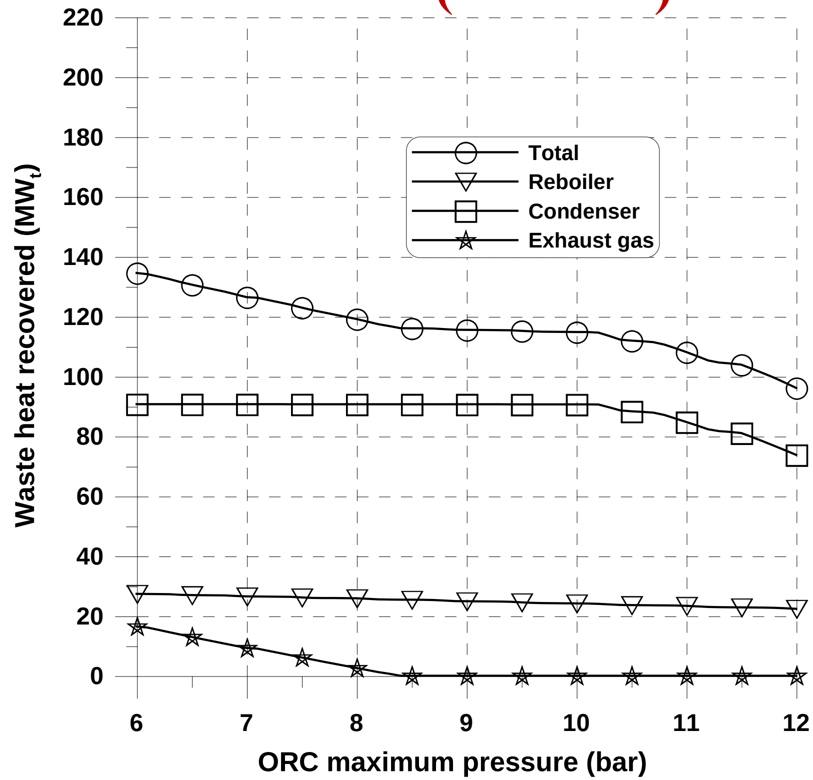
High T of saturated water (140 °C) allows to a slightly decrease of WHR from reboiler

WHR from exhaust gas is low and possible only at very low pressure.

PC



NGCC (40% EGR)



ORC net power and efficiency

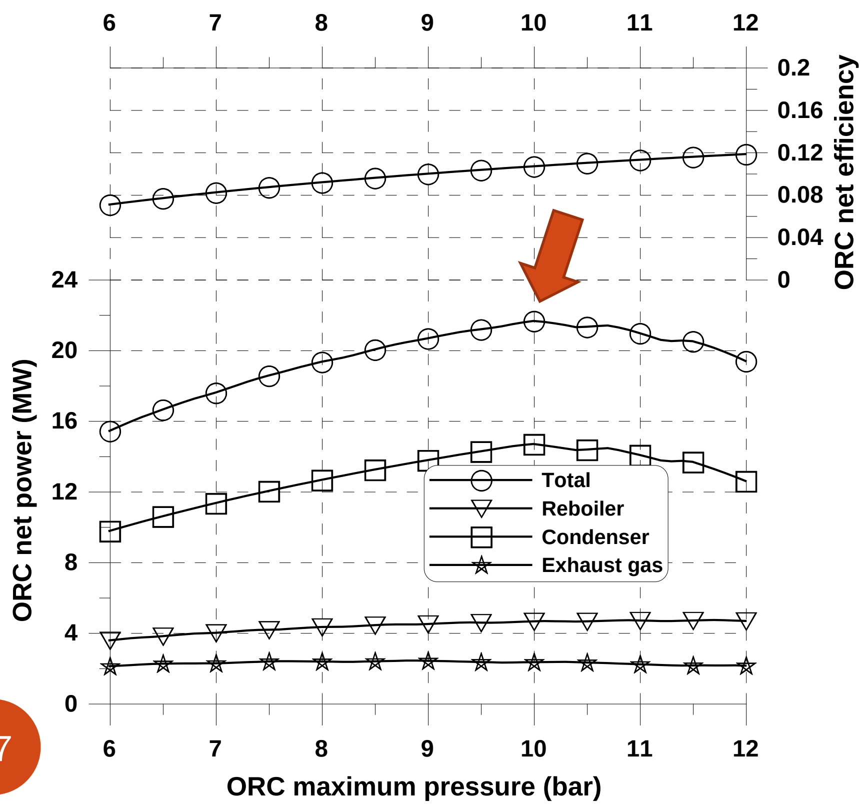
An increase of ORC maximum pressure increases ORC efficiency

7.1% of ORC efficiency for a ORC maximum pressure equal to 6 bar.

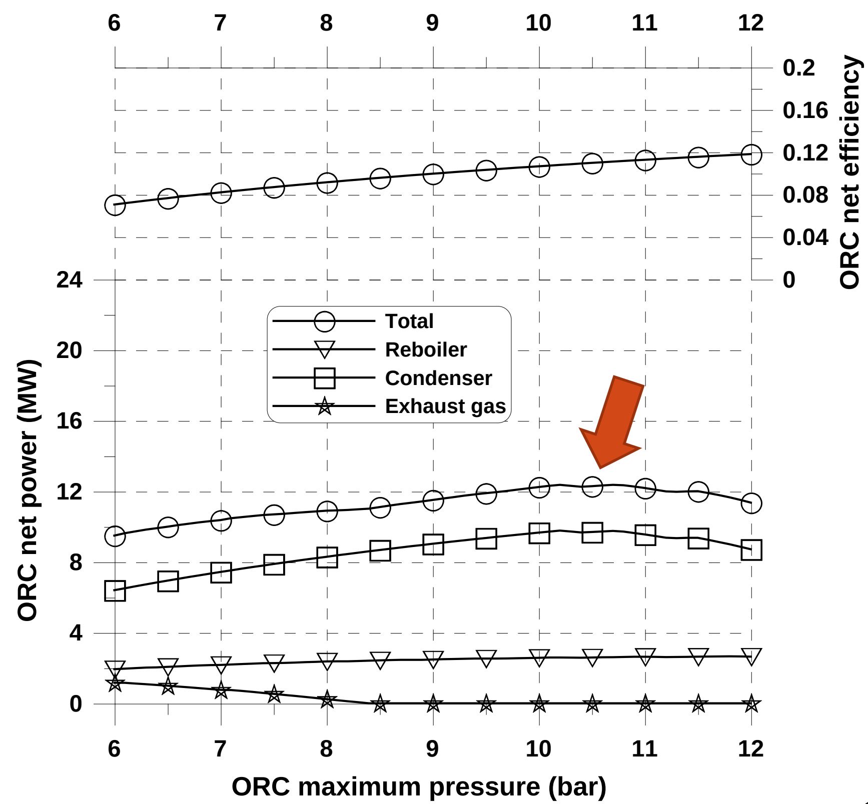
11.9% of ORC efficiency for a ORC maximum pressure equal to 12 bar.

Due to ORC efficiency trend, maximum ORC power is obtained at about 10 bar.

PC



NGCC (40% EGR)



Main plant performance

PC-CCS	
Maximum ORC net power (MW)	**21.6**
Power increase vs reference plant (%)	**6.4**
Total WHR (MW)	**203.1**
ORC net efficiency (%)	**10.7**

NGCC-CCS	
Maximum ORC net power (MW)	**12.3**
Power increase vs reference plant (%)	**2.6**
Total WHR (MW)	**112.0**
ORC net efficiency (%)	**11.0**

		PC	NGCC
Gross power of reference plant	MW	454.6	625.2
Net power of reference plant	MW	420.2	592.0
Net power of plant + CCS	MW	337.8	475.5
Net power of plant + CCS + ORC	MW	359.4	487.8
Net efficiency of reference plant	%	41.5	59.2
Net efficiency of plant + CCS	%	33.3	48.8
Net efficiency of plant + CCS + ORC	%	35.5	50.1

Conclusions

- This paper analyses option to recover low-grade heat from CO_2 capture processes for both natural gas combined cycles (**NGCC**) and Pulverize coal-fired (**PC**) steam power plants by using Organic Rankine Cycle (**ORC**) technology.
- Three different potential waste-heat sources are identified: exhaust gas cooler, amine rebolier condensate cooling and stripper condenser.
- Most appropriate ORC system layouts are discussed: serie, parallel and cascade. Parallel layout has been chosen.
- N-Butane has been chosen as an ORC working fluid. Maximum pressure equal to 10 bar leads to best results.
- Exhaust gas recirculation (**EGR**) was also considered for enhancing performance of NGCC integrated with CO_2 capture processes.
- **ORC** technology integrated with PC-CCS allow to increase net power output of about 22 MW, whereas the integration with NGCC-CCS limits the increase to about 13 MW.
- Globally an overall power plant net efficiency improvement potential of 1.3 percentage point (**NGCC**) and of 2.2 percentage point (**PC**) is estimated.
- An economic analysis should be performed in order to evaluate costs of integration.

THANK YOU FOR YOUR ATTENTION