Programme Area: Bioenergy

Project: Biomass to Power with CCS

Title: WP2 High-level Engineering Study: member dissemination event slide pack

Abstract:

This presentation was used to brief ETI members and advisors on the outcomes of the high level engineering study carried out by the Biomass to Power with CCS project team. It should be read in parallel with the full report: D2.1 Report on Selected Technology Combinations.

Context:

The Biomass to Power with CCS Phase 1 project consisted of four work packages: WP1: Landscape review of current developments; WP2: High Level Engineering Study (down-selecting from 24 to 8 Biomass to Power with CCS technologies); WP3: Parameterised Sub-System Models development; and WP4: Technology benchmarking and recommendation report. Reports generally follow this coding. We would suggest that you do not read any of the earlier deliverables in isolation as some assumptions in the reports were shown to be invalid. We would recommend that you read the project executive summaries as they provide a good summary of the overall conclusions. This work demonstrated the potential value of Biomass to Power with CCS technologies as a family, but it was clear at the time of the project, that the individual technologies were insufficiently mature to be able to ‘pick a winner’, due to the uncertainties around cost and performance associated with lower Technology Readiness Levels (TRLs).

ETI commissioned and funded Project

Techno-Economic Study of Biomass to Power with CO_2 Capture: Review WP2/3

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21 March 2012
ETI, Loughborough

www.cmclinnovations.com/TESBIC

Contents

- Re-cap: Landscape Review of biomass to power with CO_2 capture technologies
- WP2: High level Engineering Case Studies – 3 examples
- Techno-economic outcomes
- Model development and sub-model parameterisation – 2 examples
- Next steps: WP4 - Recommendations

Biomass-CCS: UK context

- IEAGHG, 2011: Despite its strong GHG reduction potential, there is a considerable **dearth of information** for **biomass CCS** as compared to that for **fossil based CCS**

- ETI's ESME toolkit's least-cost options for meeting the UK's energy demand and emissions reduction targets to 2050, identify biomass CCS as **vital** with large, **negative** emissions, **a high option value** and **high persistence**

- APGTF, 2011: RD&D strategic themes and priorities

  - whole system : focus on **virtual system simulation** and **optimisation**

  - capture technologies: focus on economics, efficiency penalty, emissions, **co-fired biomass, 2nd and 3rd generation technologies**

- **TESBiC** addresses the key technical and economic barriers of biomass CCS, and identify UK deployment potential to 2050

Summary of the TESBiC approach

- Landscape review of **28** biomass based power generation combined with carbon capture technology combinations. Based on the assessment criteria, **8** technology combinations were shortlisted

- **High-level Engineering Case Studies** were performed focusing on the material and energy balances, capital and operating expenditures, emissions and environmental performance , process control strategies, current gaps and development needs

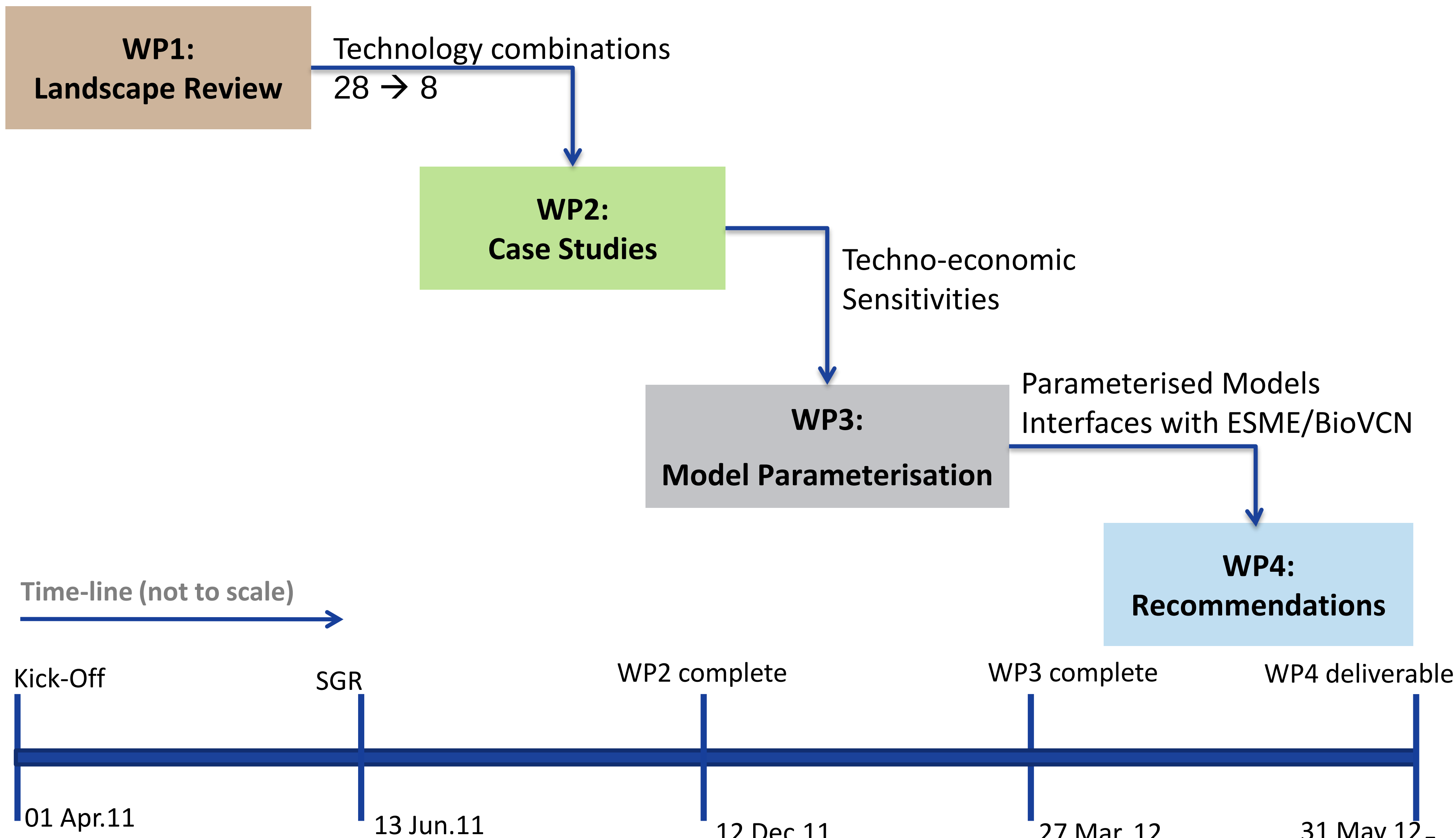
- **Models** were formulated for individual technology combinations to simulate

  the impact of **inputs**: co-firing %, carbon capture extent, nameplate and operating capacities

  on the **outputs**: CAPEX, OPEX, Generation efficiency, CO_2, SO_x, NO_x emissions.

- These models can be seamlessly integrated within ETI's modelling toolkits, namely, the **Biomass Value Chain** and the **ESME**.

TESBiC: information flow



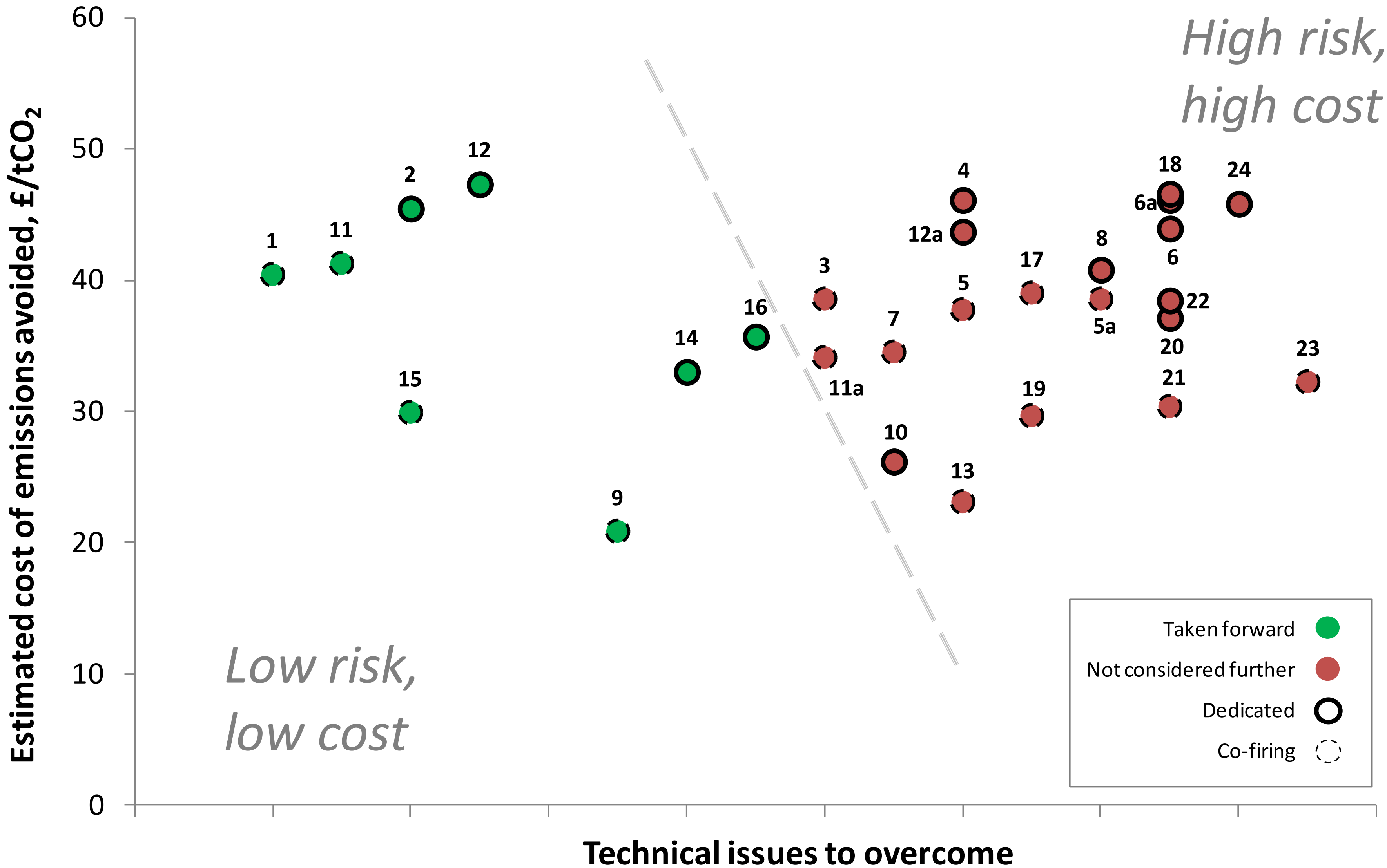
WP1: Power generation and CO_2 capture combinations

Global planned demos

		Post-combustion						Oxy-combustion			Pre-combustion				
		Solvent scrubbing, e.g. MEA, chilled ammonia	Low-temp solid sorbents, e.g. supported amines	Ionic liquids	Enzymes	Membrane separation of CO_2 from flue gas	High-temp solid sorbents, e.g. carbonate looping	Oxy-fuel boiler with cryogenic O2 separation	Oxy-fuel boiler with membrane O2 separation	Chemical-looping-combustion using solid oxygen carriers	IGCC with physical absorption e.g. Rectisol, Selexol	Membrane separation of H_2 from synthesis gases	Membrane production of syngas	Sorbent enhanced reforming using carbonate looping	ZECA concept
Coal IGCC gasification	Direct cofiring Conversion to 100% biomass	Not feasible						Not feasible			15	17	19	21	23
Pulverised coal combustion	Direct cofiring Conversion to 100% biomass	1	3	5	5a	7	9	11	11a	13	Not feasible				
Dedicated biomass combustion	Fixed grate Bubbling fluidised bed Circulating fluidised bed	2	4	6	6a	8	10	12	12a	14					
Dedicated biomass gasification	Bubbling fluidised bed Circulating fluidised bed Dual fluidised bed Entrained flow	Not feasible						Not feasible			16	18	20	22	24

Progress
Reject

Risks vs. rewards



Shortlisted technology combinations

Criteria	Co-firing amine scrubbing	Dedicated biomass with amine scrubbing	Co-firing oxy-fuel	Dedicated biomass oxy-fuel	Co-firing carbonate looping	Dedicated biomass chemical looping	Co-firing IGCC	Dedicated biomass BIGCC
Likely TRL in 2020	7 to 8	6 to 7	7	6	5 to 6	5 to 6	7	5 to 6
Key technical issues	Scale-up, amine degradation,	Scale-up, amine degradation,	O_2 energy costs, slow response	O_2 energy costs, slow response	Calciner firing, solid degradation, large purge of CaO	Loss in activity, reaction rates, dual bed operation	Complex operation, slow response, tar cleaning, retrofit impractical	Complex operation, slow response, tar cleaning, retrofit impractical
Suitability for small scale	Low	High	Low	High	Low	High	Low	High
Plant efficiency with capture	OK	Low	OK	Low	Good	Good	High,	Good
Capital costs with capture	OK	Expensive	OK	High ASU costs	OK	Low cost	OK	Expensive,
UK deployment potential	Immediate capture retrofit opportunities ,	retrofit opportunities high long-term potential	retrofit opportunities , long-term doubtful	retrofit opportunities , high long-term potential	capture retrofit opportunities, cement integration	Likely first demos in Europe, UK in ~2020. High long term potential	No current UK plants, several demos by 2020 Long-term doubt	No current UK plants, demo unlikely by 2020. High long-term potential

WP2 High level Engineering Case Studies

- Assessment and evaluation criteria
- **Post-combustion example:** co-firing biomass with amine scrubbing
- **Pre-combustion example**: co-firing IGCC with physical absorption
- **Oxy-fuel example**: dedicated biomass chemical looping combustion
- Knowledge outcomes

WP2 criteria

- An overview of the total process and the relevant engineering standards
- A preliminary process flow diagram with mass and energy balance
- A list of the major equipment items with performance specifications covering all the key aspects
- A high level process control philosophy
- An environmental performance summary
- An estimate of project and plant capital costs for both new build and retrofit
- A summary of the production costs
- A characterisation of how costs and other parameters [e.g. efficiencies] vary with scale
- An overview of the evaluation of systems performance and critical identification of knowledge gaps, technical risk areas

8 technology combinations: Case Study examples

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Harmonized parameters

Additional capital costs (£m)

Operation and utilities: 5% of Total Installed CAPEX (TIC)

Civils and land costs: 10% of TIC

Project development costs: 5% of TIC

Contingency: 10% of TIC

Fixed operating costs (£m/yr)

Maintenance and labour: 4% of TIC/yr

Insurance: 1% of TIC/yr

Feedstocks

UK coal: 1.97 £/GJ

Global bituminous coal: 3.40 £/GJ

UK forestry wood chip: 2.8 £/GJ [£50/odt]

Traded wood pellet: 7.5 £/GJ [£135/odt]

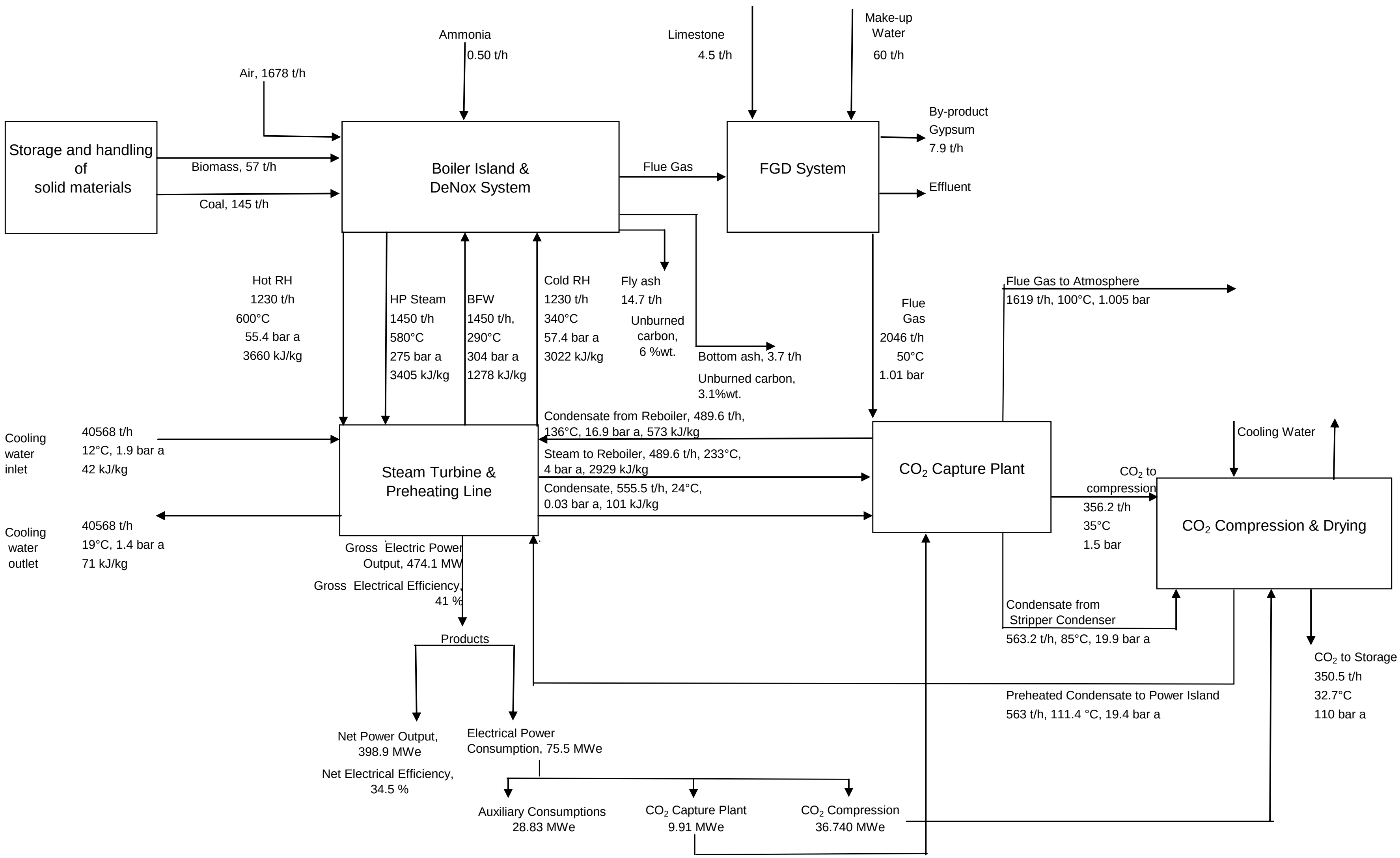
Description	Value	Units
CO_2 Compressor CAPEX	880,000	£/MW
CO_2 Compressor OPEX	0.164	MWh/tCO2
Air Separation Unit (ASU) CAPEX	250,000	£/MW
Air Separation Unit (ASU) OPEX	0.2319	MWh/tO2
Steam turbine system CAPEX	218,000	£/MW
Steam plant (boiler island) CAPEX	500,000	£/MW
Limestone	17.6	£/tonne

Capacity factor in WP2 is set at 85%.

Co-fired PC with amine scrubbing

- Biomass co-firing in a pulverised coal-fired boiler is a fairly conventional technology
- Solvent scrubbing involves the removal of the CO_2 from the combustion flue gases using a liquid solvent – commonly an aqueous solution of an organic amine.
- The combustion flue gas containing CO_2 is brought into contact with an amine solution in the absorber tower.
- The cleaned flue gas leaves the absorber, and the ‘rich’ solvent, containing chemically-bound CO_2 is pumped to the stripper or regeneration vessel, via a heat exchanger.
- The CO_2 product gas leaves the stripper via the condenser for further processing. The ‘lean’ solvent is pumped back to the absorber via the lean/rich amine heat exchanger.
- The scrubbing and stripping processes have significant requirements for:
    - Heat in the form of steam from the steam turbine circuit, and
    - Power to supply the large circulation pumps, and fans.

Co-fired PC with amine scrubbing - PFD



Co-fired PC with amine scrubbing: Efficiency and CAPEX

500 MWe PC Boiler Co-Firing Coal and Biomass			
		without CO_2 Capture	CO_2 Capture with Solvent Scrubbing
Plant Performance			
Gross Output	MWe	545.2	474.1
Net Output	MWe	518.9	398.9
Efficiency and Emissions			
Gross Electrical Efficiency (LHV)	%	47.1	41.0
Net Electrical Efficiency (LHV)	%	44.8	34.5
Actual CO_2 Emissions	g/kWh	748.5	973.7
Total CO_2 Captured	g/kWh	0.0	876.4
Economic Performance			
Capital Costs			
Storage and Handling of Solid Materials	£M	36.3	36.3
Boiler Island and Flue Gas Treating	£M	278.1	278.5
Power Island	£M	117.3	107.9
Utilities & Offsites	£M	77.6	95.0
CO_2 Capture Plant	£M	0.0	94.8
CO_2 Compression and Drying	£M	0.0	25.6
Total Installed Costs	£M	509.3	638.2
Land Purchases; Surveys and Fees (10%)	£M	50.9	63.8
Contingency (10%)	£M	50.9	63.8
Project development costs	£M	50.9	63.8
Total Investment Cost	£M	662.1	829.6
Specific Investment Costs	**£/MWe**	**1.276**	**2.079**

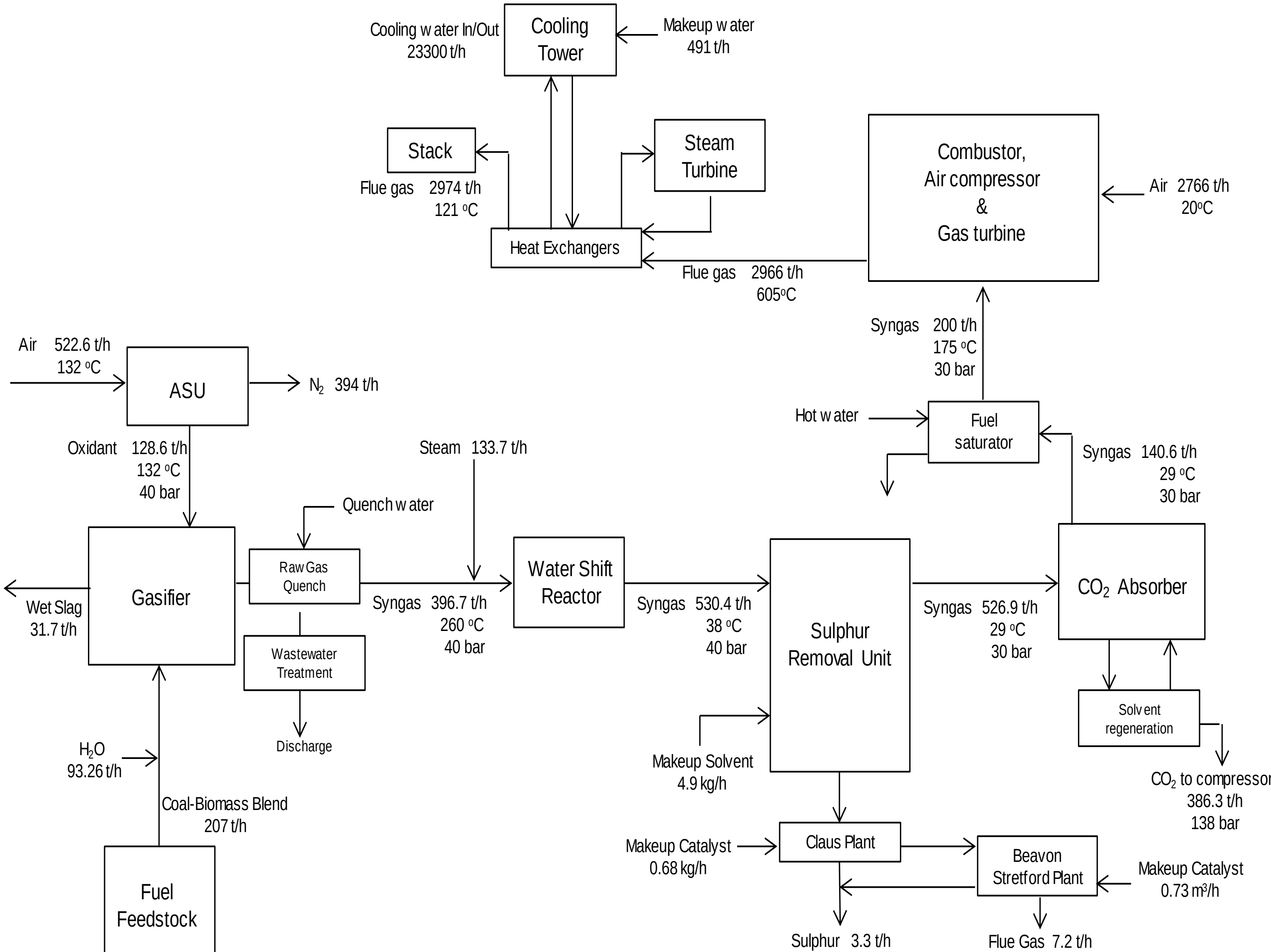
Co-fired PC with amine scrubbing - OPEX

500 MWe PC Boiler Co-Firing Coal and Biomass			
Operation and Maintenance Costs (O&M) (£M/yr)		**without CO_2 Capture**	**CO_2 Capture with Solvent Scrubbing**
Fuel Handling, Milling, Boiler Island, Power Island		17.3	16.9
CO_2 Capture Plant, CO_2 Compress., and Drying		0.0	3.0
Common Facilities (Utilities, Offsite, etc.)		1.3	1.6
Labour		5.5	5.5
Adm./gen overheads		1.7	1.7
Fixed O&M Costs		**25.8**	**28.7**
Fuel			
Coal		100.6	98.3
Biomass (dry basis)		11.2	11.0
Auxiliary Feedstock			
Make-up water		0.0	0.0
Solvents			
MEA		0.0	11.9
Catalyst		1.7	1.6
Chemicals		1.6	1.9
Waste Disposal		5.1	5.0
Variable O&M Costs		**120.2**	**129.7**
Total O&M Costs		**146.0**	**158.5**

Co-fired IGCC with physical absorption

- Fuel/water slurry fed into entrained flow gasifier with O_2 from ASU
- Water gas shift reactor converts CO and water to hydrogen and CO_2
- Solvent removal of sulphur and CO_2
- Combustion of hydrogen for power generation
- Wet cooling tower or air cooled condenser system

Co-fired IGCC with physical absorption: PFD



IGCC + physical absorption: syngas composition

Syngas composition from equilibrium calculation

Syngas Component	Coal (vol %)	Blend (vol %)
Carbon Monoxide (CO)	45.32	39.24
Hydrogen (H_2)	32.78	30.04
Methane (CH_4)	2.440e-2	1.094e-2
Ethane (C_2H_6)	0.0	0.0
Propane (C_3H_8)	0.0	0.0
Hydrogen Sulfide (H_2S)	0.5740	0.4941
Carbonyl Sulfide (COS)	2.690e-2	2.189e-2
Ammonia (NH_3)	3.000e-3	2.512e-3
Hydrochloric Acid (HCl)	5.700e-2	4.723e-2
Carbon Dioxide (CO_2)	6.151	8.644
Moisture (H_2O)	13.45	20.01
Nitrogen (N_2)	0.7160	0.6283
Argon (Ar)	0.8930	0.8601

Unregulated emissions: 10% co-fired blend

	0% CCS	95% CCS
kg/kWh	Blend	Blend
Gaseous		
CO_2	0.7817	0.08334
HCl	6.56E-04	7.64E-04
SO_2	2.57E-04	2.38E-05
NO	5.69E-05	6.28E-05
NO_2	4.59E-06	5.06E-06
Solid/Liquid		
Slag*	6.01E-02	7.00E-02
Particulate emissions to air**	6.03E-05	7.02E-05

IGCC + physical absorption: process economics

CAPEX:

Unit	0% CCS	90% CCS
	Blend	Blend
Air Separation Unit	99.136	104.58
Gasifier Area	193.73	210.82
Sulphur Control	57.42	61.98
CO2 Capture	-	121.98
Power island	170.05	169.60
Cooling Tower	11.01	11.16
CO2 compressor	-	31.4
Offsites, storage and handling	118.7	136.1
Total Installed Costs (£M)	650.0	847.6
Operation and utilities	32.50	42.38
Civils and land costs	65.00	84.76
Project development	32.50	42.38
Contingency	65.00	84.76
Total investment costs (£M)	**845.1**	**1101.9**
Specific CAPEX (£M/MW$_e$)	**1.74**	**2.39**

OPEX:

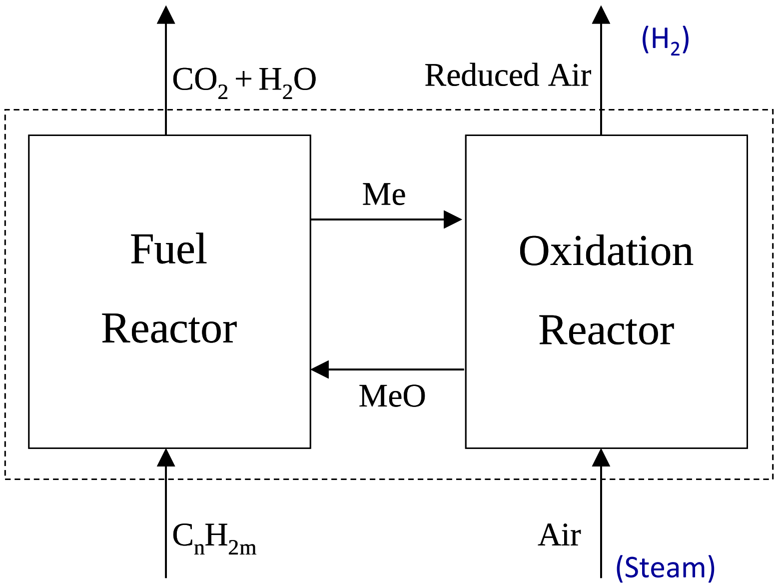
Unit	0% CCS	90% CCS
	Blend	Blend
Fuel Cost	90.69	99.53
Disposal cost	2.49	2.74
Water	1.69	2.40
Sulphur By-product Credit	1.0861	1.1919
Variable O&M (£M/yr)	95.97	105.85
Maintenance and Labour	26.00	33.90
Insurance	6.50	8.48
Fixed O&M (£M/yr)	32.50	42.38
Total O&M (£M/yr)	**128.47**	**148.23**

Chemical-looping-combustion using solid oxygen carriers

- Cu-based oxygen carrier, cycled between CuO and Cu_2O *via* the following "uncoupling" reaction:

$$4CuO \leftrightarrow 2Cu_2O + O_2$$

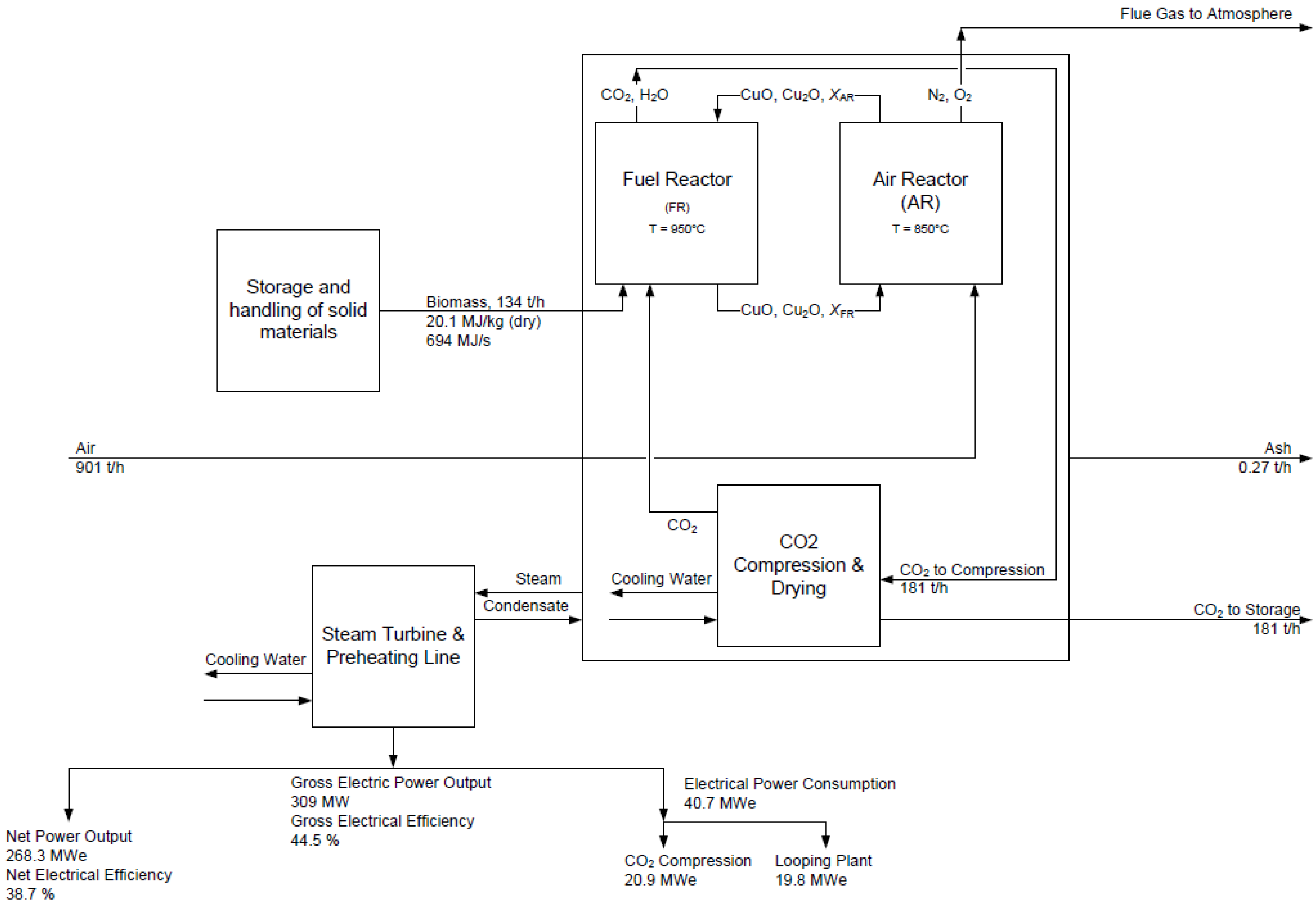
- Net reaction in the fuel reactor is exothermic, and so heat is extracted from the reactor to raise steam for power generation.



- Very high CO_2 capture rates possible, and minimal plant efficiency penalty

- Pilot and lab-scale testing at TU Darmstadt, Vienna, Chalmers, Imperial and Cambridge. Increasing industrial interest from Alstom, Air Liquide and Vattenfall

Dedicated biomass chemical looping combustion



Plant performance, CAPEX and OPEX estimates

300 MWe, net efficiency ~ 41%

Item	£M, 2011
Storage and handling of solid materials	41.1
Boiler island	220.5
CO_2 compression and drying plant	31.4
Power island	76.5
Air reactor (458 m^3)	64.8
Fuel reactor (581 m^3)	74.9
Total installed CAPEX	**509.2**
Operation and utilities (% of TIC)	25.5
Civils and land costs (% of TIC)	50.9
Project Development Costs (% of TIC)	25.5
Contingency (% of TIC)	50.9
Total investment cost	**661.9**
Specific investment cost (£M/MW_e)	**2.21**

Variable Costs	Usage	£M/yr
1. Wood fuel	8.29×10^8 kg/yr	116.0
2. Oxygen carrier (new)	1.19×10^6 kg/yr	4.74
3. Spent carrier (credit)		-4.22
4. Fly ash disposal	1.78×10^6 kg/yr	0.00356
5. Cooling water make-up	9588 kg/s	51.4
Variable costs		167.9
Maintenance and Labour		20.37
Insurance		5.09
Fixed costs		25.46
Total O&M costs		**193.36**

Capacities investigated: 40 to 300 MW_e → CLC more suitable for small scales ~40MW_e

CLC: Identification of existing gaps and development req.

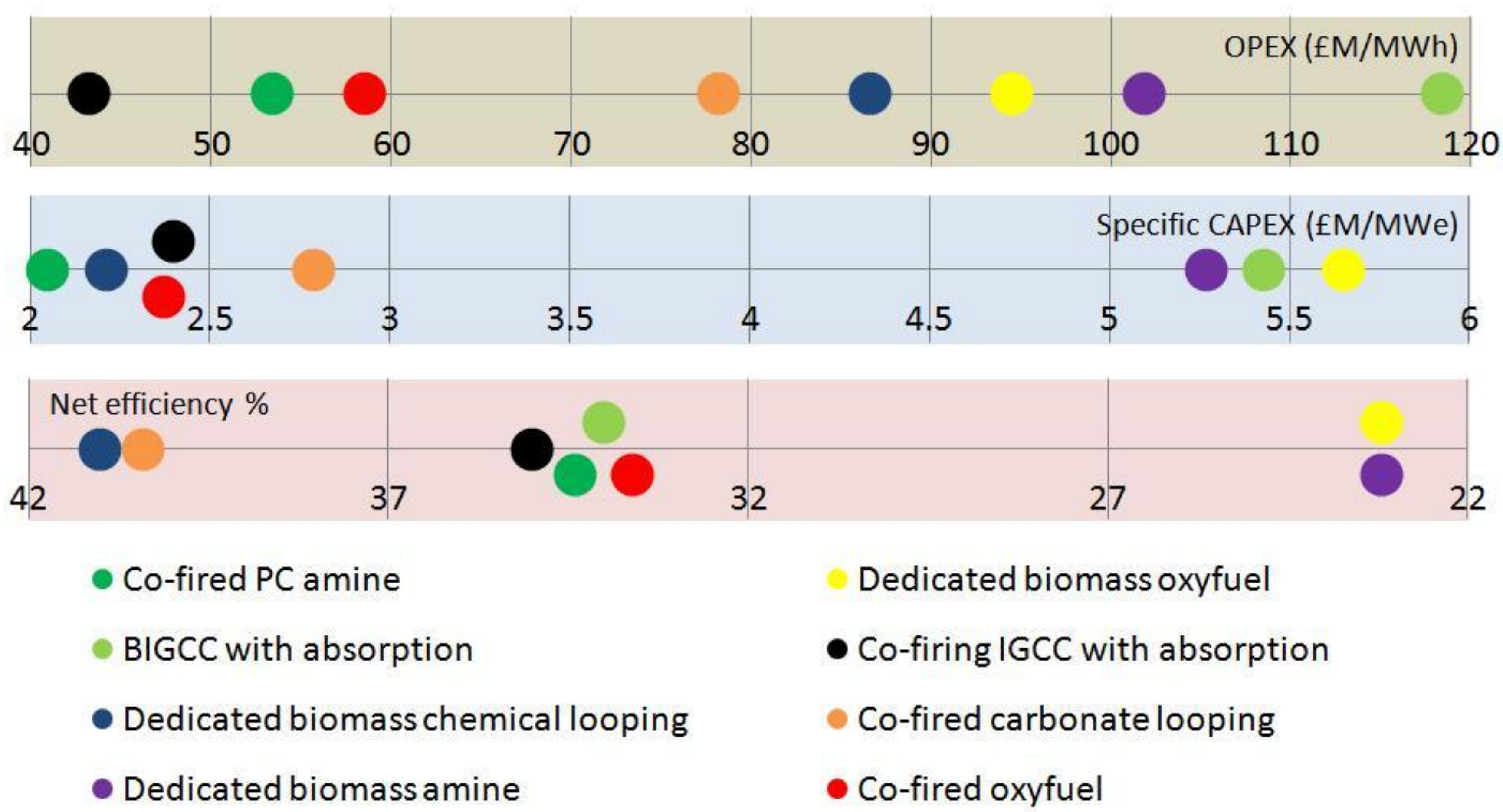
- Chemical looping combustion system is suitable for baseload operation, with relatively few shutdowns and start-up cycles. Time requirement to bring the fluidised bed reactors and the looping cycle to temperature and to steady state operation

- The large inert inventory in the form of the CuO support material (e.g. alumina) and the enhanced mixing in the fluidized bed are the two main control parameters that can be used to avoid the hotspots.

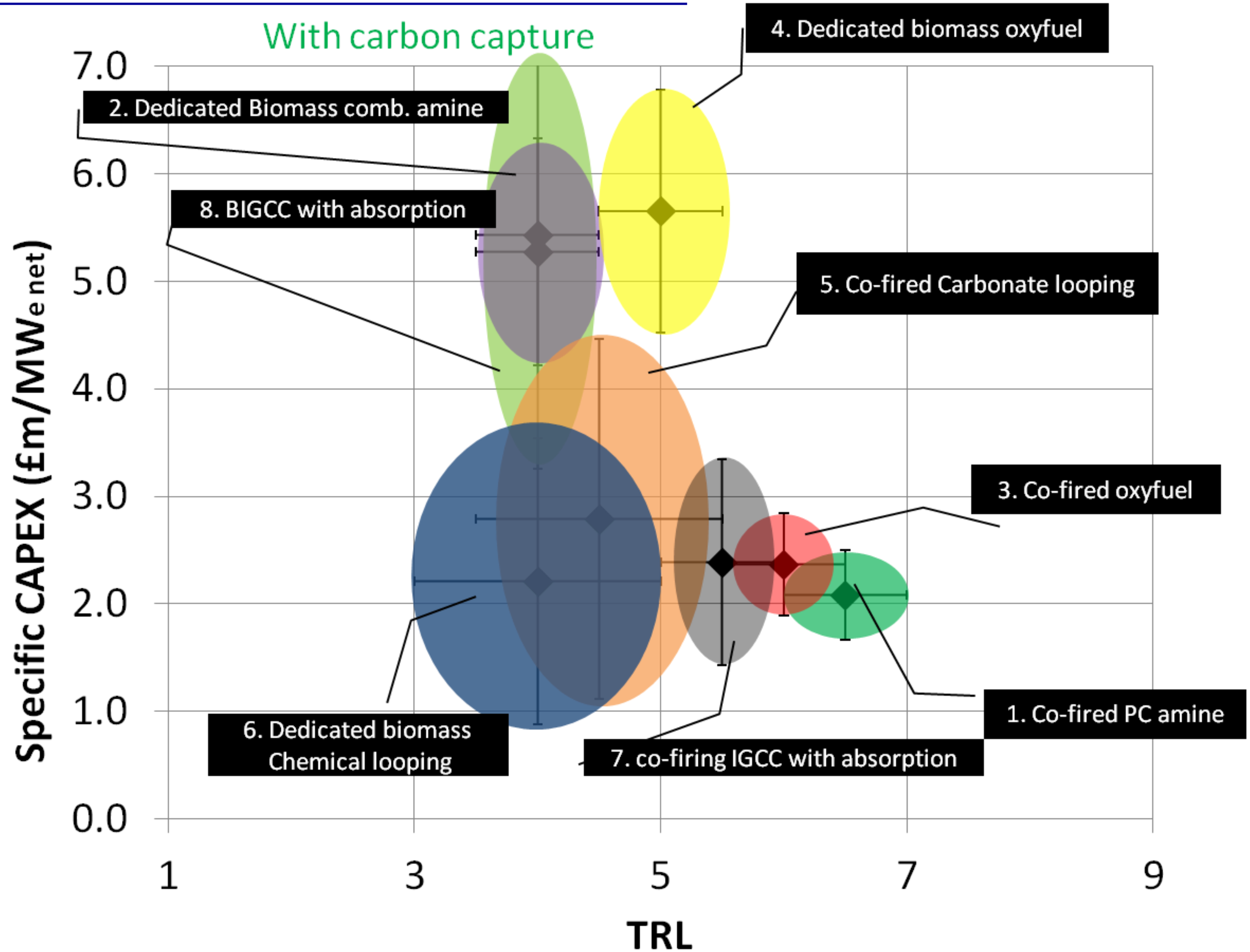
- In the event of a thermal runaway, reducing the fuel feed and increasing the flow rate of the CO_2 stream (fluidization gas) → temperature control strategy.

- NO_x emissions are a key unknown. They are expected to be lower than for the conventional biomass fired power plant boiler, and less thermal NO_x, but fuel-NO_x chemistry (the interaction with CH type radicals from the fuel) is completely unknown.

Performance and economic parameters



Capital costs and TRLs



Summary I: Techno-economic parameters

- The TESBiC consortium exploited its unique composition [industry-SMEs-academia] to rigorously debate the techno-economic parameters

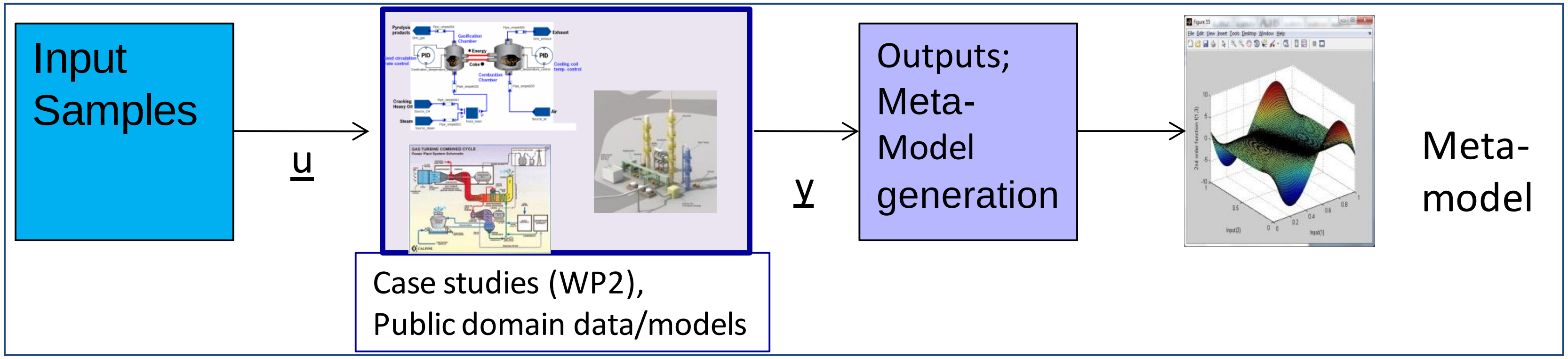
- The TRLs for the eight technology combinations and associated components assessed, varied over a wide range from **TRL 3 to TRL 8**

- Range of **techno-economic parameters** over the 8 biomass-based power generation combined with carbon capture technologies
  - ~ 5% to 15% : Range of the efficiency drop
  - ~ 45% to 130%: Range of the increase in specific CAPEX (£/MW_e) with carbon capture
  - ~ 4% to 36%: Range of increase in OPEX (£/yr) with carbon capture

WP3: sub-model development and parameterisation

- Data standardisation and model template released
- Parameter estimation based on the model template and the standardised data
- Associated documentation for user models
- Two examples:
  - Co-fired carbonate looping combustion
  - Dedicated biomass IGCC with physical absorption

Model formulation



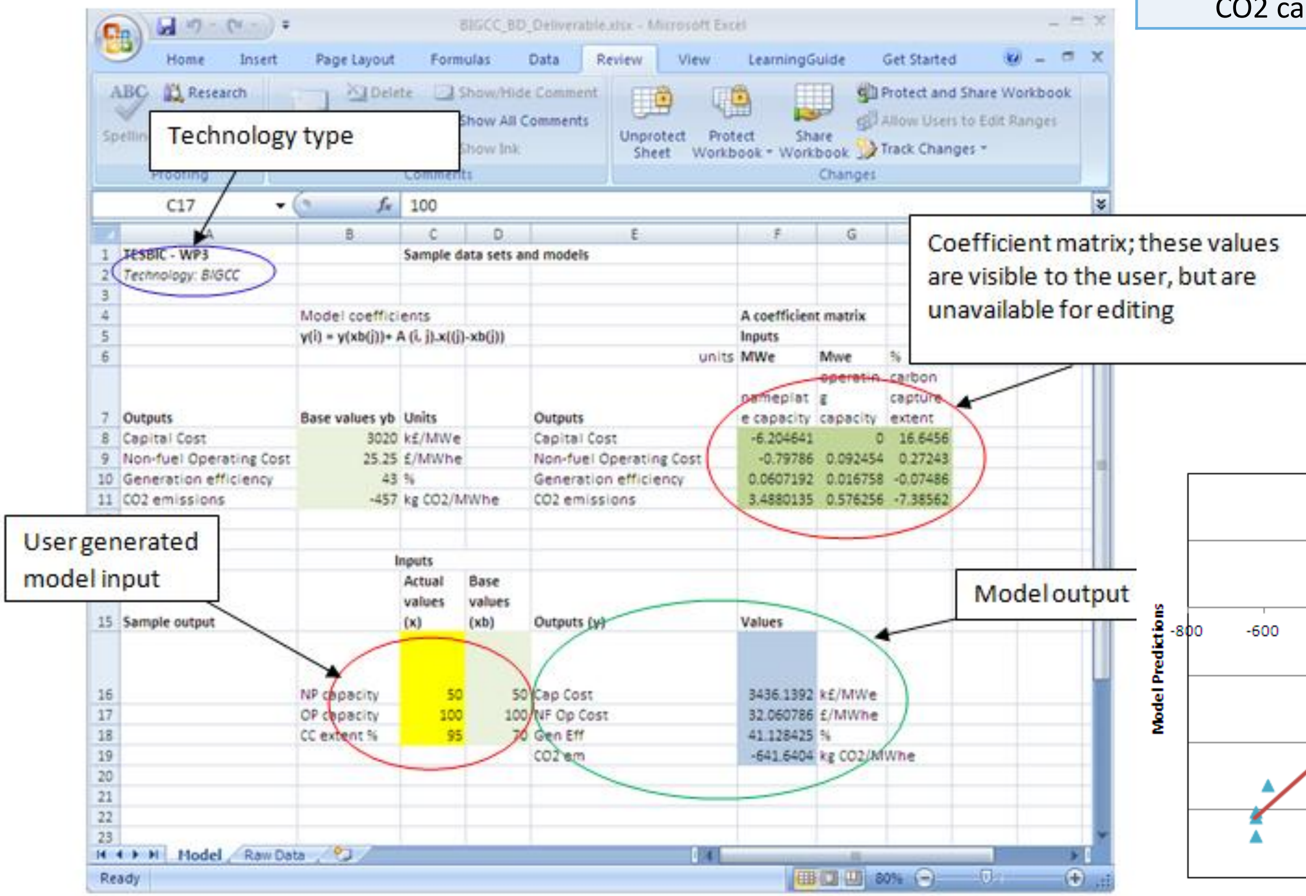
Model inputs:
- Extent of Co-firing
- Carbon capture extent
- Nameplate capacity
- Operating capacity

Model outputs:
- CAPEX
- OPEX
- Generation efficiency
- CO_2, SO_x, NO_x, PM emissions
- Solvent loss

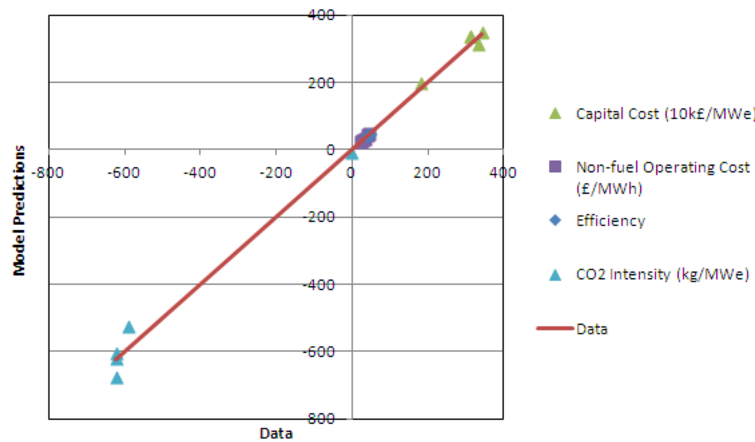
Dedicated biomass/BIGCC with physical absorption

	Lower bound	Upper bound
Nameplate capacity (MWe)	20	80
Capacity Factor (%)	60	100
CO2 capture extent (%)	50	95

Model template



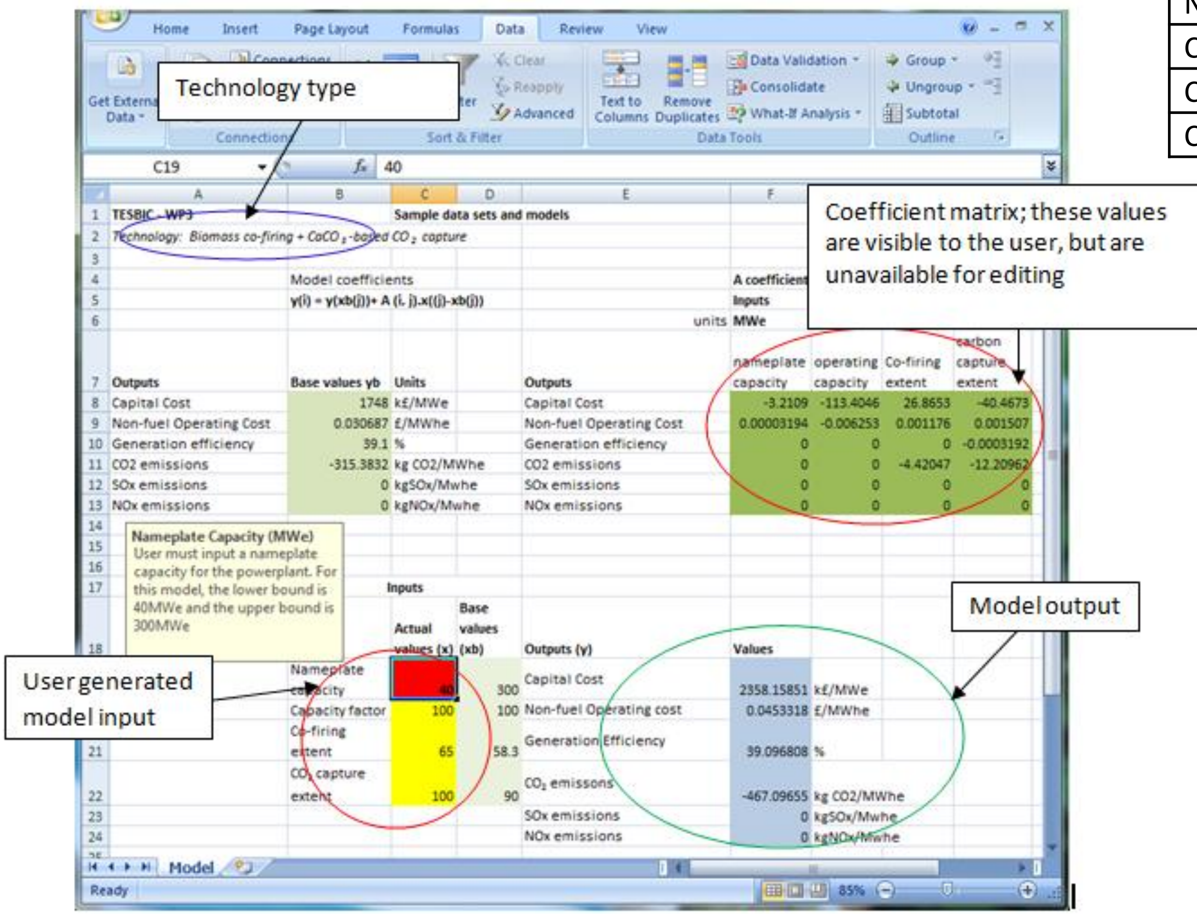
Model fidelity



Co-fired carbonate looping combustion

	Lower bound	Upper bound
Nameplate capacity (MWe)	40	300
Capacity Factor (%)	20	100
Co-firing extent	55	75
CO_2 capture extent (%)	80	100

Model template



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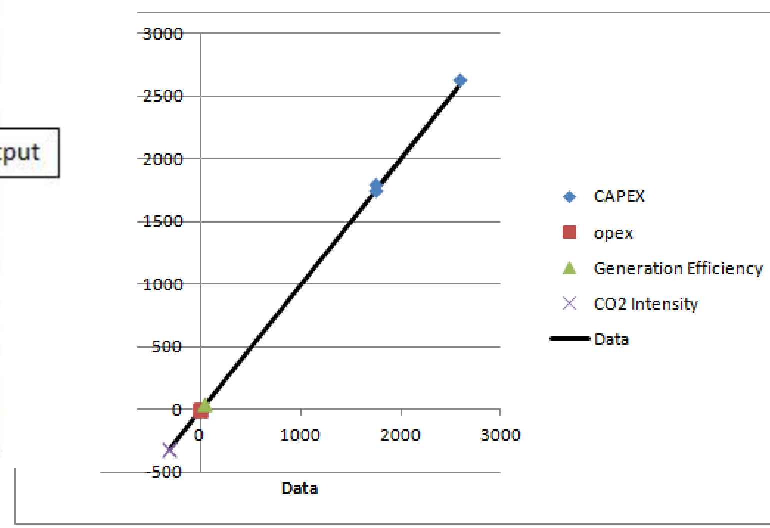
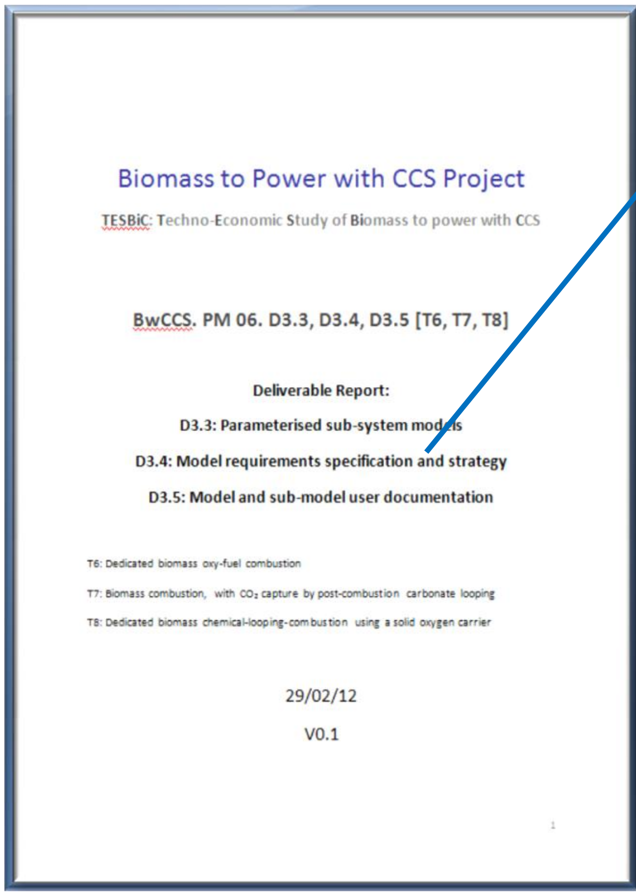


Model development – associated documentation


Biomass to Power with CCS Project

TESBiC: Techno-Economic Study of Biomass to power with CCS

BwCCS. PM 06. D3.3, D3.4, D3.5 [T6, T7, T8]

Deliverable Report:

D3.3: Parameterised sub-system models

D3.4: Model requirements specification and strategy

D3.5: Model and sub-model user documentation

T6: Dedicated biomass oxy-fuel combustion

T7: Biomass combustion, with CO_2 capture by post-combustion carbonate looping

T8: Dedicated biomass chemical-looping-combustion using a solid oxygen carrier

29/02/12

V0.1

1

Model implementation: base + delta

$$y = y_b + A(x - x_b)$$

Model results:

responses, fidelity, bounds

Data references:

These data were generated by a detailed model based on the following sources:

- Reactor design and kinetics: fuel and air reactors based on data from:
  - Eyring, E. M. Konya, G. Lighty, J. S. Sahir, A. H. Sarofim, A. F.; Whitty, K. *Oil & Gas Science and Technology – Revue d'IFP Energies nouvelles* **2011**, *66*, 13.
- Heat integration, energy balances and pinch analysis based on data from:
  - Cleeton, J. P. E. "Chemical Looping Combustion with Simultaneous Power Generation and Hydrogen Production using Iron Oxides." PhD Thesis, University of Cambridge, 2011.
- Reactor sizing, parametric sensitivity calculations based on costing data from:
  - Klara, J. "*Chemical-Looping Process in a Coal-to-Liquids Configuration: Independent Assessment of the Potential of Chemical-Looping in the Context of a Fischer-Tropsch Plant*", NETL, 2007.
- Model developed in WP2 was used to generate data as a function of the four input variables.

Summary II: Biomass-CCS Modelling

- Model response: Techno-economic (costs, efficiencies and emissions) parameters as a function of four inputs (co-firing and capture extent, operating and nameplate capacities)

- Models for all eight technology combinations were formulated predominantly using the WP2 sensitivity data

- Associated documentation and reports for the individual models

- Models developed such that they are compatible with BioVCN and ESME

WP4: Work-plan

- Benefits assessment of specific development and demonstration activities
    - Additionality of the activity
    - Commercialisation progress
    - Value to the UK

- Benefits assessment of specific deployment activities
    - Contribution to satisfying UK energy demand
    - Contribution to emissions reduction
    - Contribution to UK economic activity
    - Comparison with fossil CCS

Summary III – TESBiC progress

- To date**, little activity at industrial scale** on the application of CO_2 capture technologies to co-fired or dedicated biomass power plants
- **Dependency on fossil based CCS:** The industry's progression to the large fossil-based CCS demonstration projects is slow due to **high costs** and **requirement of significant government subsidies.** Recent setbacks and cancellations of these projects will further delay the development of biomass CCS
- **TESBiC** project focuses on addressing the **existing gaps** in understanding **biomass CCS** through a detailed landscape review, high level engineering study and robust model development and validation
- The tools developed in TESBiC are seamlessly compatible with the ETI's simulators thereby enabling **comprehensive virtual engineering and optimisation** applied to the whole biomass CCS system
- Two **dissemination activities**: Biomass CCS (Cardiff, 2011) and APGTF (London, 2012)
- **Next step**: benefits assessment, development and deployment

Q&A

Thank you for your attention!

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