Process Analysis of Part-load Performance when Co-firing Coal and Biomass in a Power Generation System Integrated with CO_2 Capture and Compression System

Presneted by: Janos Szuhanszki[a]

Usman Ali *,[a,c], Muhammad Akram[a], Carolina Font Palma[b], Derek B Ingham[a], Mohamed Pourkashanian[a]

[a]*Energy 2050, University of Sheffield, UK*
[b]*Department of Chemical Engineering, University of Chester, UK*
[c]*Department of Chemical Engineering, University of Engineering and Technology, Pakistan*

Clean Coal Technologies (CCT-2017)
8 -12 May 2017, Cagliari, Italy

Contents

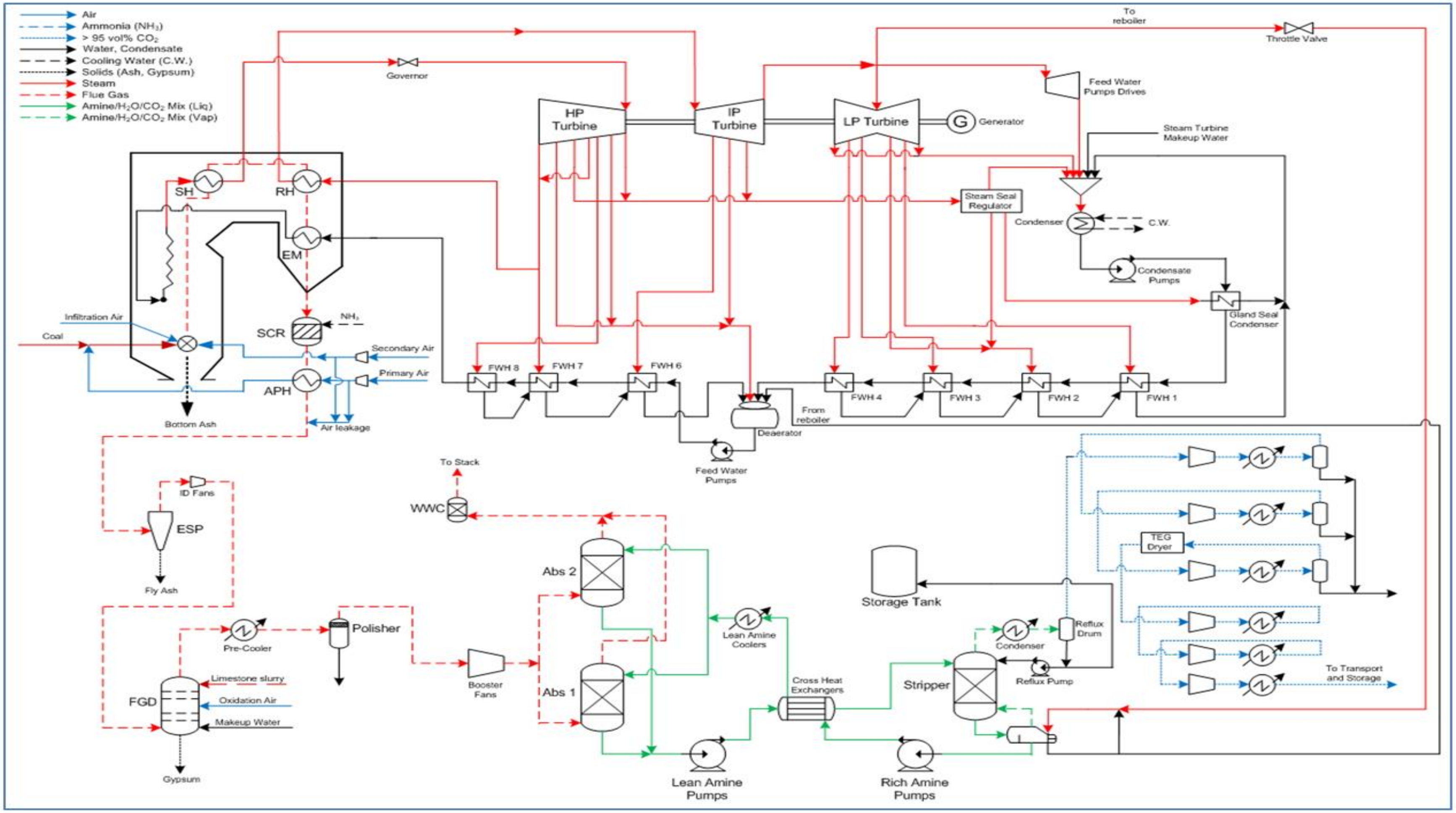
Introduction

- Biomass - EU emission reduction.
- The Drax power plant has 4 GW total capacity with 70 % biomass share.
- To meet target of 2 ° C or below, more than 1 Gt/year of negative emissions are required and BECCS is the working option.
- The Illinois Industrial CCS project is the world's first large scale industrial BECCS project and is expected to begin operation.

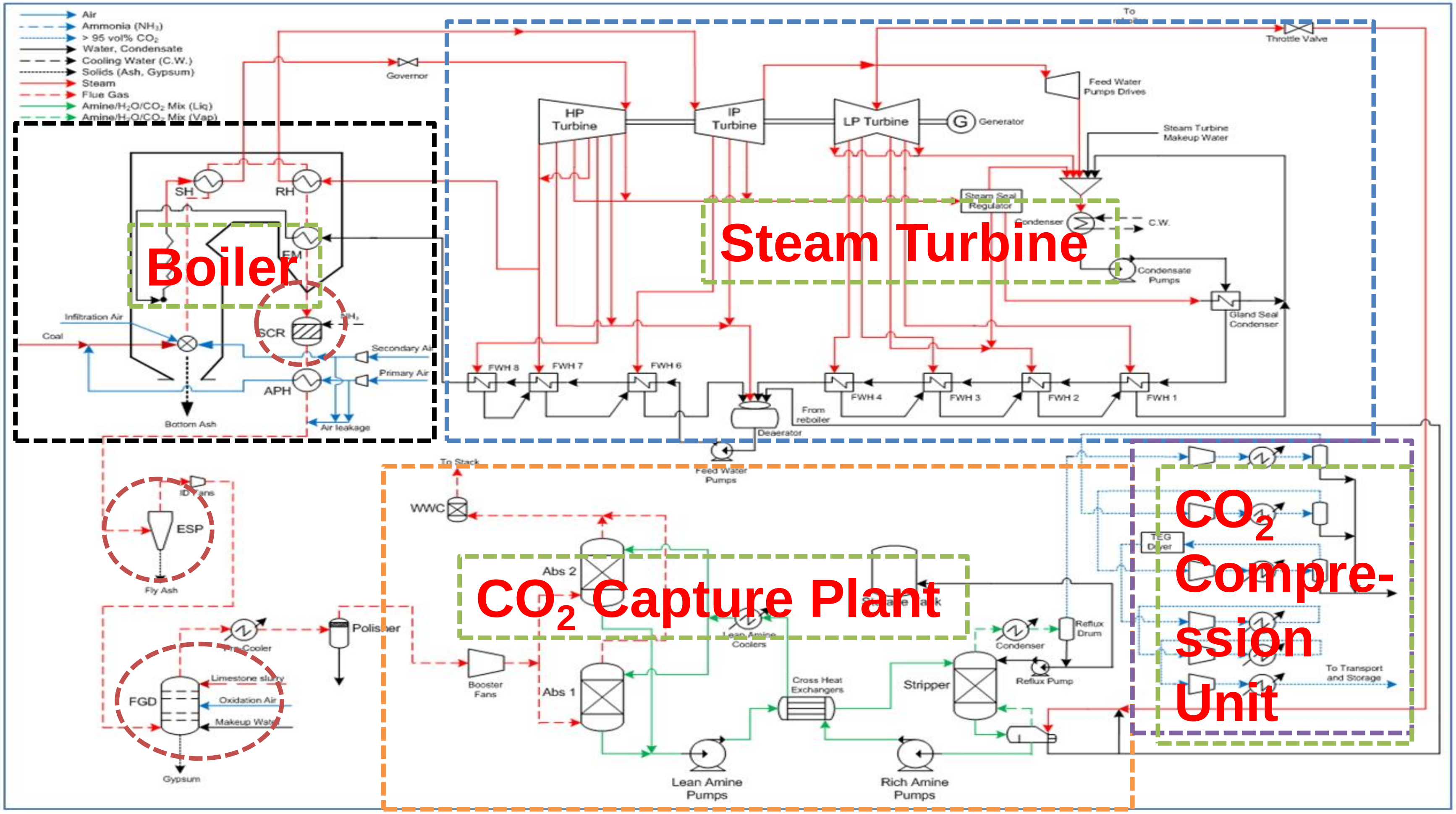
Aims and Objectives

- Detailed investigation of co-firing of coal and biomass for commercial-scale pulverised supercritical power plants.
- Integration of the CO_2 capture plant (CCP) and CO_2 compression unit (CCU).
- Two co-firing scenarios of coal and biomass - constant heat input (CHI) and constant fuel input (CFF).
- Part-load operation (100, 80, 60 and 40 %) is analysed for co-firing of coal and biomass, integrated with CCP and CCU.

Flowsheet of Commercial-scale Power Plant



Flowsheet of Commercial-scale Power Plant



SO_x and NO_x Removal Units

Flue Gas Desulphurisation:

- 98 % removal efficiency.
- Up to 10 ppmv SO_2 reduction.

$$CaCO_3(s) + SO_2(g) + 0.5\ H_2O \rightarrow CaSO_3.0.5H_2O + CO_2(g)$$

$$CaCO_3(s) + SO_2(g) + 0.5\ H_2O + 2H_2O \rightarrow CaSO_4.2H_2O + CO_2(g)$$

Selective Catalytic Reduction Unit:

- 86 % removal efficiency.
- 2 ppmv NH_3 slip at the end of catalyst life.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O + Heat$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O + Heat$$

Cases Modelled

- ❑ Supercritical
  - ✓ Constant heat input 100% coal and biomass (CHI)
  - ✓ Constant fuel input 100% coal and biomass (CFF)
  - ✓ Co-firing (CHI)
  - ✓ Co-firing (CFF)
    - ✓ Part-load 100% of total power
    - ▪ Part-load 80 % of total power
    - ▪ Part load 60 % of total power
    - ▪ Part-load 40 % of total power

Key Input Data

	Illinois No. 6 (Bituminous) Coal		Biomass (US Forestry Residue) Pellets	
Proximate Analysis	As-received (wt. %)	Dry (wt. %)	As-received (wt. %)	Dry (wt. %)
Moisture	11.12	0.00	6.69	0.00
Volatile Matter	34.99	39.37	78.10	83.70
Ash	9.70	10.91	0.70	0.75
Fixed Carbon	44.19	49.72	14.51	15.55
Total	100	100	100	100
Ultimate Analysis	As-received (wt. %)	Dry (wt. %)	As-received (wt. %)	Dry (wt. %)
C	63.75	71.72	48.44	51.87
H	4.50	5.06	6.34	6.79
N	1.25	1.41	0.15	0.16
O	6.88	7.75	37.69	40.37
S	2.51	2.82	<0.02	0.02
Cl	0.29	0.33	<0.01	0.01
Moisture	11.12	0.00	6.69	0.00
Ash	9.70	10.91	0.70	0.75
Total	100	100	100	100
Heating Value	As-received	Dry	As-received	Dry
HHV (kJ/kg)	27113	30506	19410	20802
LHV (kJ/kg)	26151	29444	18100	19398

Air Composition (Mole fraction, %)	
Nitrogen	77.32
Oxygen	20.74
Argon	0.92
Carbon Dioxide	0.03
Water	0.99 (RH : ~60%)

Co-firing Cases

Cases	Coal/Biomass mass % in fuel feed stream
Coal	100/0
C80/B20	80/20
C60/B40	60/40
C40/B60	40/60
C20/B80	20/80
Biomass	0/100

C: Coal B: Biomass

Base Load Modelling Framework

Input Specification for base load

Parameters	Value
Gross power output [MW_e]	800
Boiler efficiency [%]	88
Turbine thermal input [MW_{th}]	1705
Fabric filter efficiency [%]	99.8
SCR unit efficiency [%]	86
FGD unit efficiency [%]	98
Percent excess air [%]	15
Primary to secondary air split	0.235/0.765
Infiltration air to that of the total air [%]	2
Flue gas temperature at ESP inlet [°C]	169

CO_2 Compression Unit Data[1]

Stage	Outlet Pressure (bar)
1	3.6
2	7.8
3	17.1
4	37.6
5	82.7
6	153.0

Optimum CO_2 Capture Plant[2]

Parameter	Value
Absorber	
Number of Absorbers	2
Packing	Mellapak 250Y
Packing Height [m]	23.04
Diameter [m]	16.13
Stripper	
Number of Stripper	1
Packing Height [m]	25.62
Diameter [m]	14.61
Specific Reboiler Duty [MJ/kg CO_2]	3.69
Flue Gas Flowrate [kg/s]	821.26
MEA concentration [kg/kg]	0.3
Lean CO_2 loading [mol/mol]	0.2
Liquid/Gas Ratio [kg/kg]	2.93
Stripper pressure [bara]	1.62

[1]U.S. DOE. Cost and Performance Baseline for Fossil Energy Plants. Vol. 1: Bituminous Coal and Natural Gas to Electricity, revision 2; U.S. Department of Energy; Washington, DC, November 2010.
[2]Elvis O Agbonghae, Modelling and optimization of coal-fired power plant generation systems with CO_2 capture, PhD thesis, 2014.

Part-load Modelling Framework

- Sliding pressure control for boiler resulting in reduced power consumption.
- The heat transfer areas and temperature differences for the superheater, economiser reheater, and air preheater are kept constant.
- Stadola Law of Cones is used for the off-design steam specifications estimation.
- The isentropic efficiency is updated based on the base-load.
- Pressure drops are updated using average velocity at base and part-load and pressure drops at base load.

Part-load Modelling Framework

- Pressure drop:

$$\Delta p = \frac{fV^2L}{2g\rho d}$$

$$\Delta p_{part} = \frac{\left(\frac{V_{in_{part}} + V_{out_{part}}}{2}\right)^2}{\left(\frac{V_{in_{base}} + V_{out_{base}}}{2}\right)^2} \Delta p_{base}$$

- Stodola's Ellipse Law:

$$\frac{m_{in}}{m_{in_{base}}} = \frac{\mu\, p_{in}}{\mu_{base} p_{in_{base}}} \sqrt{\frac{p_{in_{base}} v_{in_{base}}}{p_{in} v_{in}}} \sqrt{\frac{1 - \left(\frac{p_{out}}{p_{in}}\right)^{\frac{n+1}{n}}}{1 - \left(\frac{p_{out_{base}}}{p_{in_{base}}}\right)^{\frac{n+1}{n}}}}$$

- Efficiencies:

$$\frac{\eta_{part}}{\eta_{base}} \cong 2 \frac{a}{\frac{V_{in_{base}}}{V_{in_{part}}}} \left[\left(a - \frac{a}{\frac{V_{in_{base}}}{V_{in_{part}}}} \right) + \sqrt{\left(a - \frac{a}{\frac{V_{in_{base}}}{V_{in_{part}}}} \right)^2 + 1 - a^2} \right]$$

Base Load Performance Results – CHI Case

Fuel type	Coal	C8B2	C6B4	C4B6	C2B8	Biomass
Fuel [kg/s]	71.3	75.6	80.4	85.9	92.3	99.6
Total air [kg/s]	729	726	723	720	712	702
Slag + Fly Ash [kg/s]	6.9	6	4.9	3.7	2.3	0.7
Main steam [kg/s]	630	630	630	630	630	630
Reheat from boiler [kg/s]	514	514	514	514	514	514
Steam to stripper [kg/s]	233	225	226	228	230	230
Flue gas, absorber inlet [kg/s]	832	830	829	827	819	804
CO_2 composition in flue gas [mol%]	13.28	13.42	13.56	13.73	13.93	14.35
Lean MEA solution, absorber inlet [kg/s]	2403	2414	2403	2453	2464	2470
Specific reboiler duty [MJ/kg CO_2]	3.686	3.679	3.677	3.675	3.674	3.673
Total compression duty [MW_e]	44.9	45.26	45.03	46.04	46.29	46.46
Fuel heat input, HHV [MW_{th}]	1933	1933	1933	1933	1933	1933
Power without steam extraction [MW_e]	800	800	800	800	800	800
Power with steam extraction [MW_e]	664	662	659	658	657	656
Power without CCP and CCU [MW_e]	758	758	758	758	758	758
Power with CCP only [MW_e]	602	600	598	597	596	596
Power with CCP and CCU [MW_e]	557	554	553	551	550	549
Efficiency without CCP and CCU [%]	39.22	39.3	39.3	39.3	39.3	39.3
Efficiency with CCP only [%]	31.16	31.02	30.94	30.86	30.83	30.82
Efficiency with CCP and CCU [%]	28.84	28.68	28.61	28.48	28.43	28.41

Base Load Performance Results – CFF Case

Fuel type	Coal	C8B2	C6B4	C4B6	C2B8	Biomass
Fuel [kg/s]	71.3	71.3	71.3	71.3	71.3	71.3
Total air [kg/s]	729	685	641	598	550	502
Slag + Fly Ash [kg/s]	6.9	5.6	4.4	3.1	1.8	0.5
Main steam [kg/s]	630	596	560	528	485	452
Reheat from boiler [kg/s]	514	486	457	431	396	369
Steam to stripper [kg/s]	233	212	198	188	176	163
Flue gas, absorber inlet [kg/s]	833	784	735	686	634	575
CO_2 composition in flue gas [mol%]	13.28	13.41	13.56	13.72	13.92	14.34
Lean MEA solution, absorber inlet [kg/s]	2403	2278	2128	2023	1889	1744
Specific reboiler duty [MJ/kg CO_2]	3.686	3.673	3.666	3.654	3.643	3.634
Total compression duty [MW_e]	44.9	42.8	40.06	38.22	35.82	33.21
Fuel heat input, HHV [MW_{th}]	1933	1823	1713	1603	1477	1384
Power without steam extraction [MW_e]	800	759	713	673	618	576
Power with steam extraction [MW_e]	664	627	590	555	509	475
Power without CCP and CCU [MW_e]	758	718	672	633	579	538
Power with CCP only [MW_e]	602	567	532	499	455	423
Power with CCP and CCU [MW_e]	557	524	492	461	419	390
Efficiency without CCP and CCU [%]	39.22	39.36	39.25	39.50	39.19	38.86
Efficiency with CCP only [%]	31.16	31.09	31.04	31.11	30.78	30.58
Efficiency with CCP and CCU [%]	28.84	28.75	28.70	28.72	28.36	28.18

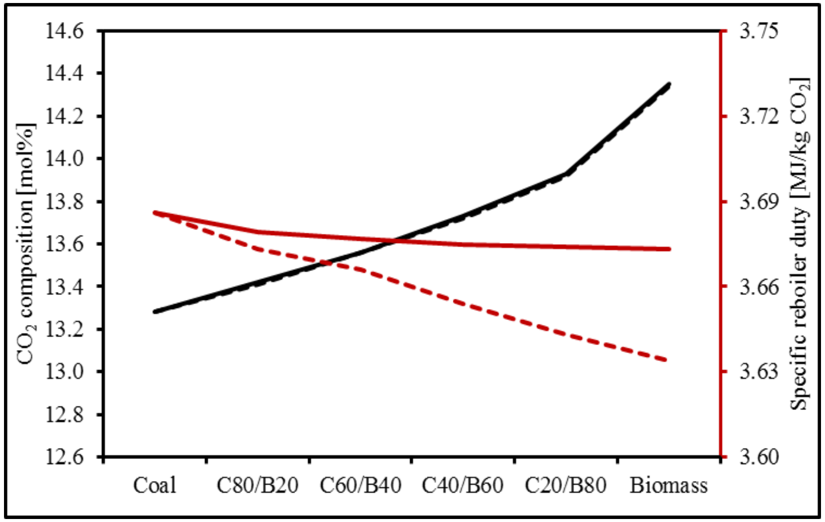
The University Of Sheffield.

energy 2050

Base Load Performance Results

- Biomass results in a lower flow rate of the flue gas with higher concentration of the CO_2, hence lower solvent requirements for scrubbing, which decreases the specific reboiler duty.

- There is a large decrease in specific reboiler duty for the CFF cases as compared to the CHI cases and this is due to the lower flue gas flowrates for the CFF cases and this results in the lower specific reboiler duty

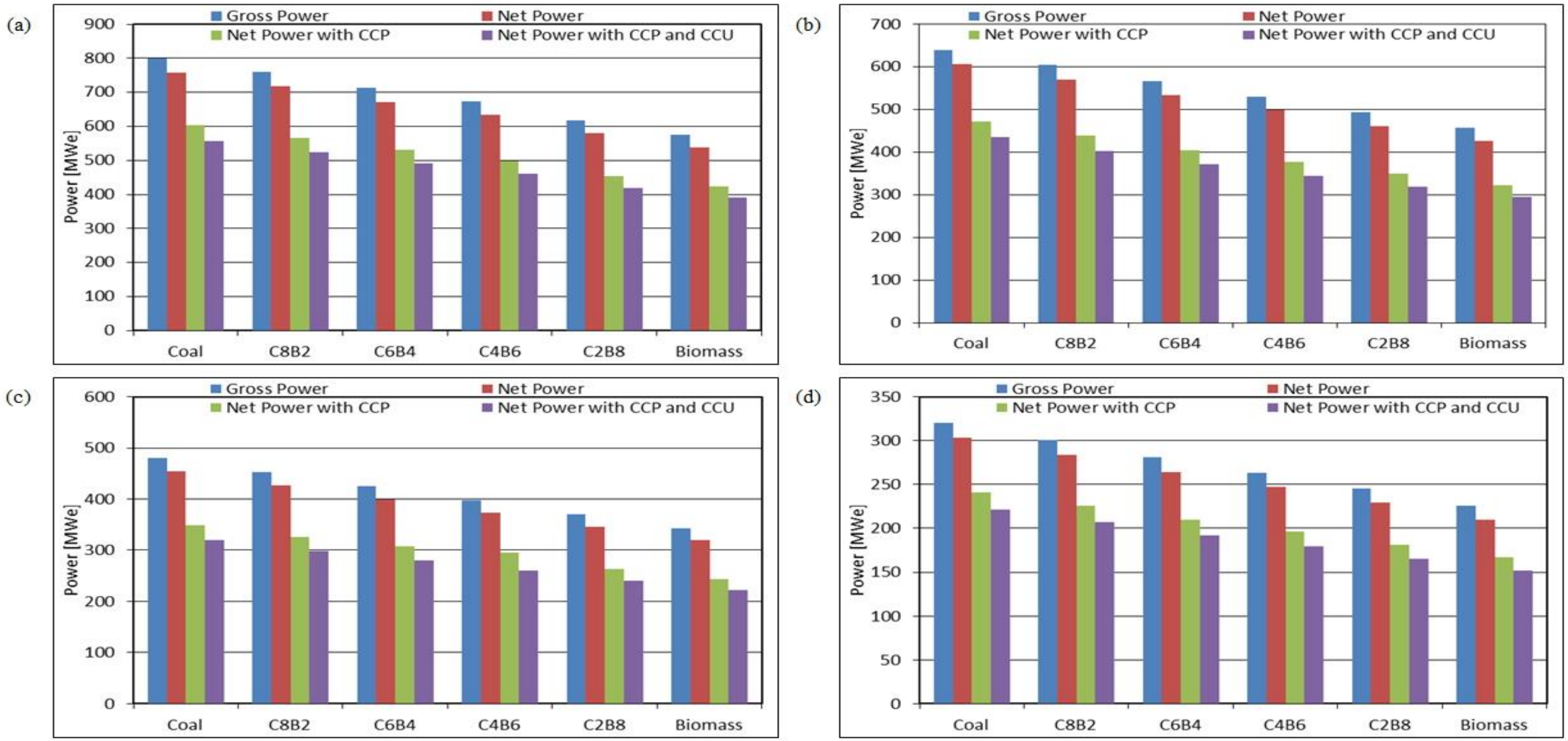


solid line represents CHI case and dashed line represents CFF case)

Part Load Performance Results

Fuel type	Coal	C8B2	C6B4	C4B6	C2B8	Biomass
	80 % part-load operation					
Fuel heat input, HHV [MW_{th}]	1615	1523	1432	1340	1248	1156
Power without steam extraction [MW_e]	640	604	567	530	493	457
Power with steam extraction [MW_e]	523	488	452	423	393	365
Power without CCP and CCU [MW_e]	606	571	534	499	461	426
Power with CCP only [MW_e]	472	439	405	377	349	323
Power with CCP and CCU [MW_e]	435	403	371	345	319	295
Efficiency without CCP and CCU [%]	37.52	37.46	37.33	37.15	36.97	36.86
Efficiency with CCP only [%]	29.24	28.87	28.27	28.14	27.95	27.92
Efficiency with CCP and CCU [%]	26.91	26.47	25.90	25.76	25.55	25.52
	60 % part-load operation					
Fuel heat input, HHV [MW_{th}]	1262	1190	1118	1046	975	903
Power without steam extraction [MW_e]	480	452	425	398	370	343
Power with steam extraction [MW_e]	388	364	343	320	298	276
Power without CCP and CCU [MW_e]	454	427	400	374	346	320
Power with CCP only [MW_e]	349	326	307	296	264	244
Power with CCP and CCU [MW_e]	320	298	280	260	241	222
Efficiency without CCP and CCU [%]	35.98	35.85	35.79	35.72	35.50	35.40
Efficiency with CCP only [%]	27.66	27.42	27.43	27.24	27.1	26.99
Efficiency with CCP and CCU [%]	25.34	25.08	25.06	24.85	24.71	24.59
	40 % part-load operation					
Fuel heat input, HHV [MW_{th}]	882	832	781	731	681	631
Power without steam extraction [MW_e]	320	301	281	263	245	226
Power with steam extraction [MW_e]	268	252	235	220	204	189
Power without CCP and CCU [MW_e]	303	284	264	247	229	210
Power with CCP only [MW_e]	241	226	210	196	181	167
Power with CCP and CCU [MW_e]	221	207	192	179	165	152
Efficiency without CCP and CCU [%]	34.30	34.12	33.84	33.73	33.61	33.32
Efficiency with CCP only [%]	27.37	27.20	26.91	26.82	26.58	26.48
Efficiency with CCP and CCU [%]	25.04	24.86	24.54	24.43	24.18	24.07

Part Load Performance Results



(a) 100 % base-load operation; (b) 80 % part-load operation; (c) 60 % part-load operation; and (d) 40 % part-load operation.

Conclusions

- At CHI, more fuel is required as the percentage of biomass is increased; e.g. for firing 100% biomass, 40% more fuel is fed.
- At CFF, derating occurs as the fraction of the biomass in the fuel stream increases, e.g. 30% derating of the power output.
- Higher specific CO_2 capture - when the share of biomass in the fuel feed increases due to increases in the CO_2 content in the flue gas.
- A larger decrease in specific reboiler duty is observed for the CFF cases as compared to the CHI cases.
- A FGD unit may not be required at the higher biomass shares.
- The net power output and net efficiency decrease when the fraction of biomass increases for both cases.

Conclusions

- Co-firing of coal and biomass resulted in substantial power derating at each part-load operation. An overall 30 to 32 % derating of the power output capacity is expected for 100% biomass.
- At each part-load operation, specific reboiler duty decreases when the biomass fraction increases.
- The by-products –gypsum from FGD, fly-ash from ESP, slag from boiler and NH_3 requirement in SCR– decrease for the co-firing at any part-load operation.

THANK YOU!

Email: chemaliusman@gmail.com
usmanali@uet.edu.pk

Acknowledgments:

- Usman Ali acknowledges the Grant provided by the University of Engineering and Technology, Lahore Pakistan and the partial support by University of Sheffield, UK, in support of this research.

The University Of Sheffield.

To Discover And Understand.

A WORLD TOP 100 UNIVERSITY