Heat Integration study of Combined Cycle Gas Turbine (CCGT) Power Plant Integrated With Post-combustion CO_2 Capture (PCC) and Compression

WATER AND ENERGY WORKSHOP
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OUTLINE

- ❑ Motivation
- ❑ Model Development
- ❑ Integration of CCGT, PCC and compression
- ❑ Case studies
- ❑ Summary

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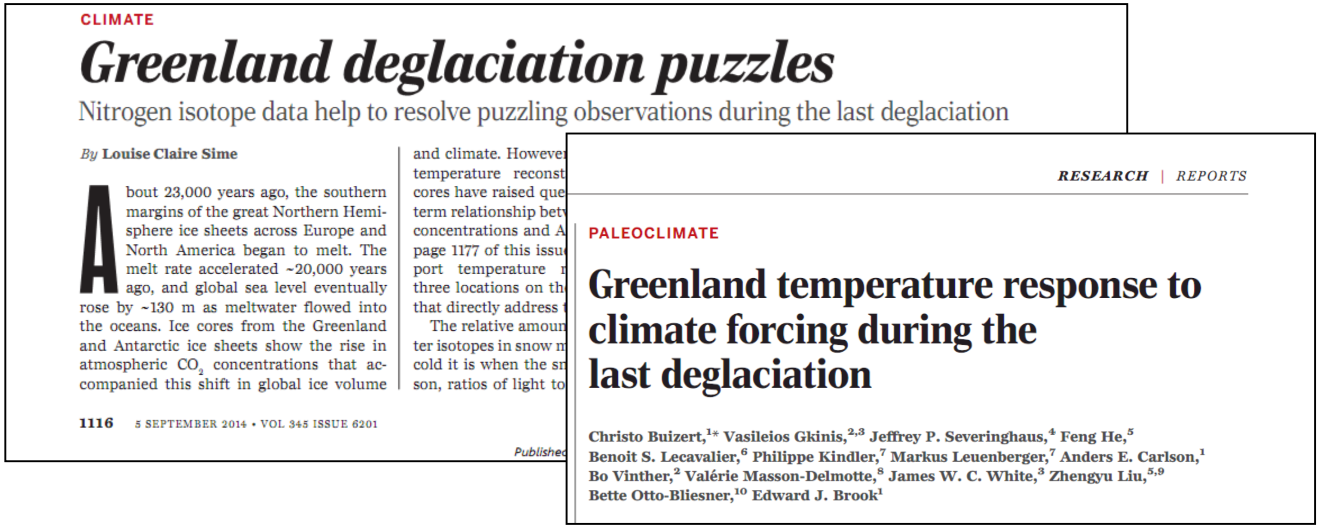
Motivation



CLIMATE

Greenland deglaciation puzzles

Nitrogen isotope data help to resolve puzzling observations during the last deglaciation

By Louise Claire Sime

About 23,000 years ago, the southern margins of the great Northern Hemisphere ice sheets across Europe and North America began to melt. The melt rate accelerated ~20,000 years ago, and global sea level eventually rose by ~130 m as meltwater flowed into the oceans. Ice cores from the Greenland and Antarctic ice sheets show the rise in atmospheric CO_2 concentrations that accompanied this shift in global ice volume

and climate. However temperature reconst cores have raised que term relationship bet concentrations and A page 1177 of this issu port temperature r three locations on th that directly address t

The relative amoun ter isotopes in snow m cold it is when the sn son, ratios of light to

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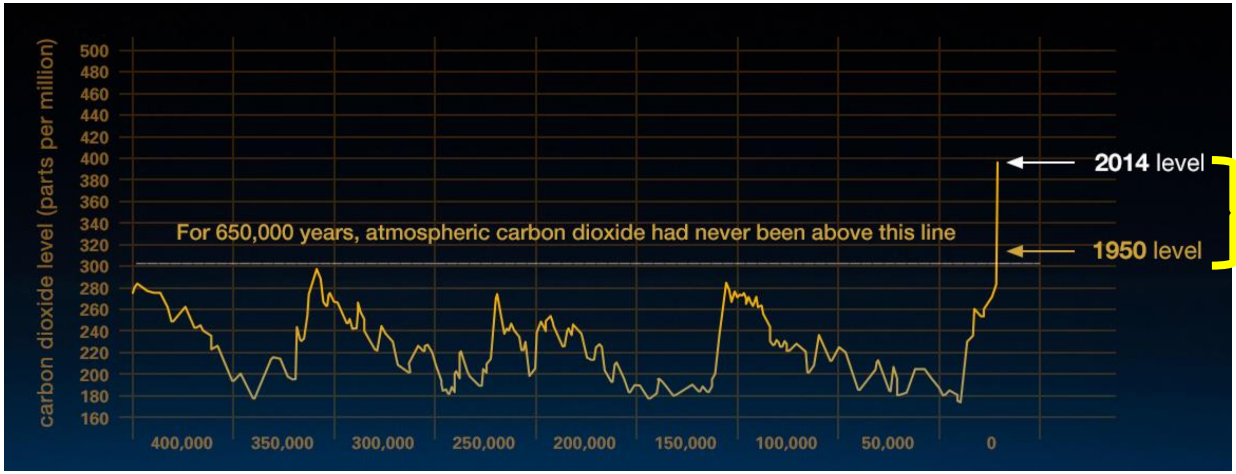
RESEARCH | *REPORTS*

PALEOCLIMATE

Greenland temperature response to climate forcing during the last deglaciation

Christo Buizert,[1*] Vasileios Gkinis,[2,3] Jeffrey P. Severinghaus,[4] Feng He,[5] Benoit S. Lecavalier,[6] Philippe Kindler,[7] Markus Leuenberger,[7] Anders E. Carlson,[1] Bo Vinther,[2] Valérie Masson-Delmotte,[8] James W. C. White,[3] Zhengyu Liu,[5,9] Bette Otto-Bliesner,[10] Edward J. Brook[1]

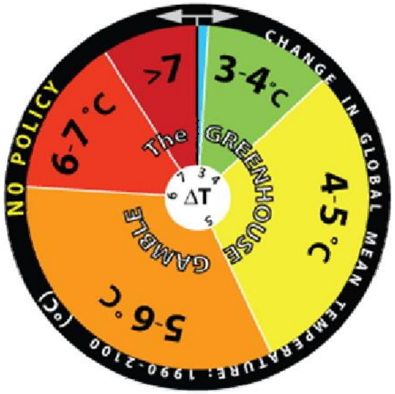


anthropogenic CO_2 emission

(Source: Vostok ice core data/J.R. Petit et al.; NOAA Mauna Loa CO2 record)

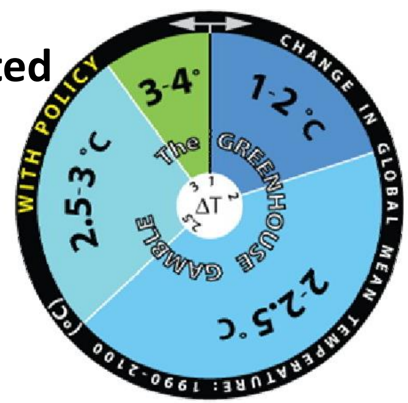
Motivation

No Action



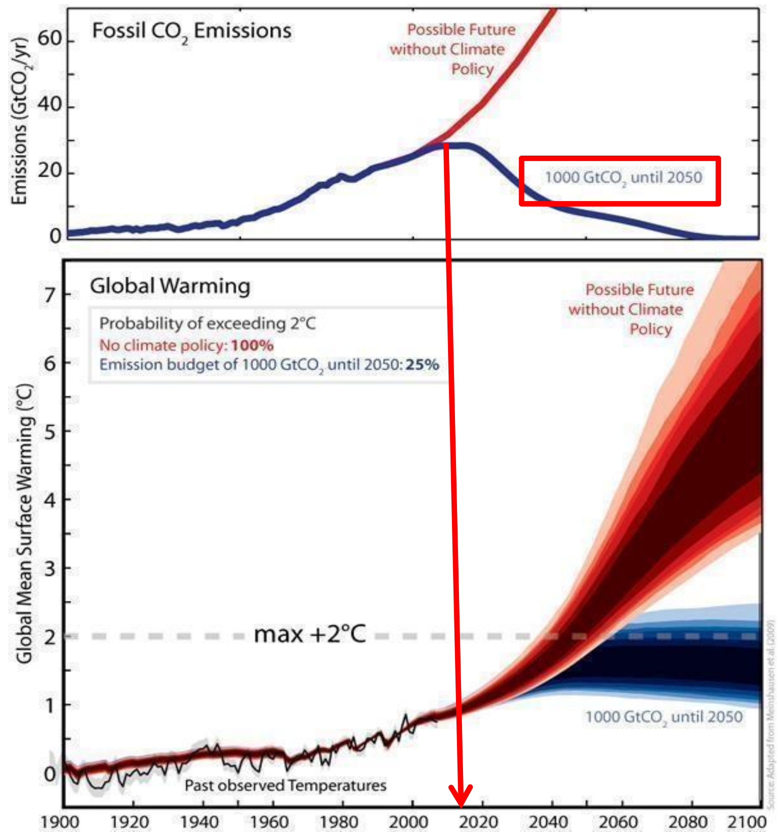
No Action: The median warming level or the temperature at which there is a 50% chance of falling above or below that level (even odds) is 5.2 °C.

Policies enacted



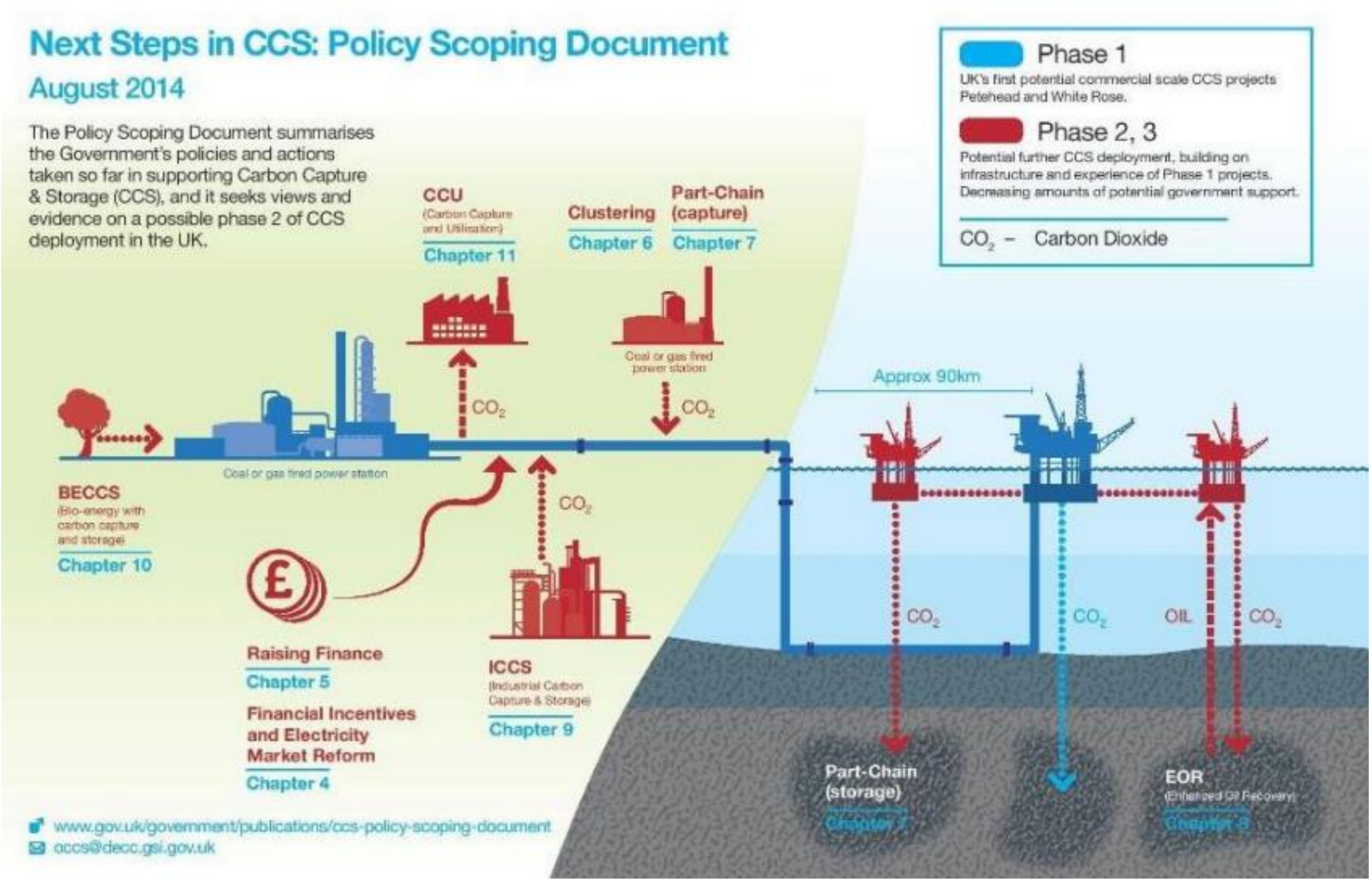
Policies enacted: The median warming level or the temperature at which there is a 50% chance of falling above or below that level (even odds) is 2.3 °C.

CO_2 emissions and warming prediction (M. Pourkashanian, 2014 in 10th ECCRIA)



Global CO_2 emissions and warming prediction (ETH Zurich, 2009)

Motivation



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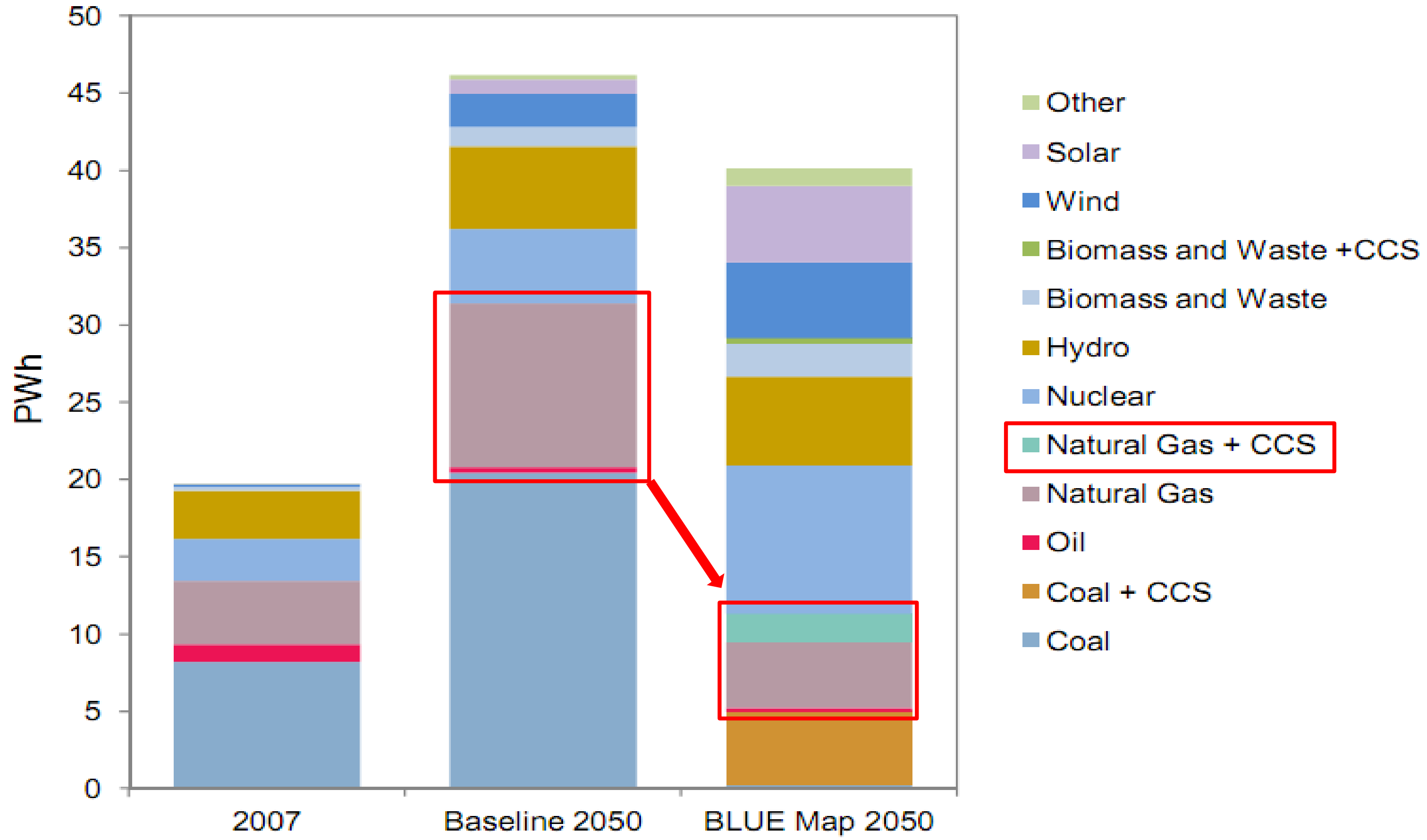
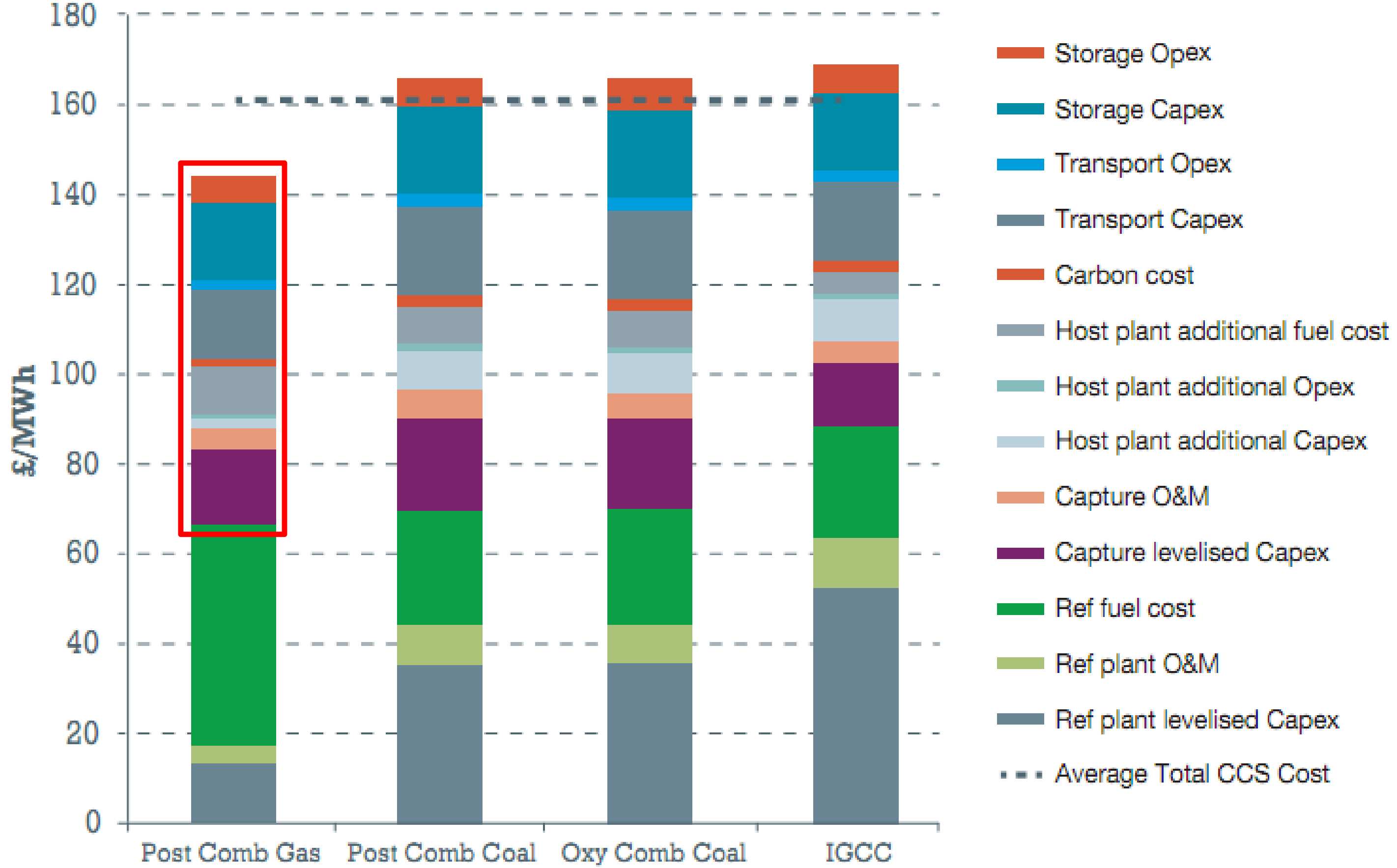
Motivation

BLUE map emission reduction plant (IEAGHG, 2012)



Motivation



LCOE of FID 2013 CCS technologies (£/MWh 2012 money) ((DECC of UK, 2013)

Motivation

❑Aim

- The aim of this study is to evaluate integration options of CCGT power plant with PCC process and compressors via process modelling and simulation, in order to improve the thermal efficiency of the power plant and to reduce the cost of CCS deployment.

❑Objectives

- model development and validation of CCGT power plant
- model development and validation of PCC and CO_2 compression
- process integration between CCGT and PCC and compression
- Case studies including evaluation of heat integration options

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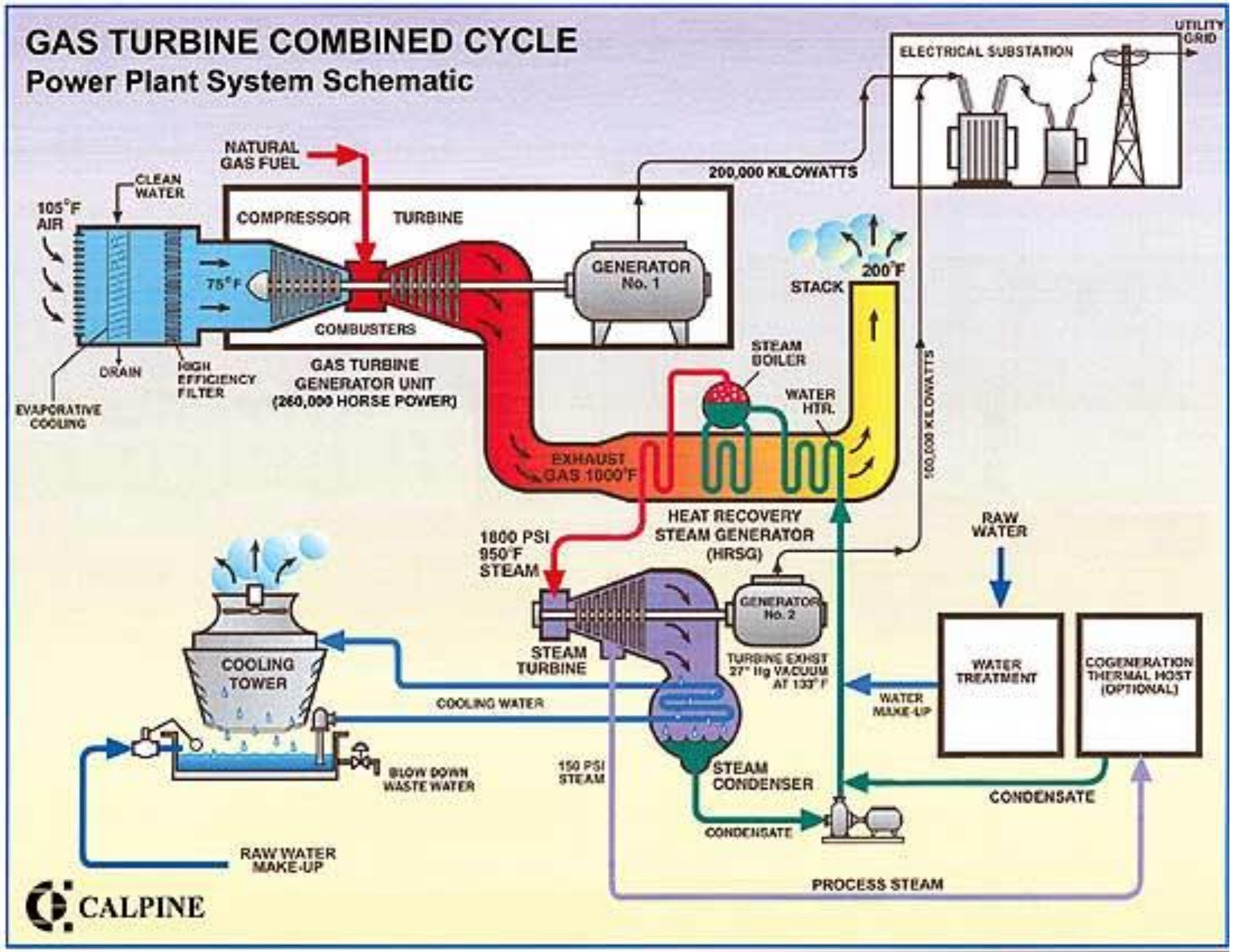
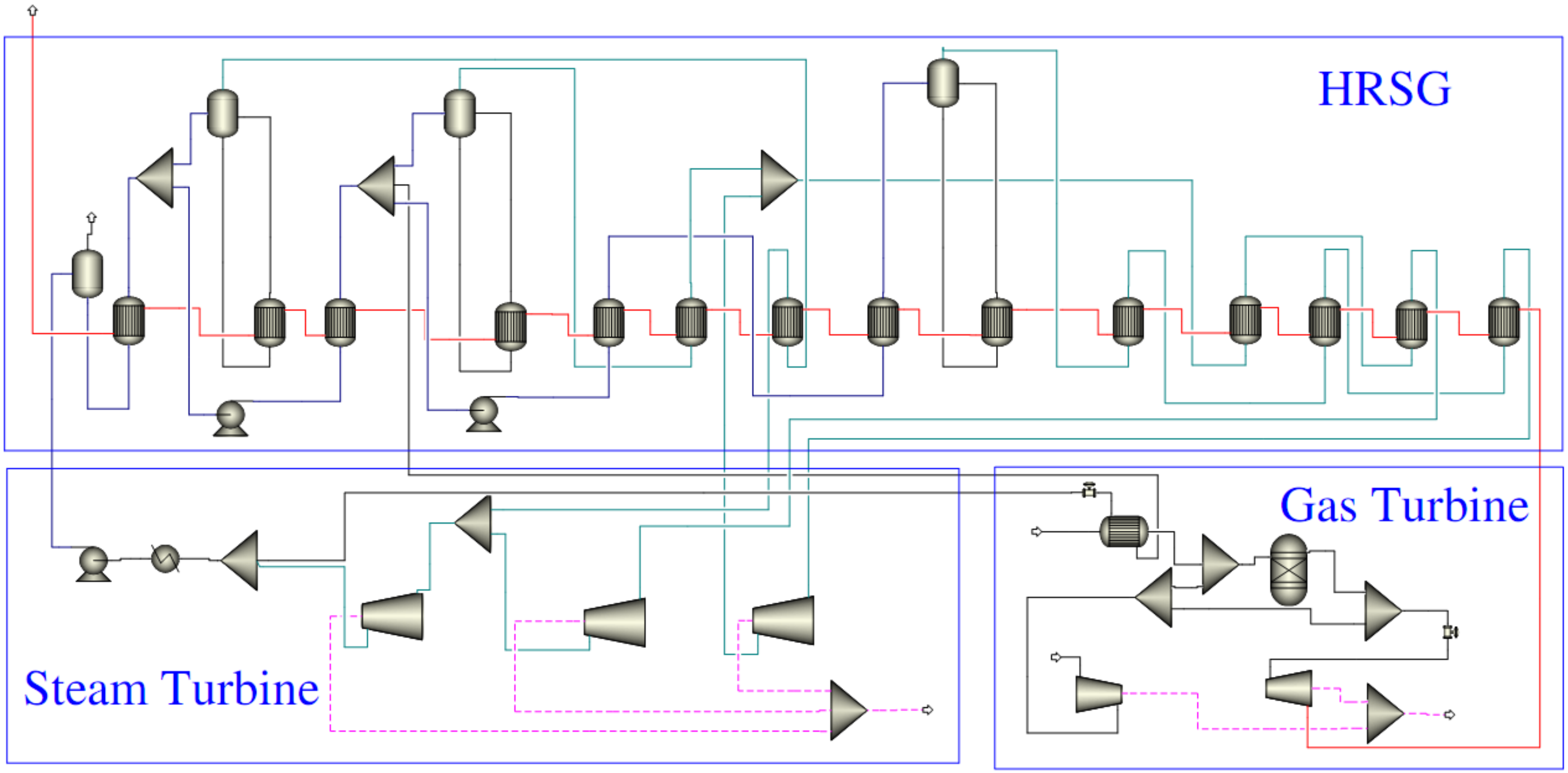
CCGT Model Development and Validation



Combined-Cycle Gas Turbine Power Plant Schematic (Source: Calpine 2012)

CCGT Model Development and Validation



CCGT Model Development and Validation

- Net power output: 453MW$_e$
- Gas turbine model: GE 9371FB
- HRGS: 3 level pressure with reheat
  - high pressure steam are 170 bar and 600 °C compared with 120 bar and 556°C in normal
  - The pressure and temperature of intermediate pressure steam are 40 bar and 600 °C compared with 30 bar and 550°C in normal .
  - similar steam conditions will be common practice for NGCC plant by 2020 suggested by original equipment manufacturers (OEMs)
- EOS: PR-BM for gas cycles and STEAMNBS for steam cycles

- Model validation with published data for the results from GT PRO® (IEAGHG, 2012)

Parameters	IEAGHG, (2012)	This study
Fuel flow rate (kg/s)	16.62	16.62
Air flow rate(kg/s)	656.94	656.94
Temperature of flue gas to HRSG (°C)	638.4	638.4
Flow rate of flue gas to HRSG (kg/s)	114.97	114.97
HP turbine inlet pressure, temperature (bar/°C)	172.5/601.7	172.6/601.7
IP turbine inlet pressure, temperature (bar/°C)	41.4/601.5	41.5/601.0
LP turbine inlet pressure, temperature (bar/°C)	5.81/293.3	5.8/293.1
Condenser pressure and temperature (mbar/°C)	0.04/29.2	0.039/29.0
Gas turbine power output (MWel)	295.238	295.03
Steam turbine power output (MWel)	171.78	170.71
Net plant power output (MWel)	455.15	453.872
Net plant efficiency (%,LHV)	58.87	58.74

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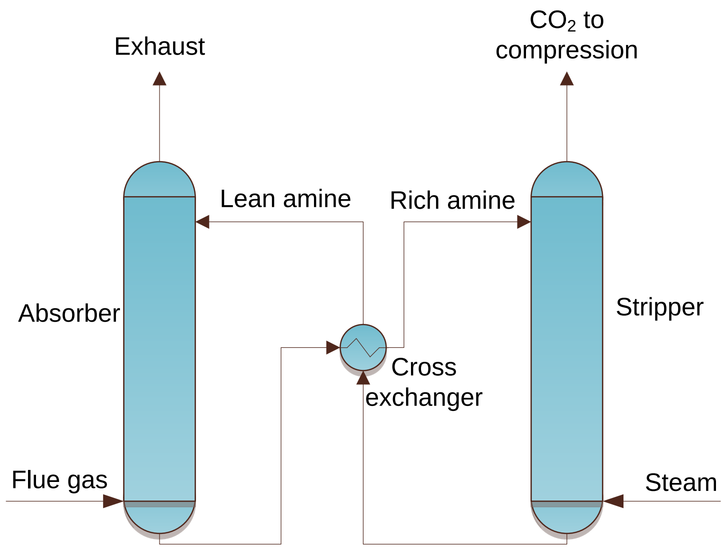
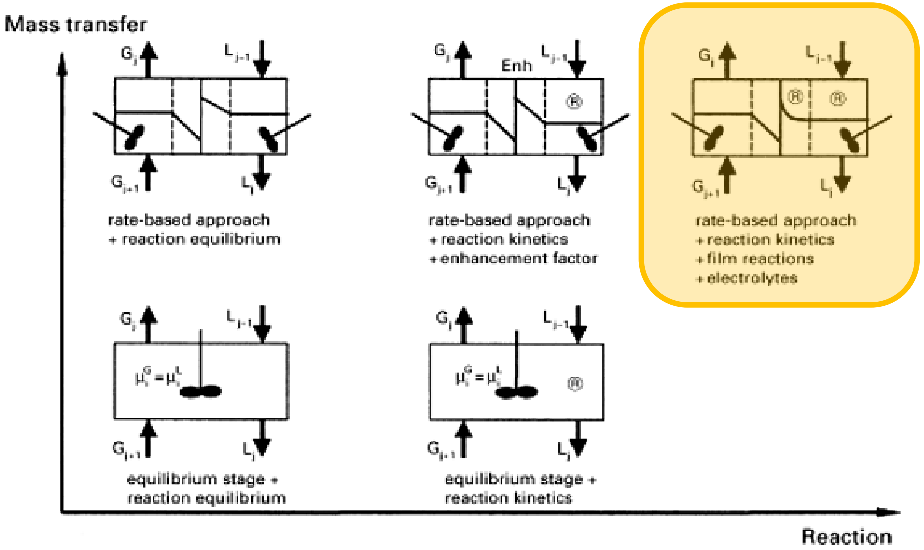
PCC Model Development and Validation

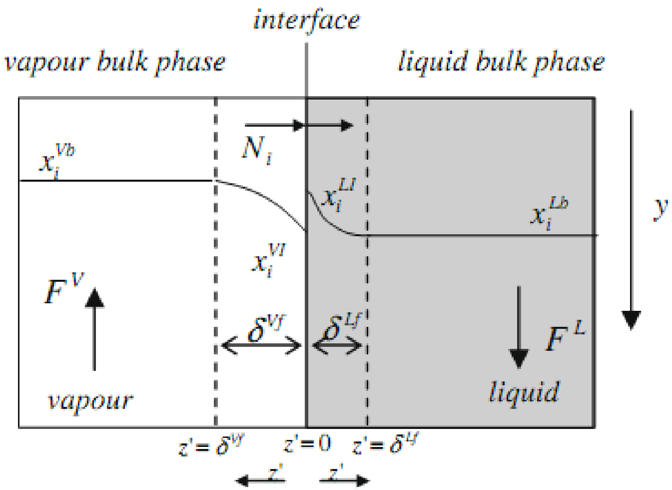
- Model complexity and accuracy for reactive absorption process
  - Rate-based mass transfer
  - Kinetics-controled reactions
  - Electrolytes system





PCC Model Development and Validation

- Rate-based mass transfer
  - two films theory
  - discretization of liquid film



- MEA-H_2O-CO_2 system
  - Kenitic-controlled
  - ELEC-NRTL physical property method

The equilibrium reactions are defined as:

$$2H_2O \leftrightarrow H_3O^+ + OH^-$$

$$HCO_3^- + H_2O \leftrightarrow H_3O^+ + CO_3^{2-}$$

$$MEAH^+ + H_2O \leftrightarrow MEA + H_3O^+$$

The following set of rate-controlled reactions has been defined:

$$CO_2 + OH^- \rightarrow HCO_3^-$$

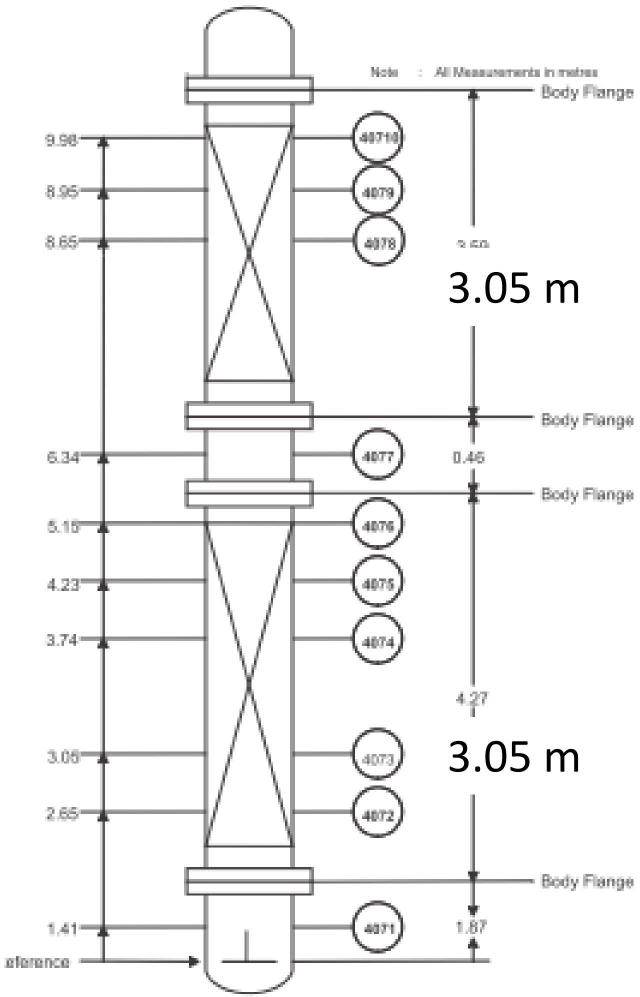
$$HCO_3^- \rightarrow CO_2 + OH^-$$

$$MEA + CO_2 + H_2O \rightarrow MEACOO^- + H_3O^+$$

$$MEACOO^- + H_3O^+ \rightarrow MEA + CO_2 + H_2O$$

PCC Model Development and Validation

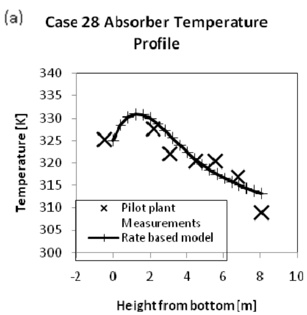
- University of Texas at Austin pilot plant.
- Column diameter is equal to 0.427 m
- Two 3.05 m packing bed sections
- 32.5 wt% acqueos MEA solvent
- Closed loop absorption and stripping facility

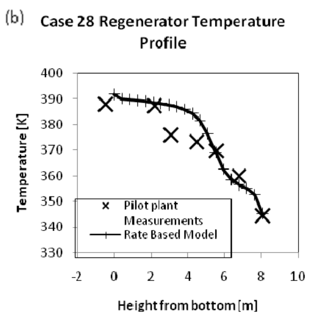


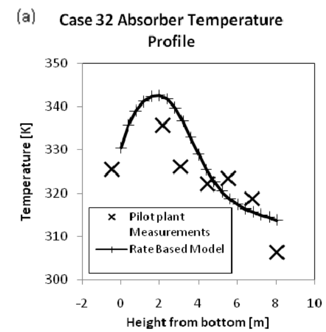
PCC Model Development and Validation

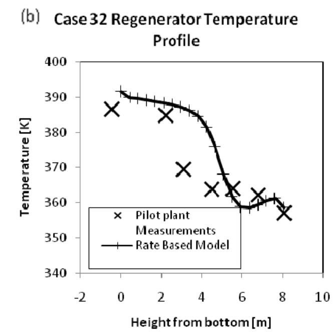
- Validation by pilot plant data from the University of Texas at Austin

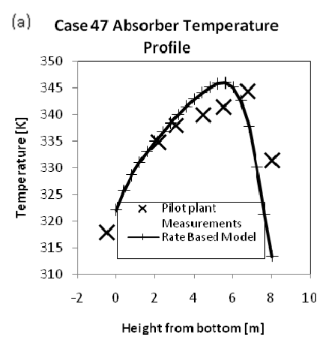
Case	Lean loading [mol CO_2/mol MEA]	Rich loading [mol CO_2/mol MEA]			CO_2 capture level [%]		
	Experimental	Experimental	Rate based model	Zhang et al. model	Experimental	Rate based model	Zhang et al. model
28	0.287	0.412	0.409	0.405	86	71.0	74
32	0.279	0.428	0.438	0.432	95	88.9	90
47	0.281	0.539	0.467	0.480	69	68.7	68

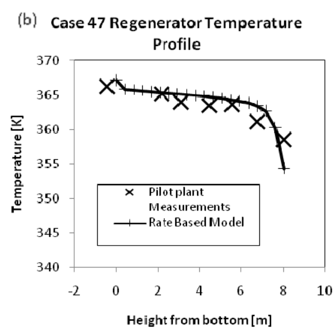












PCC Model Development and Validation

- Scale-up to match full scale power plant with a capacity of 453MW$_e$

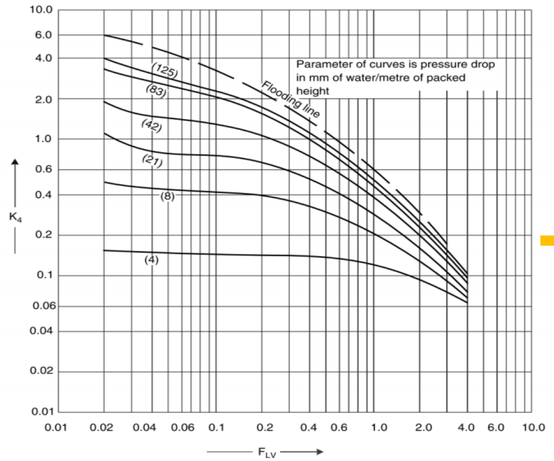


FIGURE 4.11: Generalized pressure drop correlation from Sinnot

$$k_4 = \frac{13.1(V_w^*)^2 F_p(\mu_L/\rho_L)^{0.1}}{\rho_V(\rho_L - \rho_V)}$$

$$F_{LV} = \frac{L_w^*}{V_w^*}\sqrt{\frac{\rho_V}{\rho_L}}$$

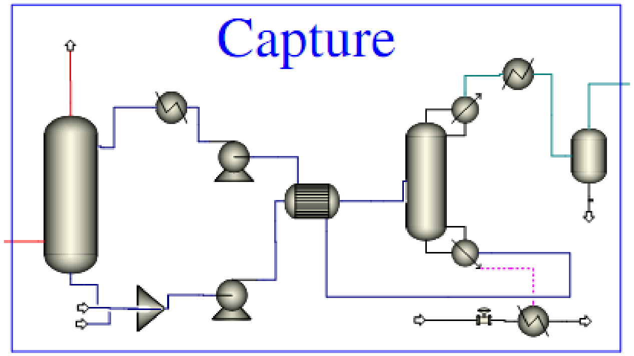


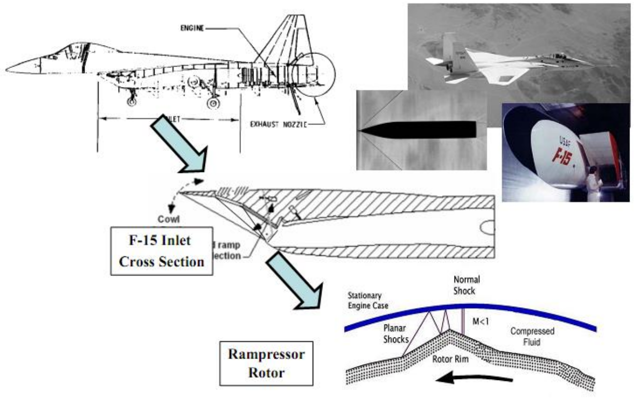
Table 9: Absorber and Regenerator sizing first guess solution: assumptions and results

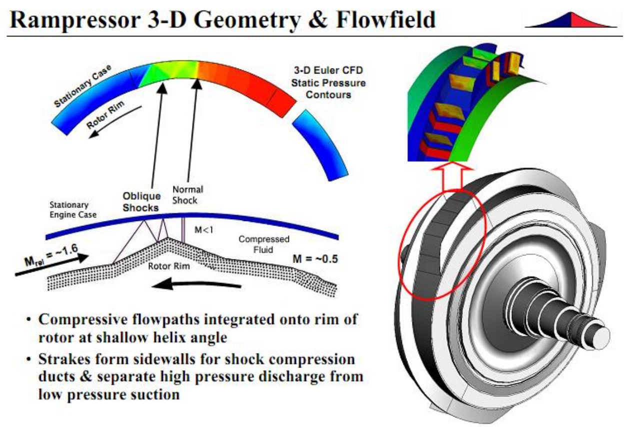
Assumptions	Absorber	Regenerator
	1.736	9.445
ρ_V [kg/m^3]	1.092	1.100
ρ_L [kg/m^3]	1015.6	1019.6
Pressure drop [mmH2O / (m packing)]	42	42
F_p [1/m]	78.74	168.2
μ_L [Pa		
	0.00355	0.000969

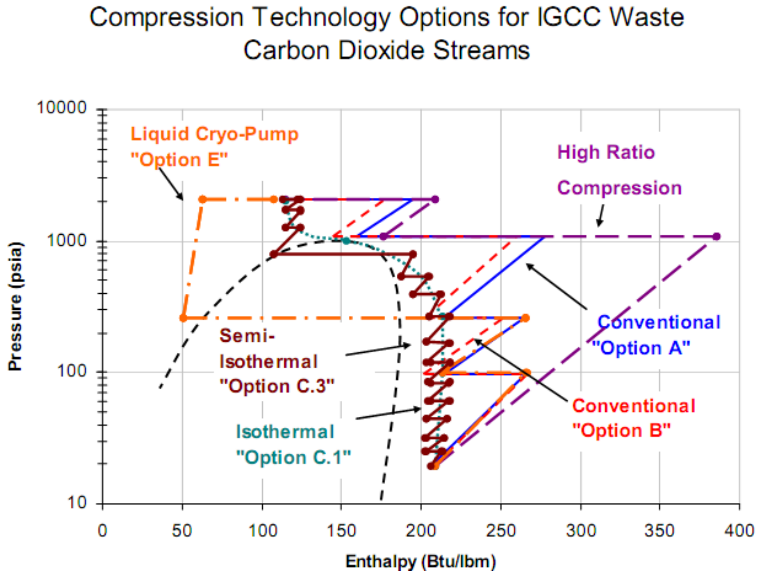
Parameter	Value
CO_2 concentration in flue gas (mol%)	4.4
CO_2 capture level (%)	90
CO_2 captured (kg/s)	41.4
Columns flooding (%)	65
Lean loading (mol/mol)	0.32
Rich loading (mol/mol)	0.461
L/G (mol/mol)	1.79
Reboiler duty (kW)	188,805
Reboiler duty (GJ/tonne CO_2)	4.56
Lean solvent MEA concentration (wt%)	32.5
Lean solvent temperature (K)	303.15
Absorber columns pressure (bar)	1
Absorber columns pressure loss (bar)	0.069
Absorber columns packing	IMTP no. 40
Absorber columns packing height (m)	25
Absorber columns cross-section area (m^2)	307.91
Regenerator column pressure (bar)	2.1
Regenerator column pressure loss (bar)	0.01355
Regenerator column packing	Flexipack 1Y
Regenerator column packing height (m)	15
Regenerator column cross-section area (m^2)	81.71

Supersonic shock wave compression

- supersonic shock wave compression technology (Ramgen Power Systems Ltd., 2008)
  - only needs 2 stages of compression (VS. 5 to 8 stages for the conventional multi-stage approach)
  - 50% potential capital cost saving (Ciferno et al, 2009)
  - the discharge temperature : 220ºC-240ºC (VS. 70ºC-90ºC for conventional multi-stages)





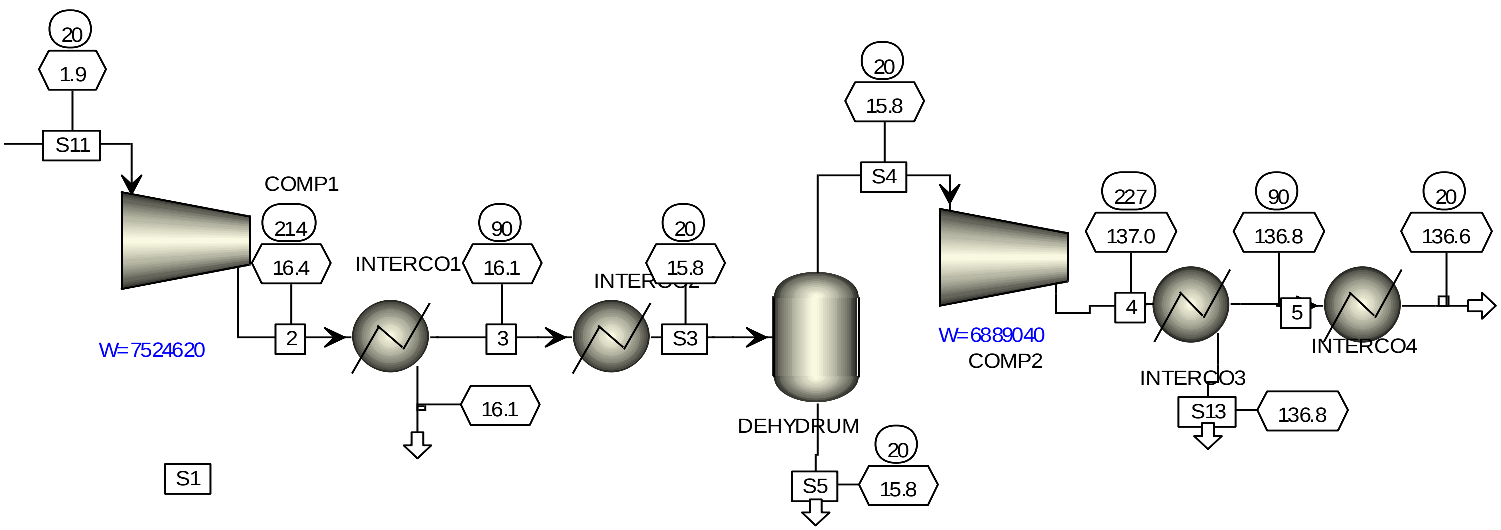


(Ramgen Power Systems Ltd., 2008)

Supersonic shock wave compression

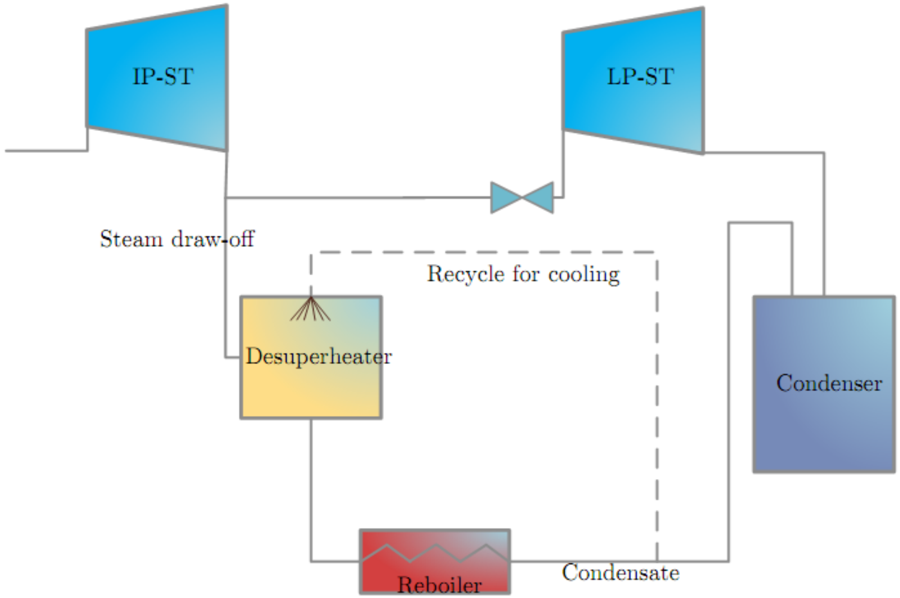
- Compression model was validated with published data from RAMGEN Power System (Shawn Lawlor, 2010)

- Key parameters of compression train (for this study):
  - Outlet pressure: >=136 bar
  - Efficiency: 0.85
  - Pressure ratio:8.65
  - Recover temperature : 90°C
  - Exit temperature of intercoolers: 20°C



CCGT Integrated with PCC

- Basic interfaces of CCGT integrated with PCC
  - Flue gas from HRSG to the capture plant
  - Low pressure steam extraction for solvent regeneration
  - Steam condensate returns to NGCC power plant
  - Electrical power supply for the capture plant



CCGT Integrated with PCC

	NGCC without CO_2 capture	NGCC with CO_2 capture
Gas turbine power output (MW_{el})	295.03	295.03
Steam turbine power output (MW_{el})	170.71	113.56
Power island auxiliary power consumption (MW_{el})	11.69	9.7
CO_2 capture level (%)	–	90
CO_2 captured (kg/s)	–	41.4
CO_2 compression power consumption (MW_{el})	–	15.73
Mechanical power consumption in capture process (MW_{el})	–	4.24
Desorber reboiler duty (MW_{th})	–	188.8
Steam extracted for reboiler (kg/s)	–	76.39
Specific reboiler duty (MJ_{th}/kg CO_2)	–	4.56
Net plant power output (MW_{el})	453.872	378.92
Net plant efficiency (%, fuel lower heating value)	58.74	49.04
Efficiency decrease(%-points) compared with reference case	–	9.70

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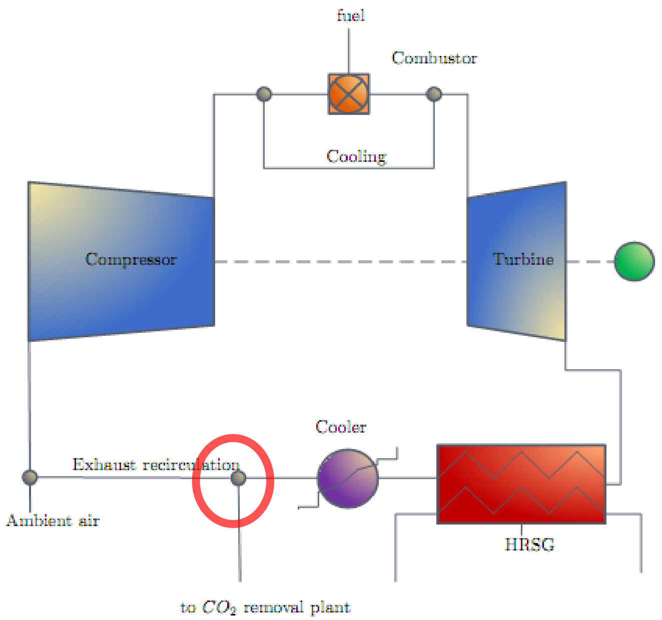
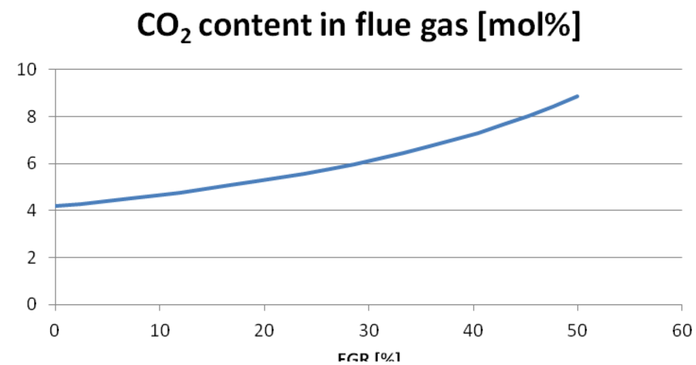
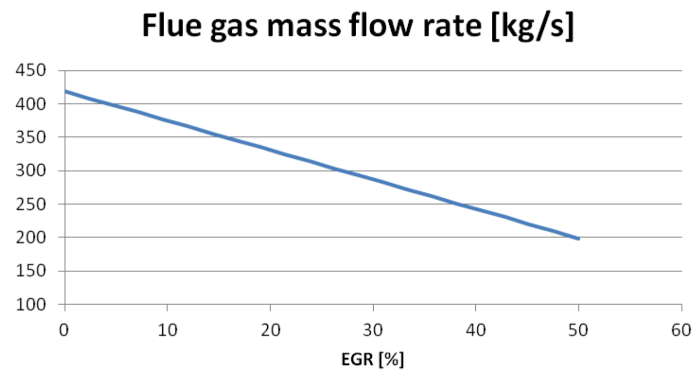
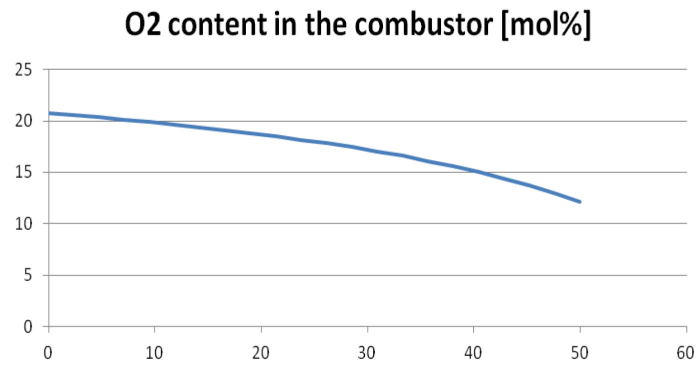
CCGT Integrated with PCC

- Exhaust gas recirculation (EGR)
  - The flow rate of flue gas going to the capture plant reduces 38%
  - CO_2 concentration increase to 7.3 mol% from 4.4 mol%
  - The vent O2 in flue gas decease to 6.6 mol% from 11.4 mol%









NGCC Integrated with PCC

Parameter	without EGR	with EGR
CO2 concentration in flue gas (mol%)	4.4	7.32
CO_2 capture level (%)	90	90
CO_2 captured (kg/s)	41.4	40.9
Columns flooding (%)	65	65
Lean loading (mol/mol)	0.32	0.32
Rich loading (mol/mol)	0.461	0.472
L/G (mol/mol)	1.79	2.71
Reboiler duty (kW)	188,805	176,227
Reboiler duty (GJ/tonne CO_2)	4.56	4.31
Lean solvent MEA concentration (wt%)	32.5	32.5
Lean solvent temperature (K)	303.15	303.15
Absorber columns pressure (bar)	1	1
Absorber columns pressure loss (bar)	0.069	0.054
Absorber columns cross-section area (m^2)	307.91	216.42
Regenerator column pressure (bar)	2.1	2.1
Regenerator column pressure loss (bar)	0.01355	0.01344
Regenerator column cross-section area (m^2)	81.71	75.43

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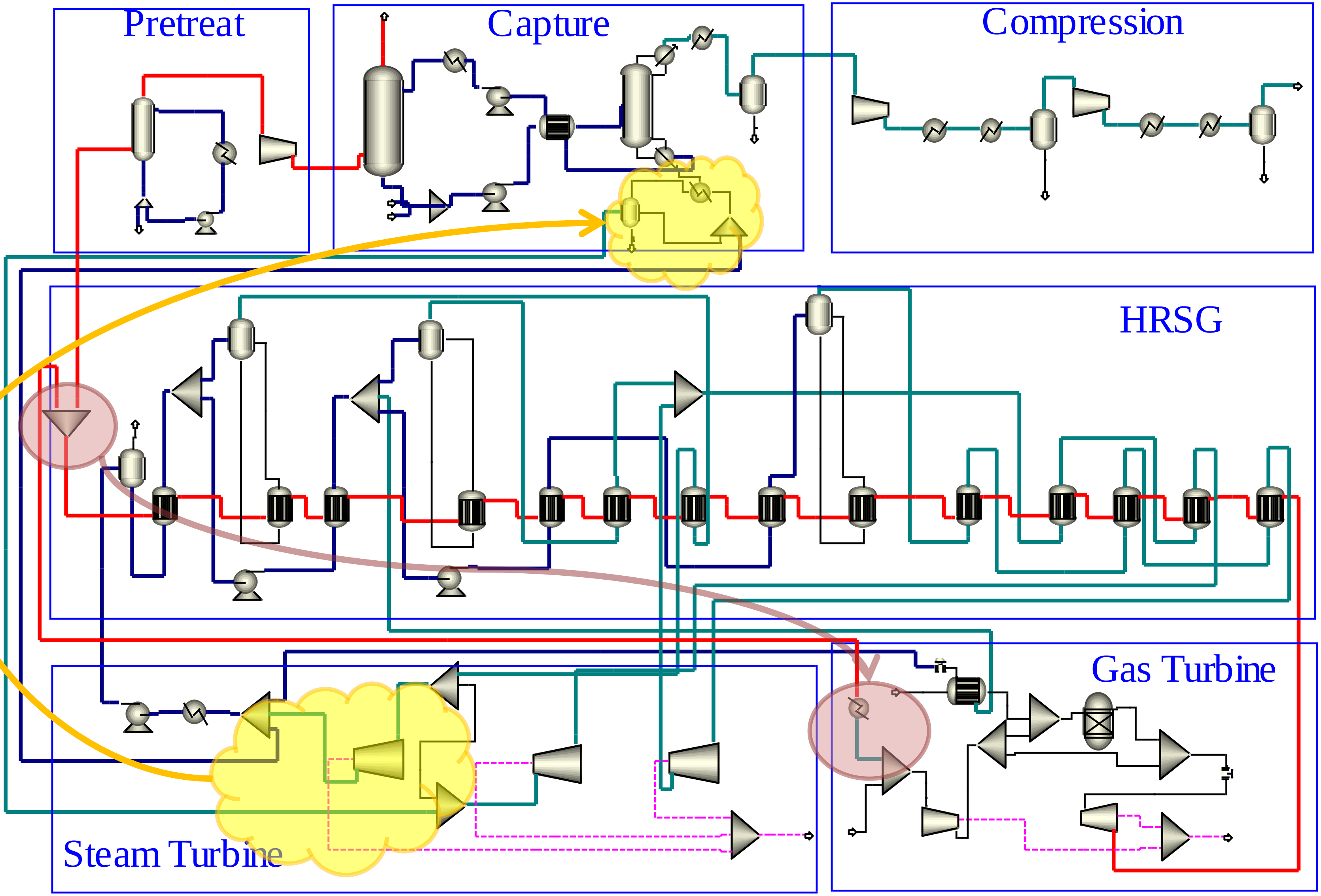
CCGT Integrated with PCC



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Case Study

Case settings:

- Reference case: CCGT power plant stand alone

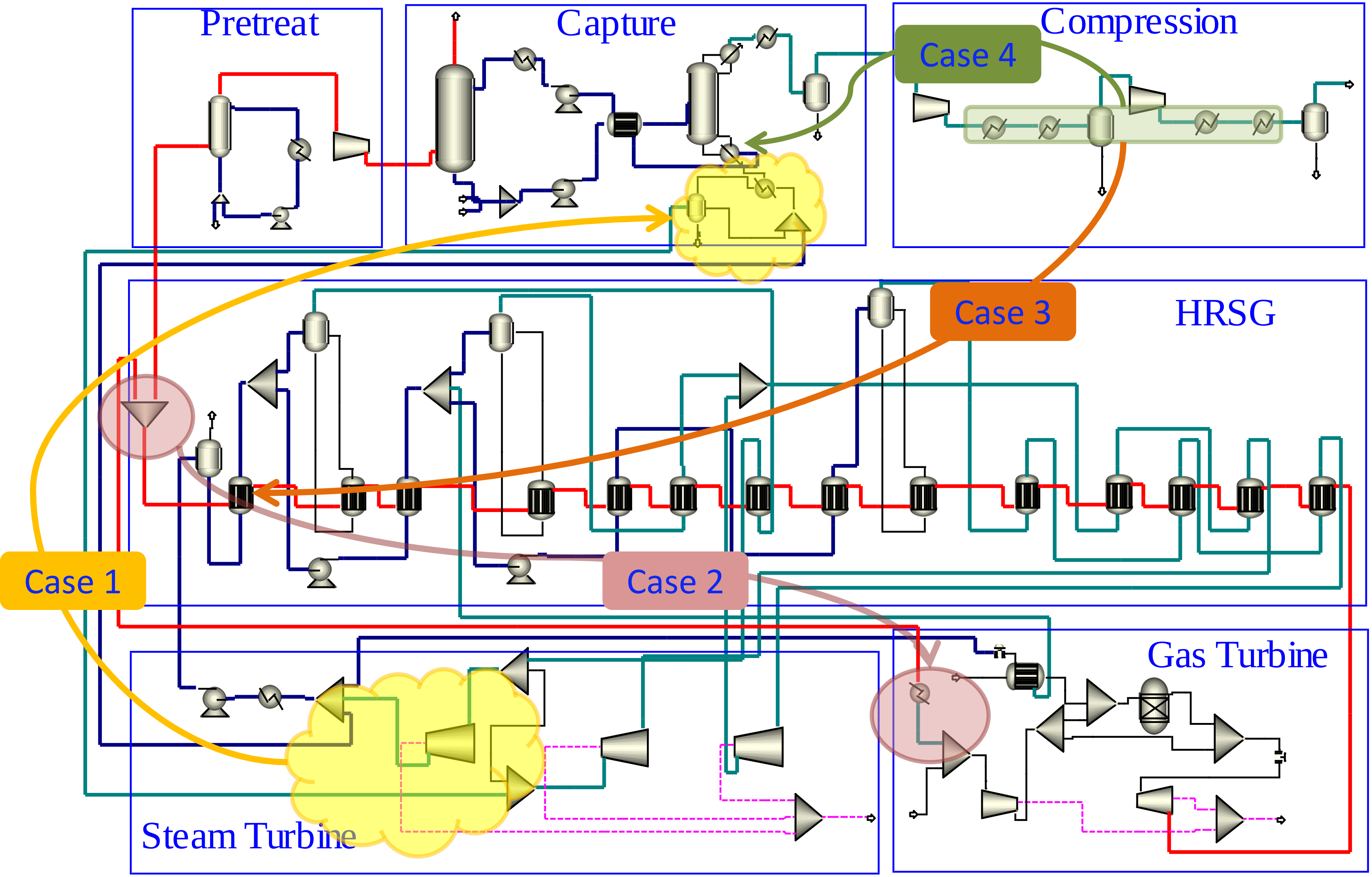
- Case 1: CCGT integrated PCC without EGR

- Case 2: CCGT integrated PCC with EGR
  - ❖ EGR ratio is 0.38 to maintain 16% O_2 concentration in combustion air
  - ❖ A cooler is added to cold down the recycled gas to 15°C to get rid of most of free water

- Case 3: Case 2+ compression heat integration with HRSG
  - ❖ An economizer heat exchanger was added to integrate the compression heat to generate more low pressure steam for LP turbine
  - ❖ No optimal design was conducted for other parts of HRSG configuration

- Case 4: Case 2+ compression heat integration with stripper reboiler
  - ❖ A multi-hot-stream kettle model was used for stripper reboiler
  - ❖ The outlet temperatures of hot streams are 135°C to meet a minimum pinch temperature for the reboiler

CCGT Integrated with PCC



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Results

Description	Reference	Case 1	Case 2	Case 3	Case 4
	NGCC	NGCC +PCC	NGCC +PCC	NGCC +PCC	NGCC +PCC
EGR	without EGR	without EGR	with EGR	with EGR	with EGR
Compresion heat integration	without	without	without	with HRSG	with stripper reboiler
Gas turbine power output (MW_{el})	295.03	295.03	294.64	294.64	294.64
Steam turbine power output (MW_{el})	170.71	113.56	117.69	120.14	121.85
Power island auxiliary power consumption (MW_{el})	11.69	9.7	9.7	9.7	9.7
CO_2 compression power consumption (MW_{el})	–	14.8	14.8	14.8	14.8
Mechanical power consumption in capture process (MW_{el})	–	4.24	2.035	2.035	2.035
Desorber reboiler duty (MW_{th})	–	188.8	176.2	176.2	176.2
Steam extracted for reboiler (kg/s)	–	76.39	71.06	71.06	65.50
CO_2 captured (kg/s)	–	41.4	41.4	41.4	41.4
Specific reboiler duty ($MJ_{th}/kg\ CO_2$)	–	4.56	4.31	4.31	4.31
Net plant power output (MW_{el})	453.872	379.85	385.795	388.245	389.955
Net plant efficiency (%, fuel lower heating value)	58.74	49.16	49.93	50.25	50.47
Efficiency decrease(%-points) compared with reference case	–	9.58	8.81	8.49	8.27
Overall efficiency improvement(%-points) compared with case 1	–	–	0.77	1.09	1.31

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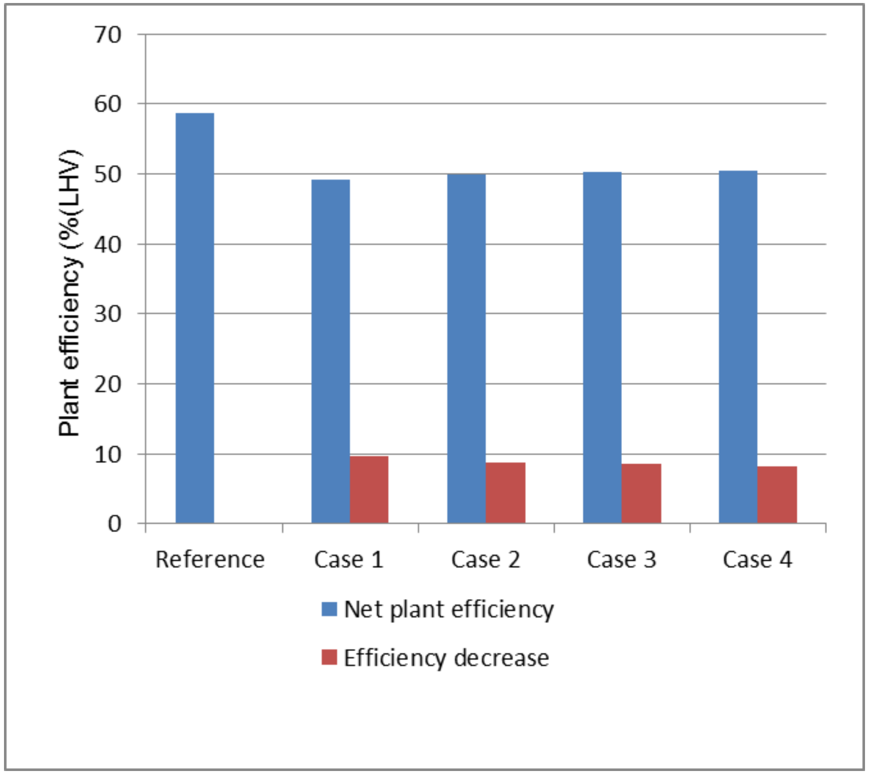
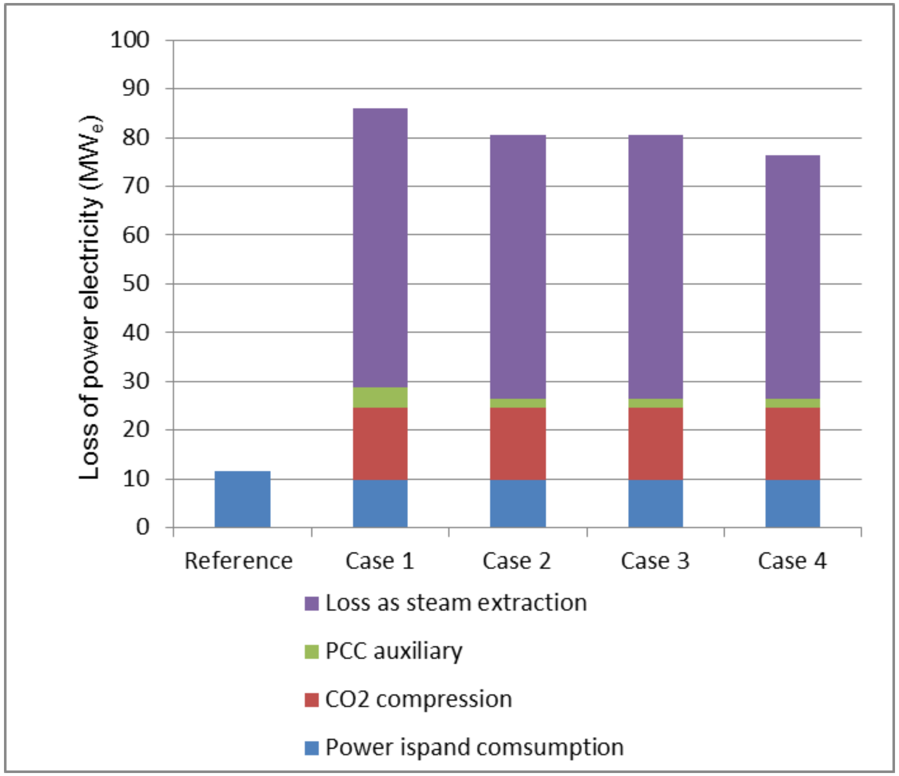
Results



Plant efficiency (%(LHV)
70
60
50
40
30
20
10
0
Reference
Case 1
Case 2
Case 3
Case 4
Net plant efficiency
Efficiency decrease



Loss of power electricity (MW_e)
100
90
80
70
60
50
40
30
20
10
0
Reference
Case 1
Case 2
Case 3
Case 4
Loss as steam extraction
PCC auxiliary
CO2 compression
Power ispand comsumption

Summary

- The efficiency (LHV) deceases to 49.16 % from 58.74% for conventional capture plant (Case 1):
  - ~7.40% points for steam extraction for solvent regeneration
  - ~0.55% points for capture plant auxiliary power consumption
  - ~1.92% points for CO2 compression

- EGR has a lower CAPEX investment because of smaller cross-section area of
  - the absorber (216.42m^2 VS 303.15m^2→ 28.6% reduction)
  - the stripper (75.43m^2 VS 81.71m^2 → 7.69% reduction)

- EGR has 0.77% points efficiency improvement (Case 2 VS Case 1) because of:
  - 7% lower steam consumption
  - 52% blower power consumption
  - A litter lower solvent pumps power consumption

Summary

- Compression heat integration with HRSG has 0.32% points efficiency improvement (Case 3 VS Case 2). Optimal design of HSRG configuration combining compression heat could help to achieve more efficiency improvement for Case 3.

- Compression heat integration with stripper reboiler achieves 0.54% points efficiency improvement (Case 4 VS Case 2). The return temperature of the stream from compression train is 135°C (in Case 4) after is introduced to heat the reboiler, which provide the potentials to do more integration.

- In a summary, CCGT with EGR integrated with PCC and supersonic shock wave compression with compression heat integration into main process could be the future direction of carbon capture deployment for CCGT power plant

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Heat integration of natural gas combined cycle power plant integrated with post-combustion CO_2 capture and compression

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Reference

- Canepa, R., Wang, M., Biliyok, C. & Satta, A. (2013), "Thermodynamic analysis of combined cycle gas turbine power plant with post-combustion CO_2 capture and exhaust gas recirculation." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering,* Vol. 227, No.2: pp. 89-105.
- Ciferno, J. P., Fout, T. E., Jones, A. P. & Murphy, J. T. (2009), "Capturing carbon from existing coal-fired power plants." *Chemical Engineering Progress,* Vol. 105, No.4: pp. 33-41.
- IEA (2012), "*Energy Technology Perspectives 2012,"* Paris, International Energy Agency.
- Karimi, M., Hillestad, M. & Svendsen, H. F. (2012), "Natural Gas Combined Cycle Power Plant Integrated to Capture Plant." *Energy & Fuels,* Vol. 26, No.3: pp. 1805-1813.
- Lawlor, S. (2010), CO_2 Compression Using Supersonic Shock Wave Technology. Ramgen Power Systems.
- Marchioro Ystad, P. A., Lakew, A. A. & Bolland, O. (2013), "Integration of low-temperature transcritical CO2 Rankine cycle in natural gas-fired combined cycle (NGCC) with post-combustion CO2 capture." *International Journal of Greenhouse Gas Control,* Vol. 12, No.0: pp. 213-219.
- Witkowski, A. & Majkut, M. (2012), "The impact of CO_2 compression systems on the compressor power required for a pulverized coal-fired power plant in post-combustion carbon dioxide sequestration." *Archive of Mechanical Engineering,* Vol. 59, No.3: pp. 343-360.
- ETH Zurich. "Climate Change: Halving Carbon Dioxide Emissions By 2050 Could Stabilize Global Warming." ScienceDaily. ScienceDaily, 4 May 2009. <www.sciencedaily.com/releases/2009/05/090502092019.htm>.

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