Programme Area: Bioenergy

Project: Biomass to Power with CCS

Title: Biomass to Power with CCS model requirements, specification, strategy and user documentation

Abstract:

This document (from Work Package 3) provides the specification and user guidance for three, of eight, parameterised technology models that will be used by the Bioenergy Value Chain Modelling (BVCM) project. The three technologies covered in this report are biomass co-firing in a pulverised coal-fired power plant with post combustion amine scrubbing-based carbon capture, biomass combustion in a dedicated power plant with carbon capture by solvent scrubbing, and biomass co-firing in a large pulverised coal power plant with carbon capture by oxyfuel firing.

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).

Biomass to Power with CCS Project

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

BwCCS. PM 05. D3.3, D3.4, D3.5 [T3,T4,T5]

Deliverable Report:

D3.3: Parameterised sub-system models

D3.4: Model requirements specification and strategy

D3.5: Model and sub-model user documentation

T3: Biomass co-firing in a pulverised coal-fired power plant with post combustion amine scrubbing-based carbon capture

T4: Biomass combustion in a dedicated power plant with carbon capture by solvent scrubbing

T5: Biomass co-firing in a large pulverised coal power plant with carbon capture by oxyfuel firing

29/02/12

V0.2

Title	Deliverable on parameterised sub-system models, model requirements specification, modelling strategy and model user documentation
Client	Energy Technologies Institute LLP (ETI)
Reference	BwCCS PM04 D3.3, D3.4, D3.5 (T3,T4,T5)
Date	29 February 2012
Version	0.2
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Distribution

CONTENTS

EXECUTIVE SUMMARY

The Techno-economic Study of Biomass to Power with CCS (TESBIC) project, which has been commissioned by ETI, is concerned with the performance of an overview techno-economic assessment of the current and potential future approaches to the combination of technologies which involve the generation of electricity from biomass materials, and those which involve carbon dioxide capture. The present document forms the deliverable within work package, WP3; and it covers the work on:

D3.3: Parameterised sub-system models

D3.4: Model requirements and specifications and modelling strategy

D3.5: Model and sub-model user documentation

Following the first variation of Contract/Agreement with ETI, the aforementioned deliverables have been applied to next three (T3,T4,T5) out of eight technology combinations.

T3 denotes biomass co-firing in a pulverised coal-fired power plant with post combustion amine scrubbing-based carbon capture

T4 represents biomass combustion in a dedicated power plant with carbon capture by solvent scrubbing

T5 represents biomass co-firing in a large pulverised coal power plant with carbon capture by oxyfuel firing

The overall model structure finalised for WP3 employs the “base+delta” modelling framework (see D3.1 and D3.2). This fits the requirements for the capture of information and transfer to ETI and compatibility with the Biomass Value Chain Modelling (BVCM) and ETI’s Energy System Modelling (ESME) projects. The models were developed based on the techno-economic sensitivity data obtained from WP2 and additional available data. The “base+delta” model is readily implementable in MS-Excel™.

This document also provides user documentation of the models and its sub-models developed as part of WP3. This document is intended to enable any potential user to use and understand the models and their application. Data standard validation, parameter estimation and improvement of model robustness were carried out using the Model Development Suite (MoDS). Overall, the models offer evaluation of key techno-economic variables such as CAPEX, OPEX, efficiencies, and emissions as a function of inputs such as co-firing, capacity factor, nameplate capacity and extent of carbon capture.

Within WP3, the next deliverable of the project will focus on utilising the methodology and infrastructure developed in the present deliverable along with the techno-economic sensitivity data from WP2 for the last three technology combinations.

1. MODEL REQUIREMENTS OVERVIEW

The models developed within WP3 should be easily translated into the modelling structures of the Biomass Value Chain Modelling (BVCM) and ETI's Energy System Modelling (ESME) projects. As discussed in the project proposal and the acceptance criteria, WP3 will use the detailed models and results of WP2 and other available data (as shown in Figure 1) to generate meta-models (rather than first principles models) for delivery to the ETI.

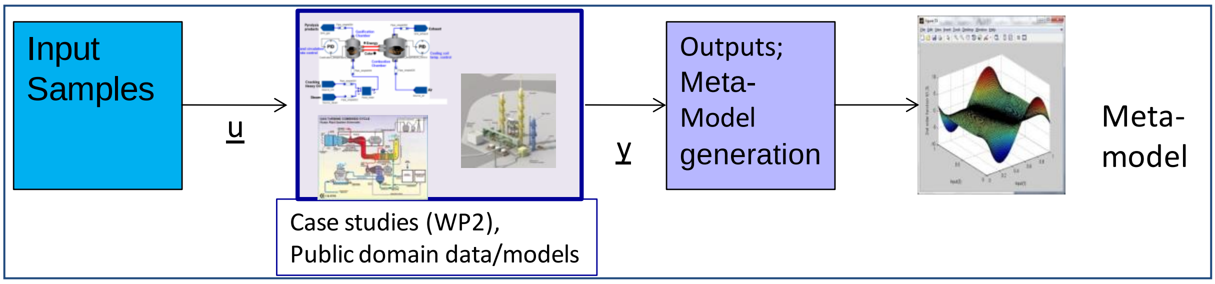

Figure 1: Overview of metamodelling approach.

The detailed "base+delta" model description as well as the implementation of the parameter estimation methodology were explained in the previous Deliverable report that focused on first two technologies (T1,T2), and hence will not be repeated in the present report.

2. MODEL DETAILS: Coal combustion with co-firing and amine scrubbing [T3]

For this technology, the data was of the form:

- Inputs (4-dimensional vector x)
  - Nameplate capacity (MWe)
  - Operating capacity (MWe)
  - Co-firing (%)
  - Carbon capture extent (%)
- Outputs (6-dimensional vector $y = (y_1, y_2, y_3, y_4, y_5, y_6)^T$))
  - Capital cost (k £/MWe)
  - Non-fuel operating cost (k £/MWhe)
  - Generation efficiency (%)
  - CO_2 emissions (kg CO_2/MWhe)
  - SO_2 emissions (kg SO_2/MWhe)
  - NO_x emissions (kg NO_x/MWhe)

The data were obtained from the WP2 report and activities as well as a range of sources as described later. The process flow diagram is illustrated in Figure 2 below.

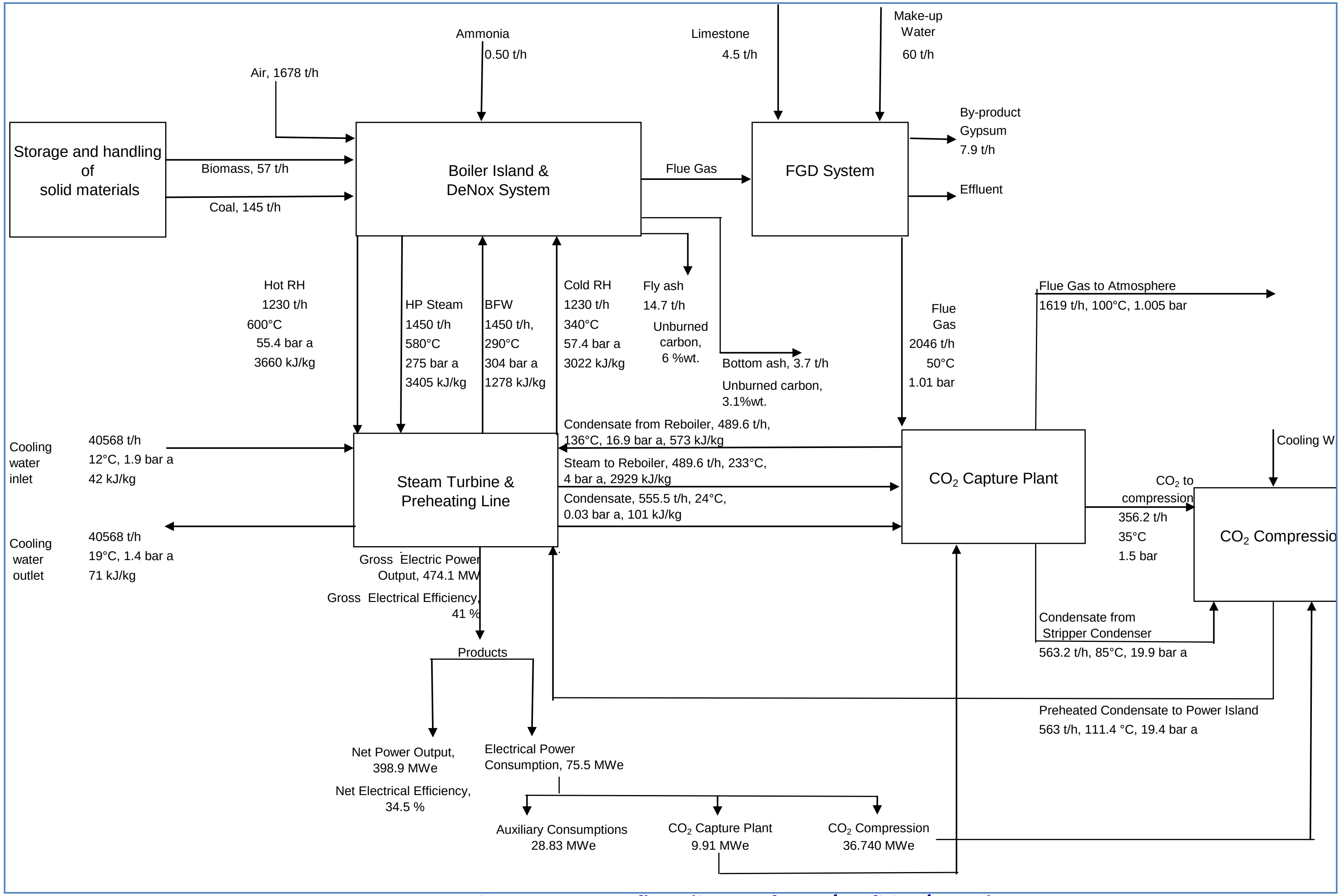

Figure 2. Process flow diagram for PC/Co-firing/PCC plant

A variety of data sets were used to generate the meta-models; these are summarised in Appendix 1.

3. MODEL DETAILS: Dedicated biomass combustion with amine scrubbing [T4]

Input and output data: This technology does not have co-firing, and so the inputs and outputs are:

- Inputs (3-dimensional vector x)
  - Nameplate capacity (MWe)
  - Operating capacity (MWe)
  - Carbon capture extent (%)
- Outputs (6-dimensional vector $y = (y_1, y_2, y_3, y_4, y_5, y_6)^T$))
  - Capital cost (k £/MWe)
  - Non-fuel operating cost (k £/MWhe)
  - Generation efficiency (%)
  - CO_2 emissions (kg CO_2/MWhe)
  - SO_2 emissions (kg SO_2/MWhe)
  - NO_x emissions (kg NO_x/MWhe)

A variety of data sets were used to generate the meta-models; these are summarised in Appendix 2.

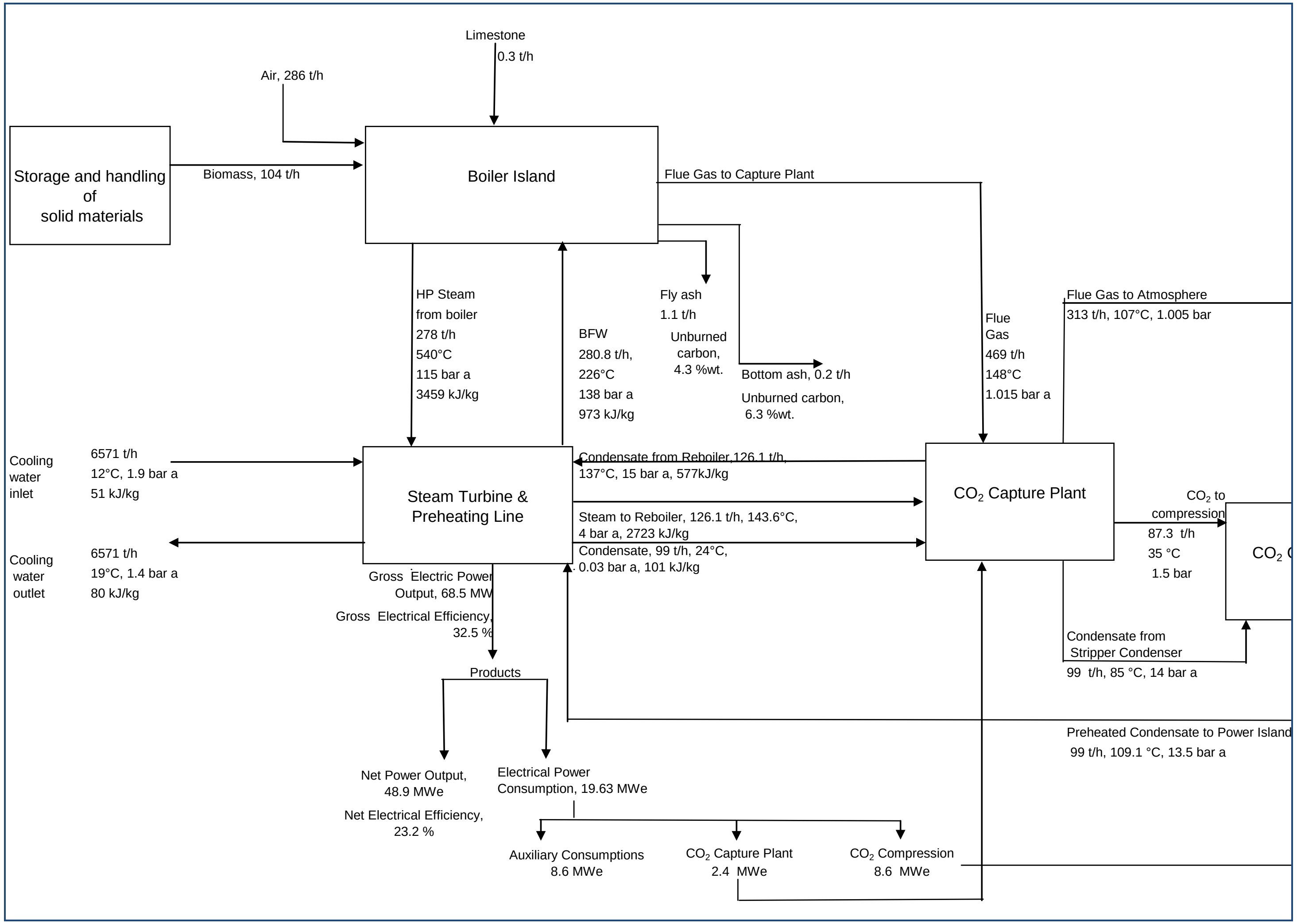

Figure 3. Process flow diagram for biomass combustion with solvent scrubbing

4. MODEL DETAILS: Coal co-firing with oxy-combustion [T5]

Input and output data: This technology has the following inputs and outputs:

- Inputs (4-dimensional vector x)
  - Nameplate capacity (MWe)
  - Operating capacity (MWe)
  - Co-firing extent (%)
  - Carbon capture extent (%)
- Outputs (6-dimensional vector $y = (y_1, y_2, y_3, y_4, y_5, y_6)^T$))
  - Capital cost (k £/MWe)
  - Non-fuel operating cost (k £/MWhe)
  - Generation efficiency (%)
  - CO_2 emissions (kg CO_2/MWhe)
  - SO_2 emissions (kg SO_2/MWhe)
  - NO_x emissions (kg NO_x/MWhe)

A variety of data sets were used to generate the meta-models; these are summarised in Appendix 2.

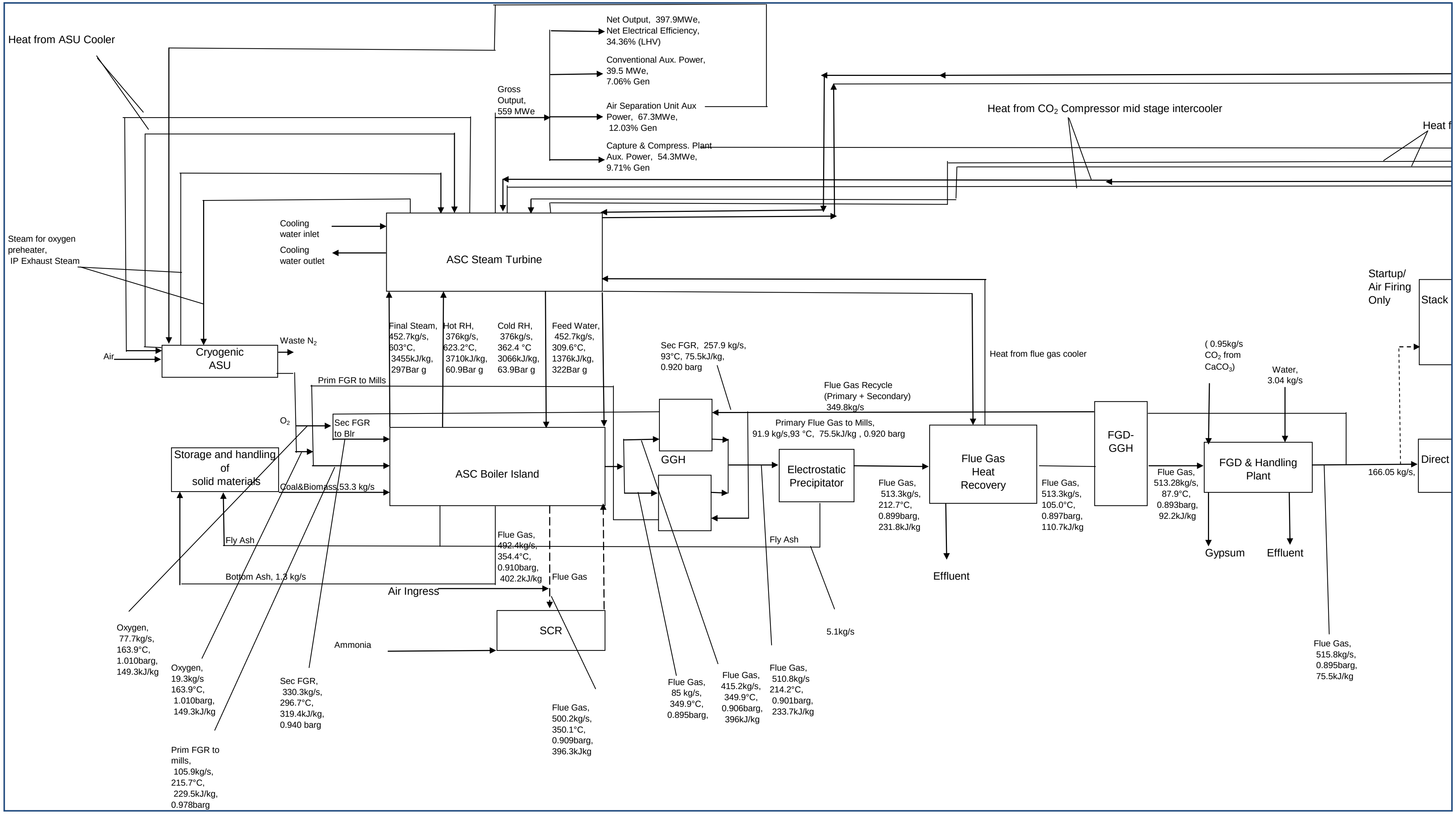

Figure 4. Process flow diagram for coal/biomass oxy-combustion

5. MODEL OVERVIEW, APPLICATION RANGE AND USER-DOCUMENTATION: CO-FIRED COMBUSTION WITH AMINE SCRUBBING

A sample model has been developed in Microsoft Excel™. We note that in the case of the co-fired combustion with amine scrubbing technology [T3], the applicable operation ranges of this model are presented in Table 1.

Table 1: Operating range of Co-fired combustion with amine scrubbing (*: of actual capacity)

	Lower bound	Upper bound
Nameplate capacity (MWe)	300	1000
Capacity Factor* (%)	60	100
Co-firing extent	0	50
CO_2 capture extent (%)	50	98

A screenshot of a sample model for a PC power plant with co-firing and amine-based CO_2 capture is shown in Figure 5 with some explanations provided below.

The required user inputs are highlighted in yellow. These are the plant nameplate capacity, its operating capacity and the extent of CO_2 capture. In order to use this model, the user must provide these inputs within the operating ranges specified in Table 1.

The model outputs are highlighted in blue. These are the plant capital cost, the non-fuel operating cost, the plant efficiency and the CO_2 emissions. These inputs and outputs can then be entered into the BVCM technology database and the ESME data sheets.

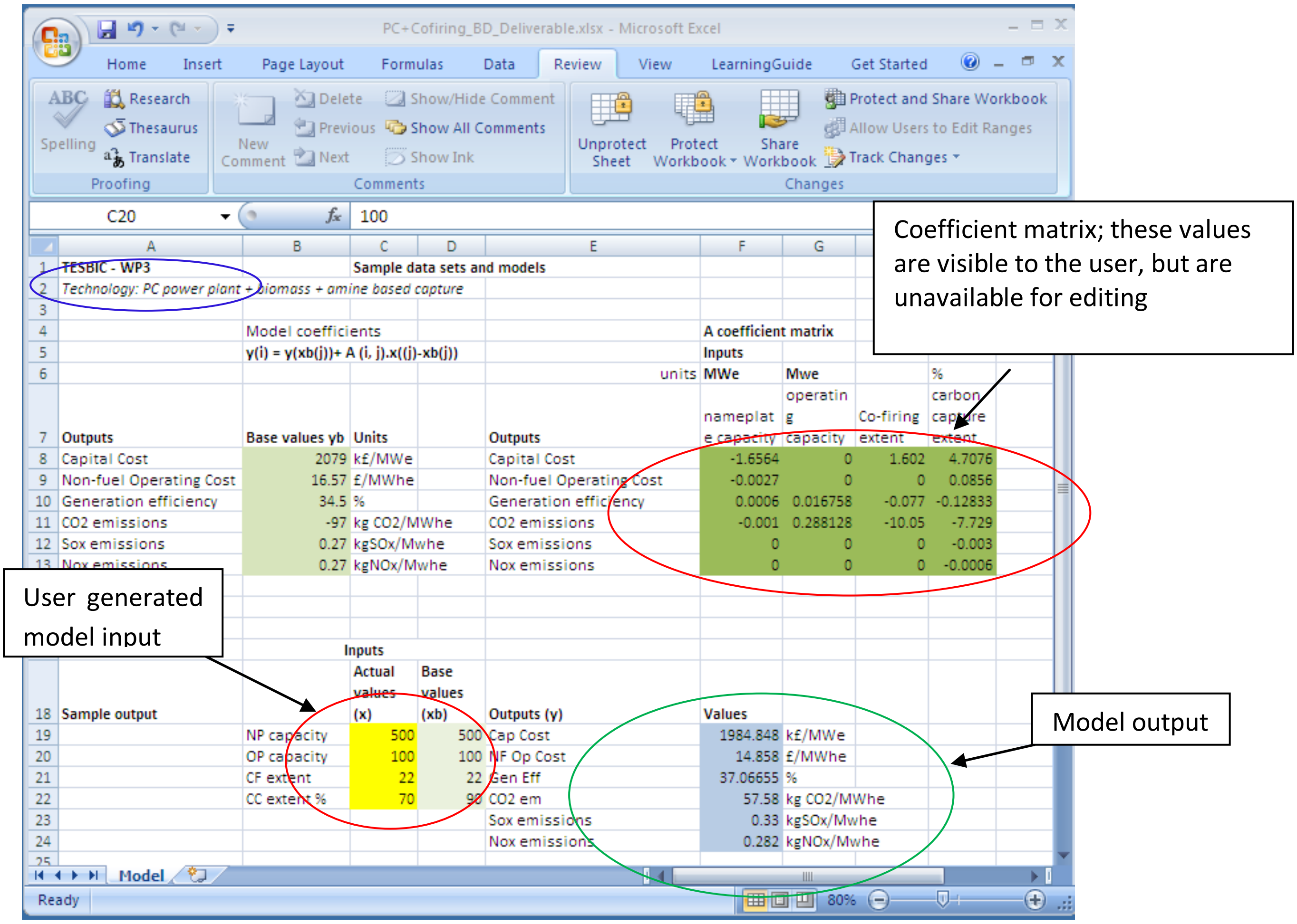

Figure 5: Screenshot of PC power plant with co-firing and amine-based CO_2 capture model. Required user inputs are highlighted in yellow, model parameters are highlighted in green and model outputs are highlighted in blue. Only the cells corresponding to user inputs are editable, all other cells are protected

Model Fidelity

In this section, we present an analysis of the fidelity of the proposed model.

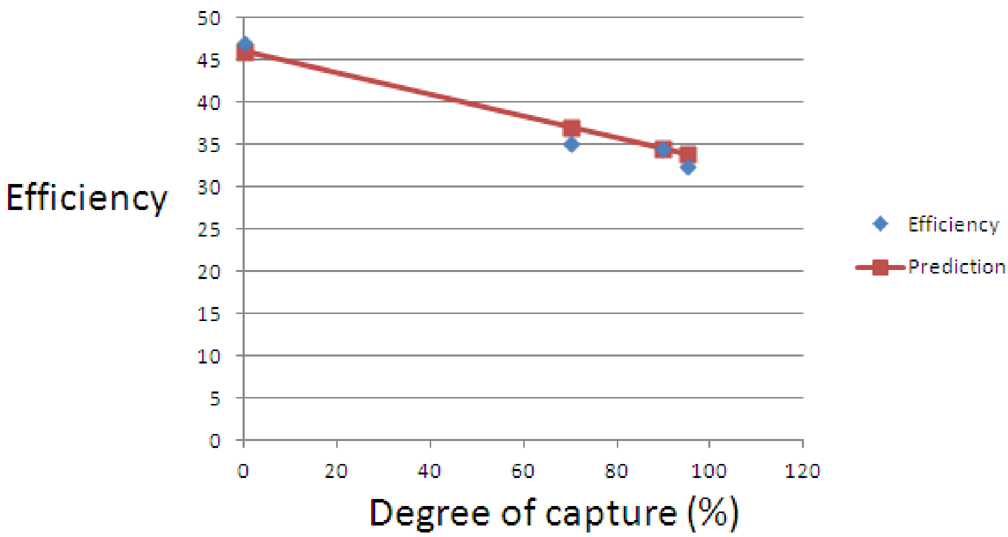

Figure Figure 6: Efficiency data fit as a function of degree of capture

As can be observed from Figures 6-10, the proposed model gives a quantitatively reliable description of the data available from WP2. Thus, this model is considered suitable for data generation for the BVCM and ESME teams.

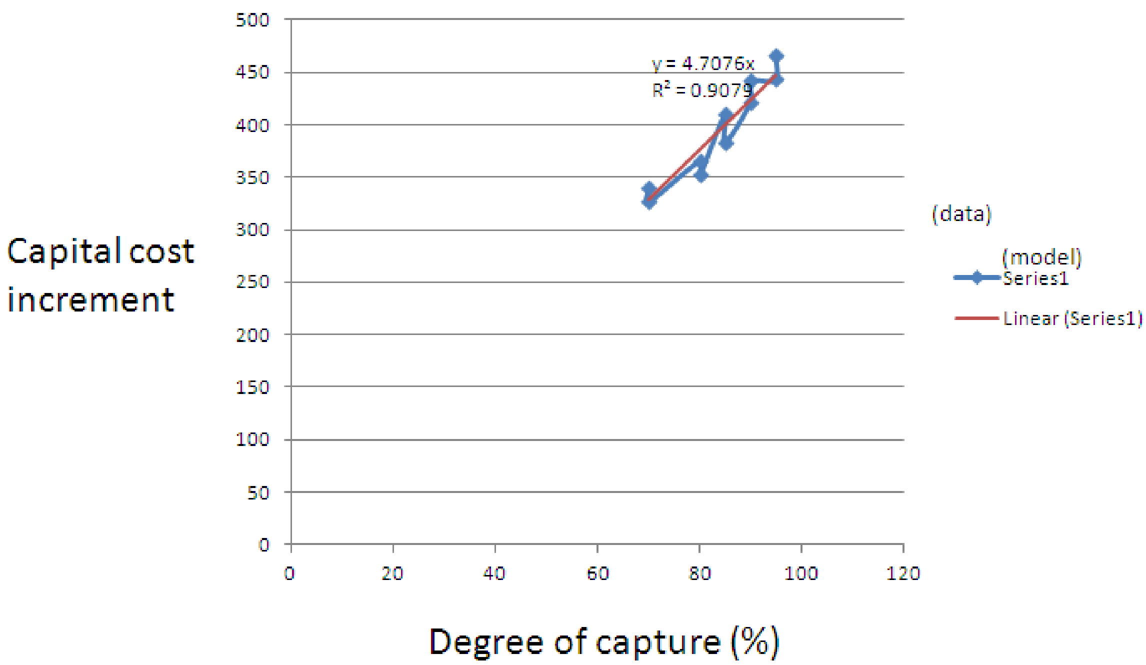

Figure 7: Capital cost data fit as a function of degree of capture.

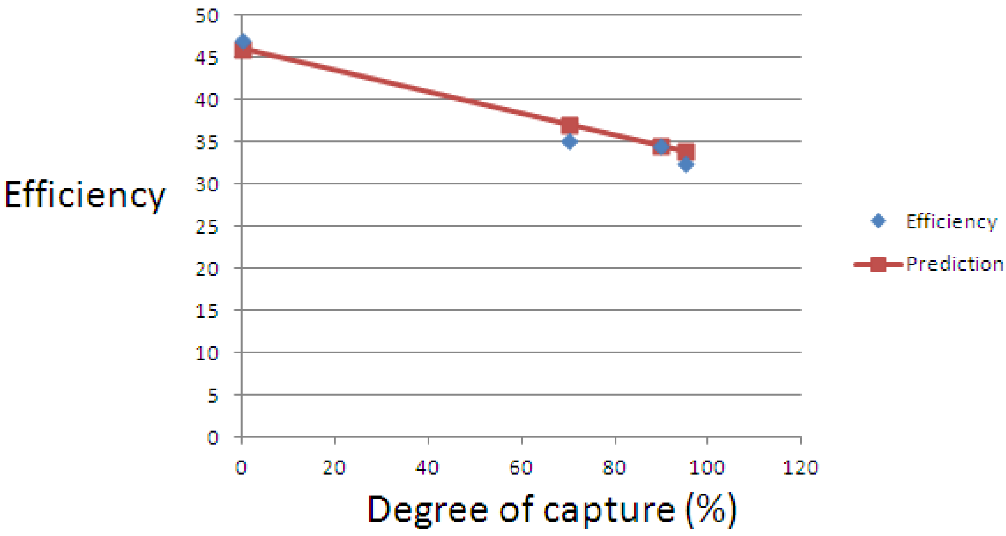

Figure 8: Efficiency data fit as a function of degree of capture

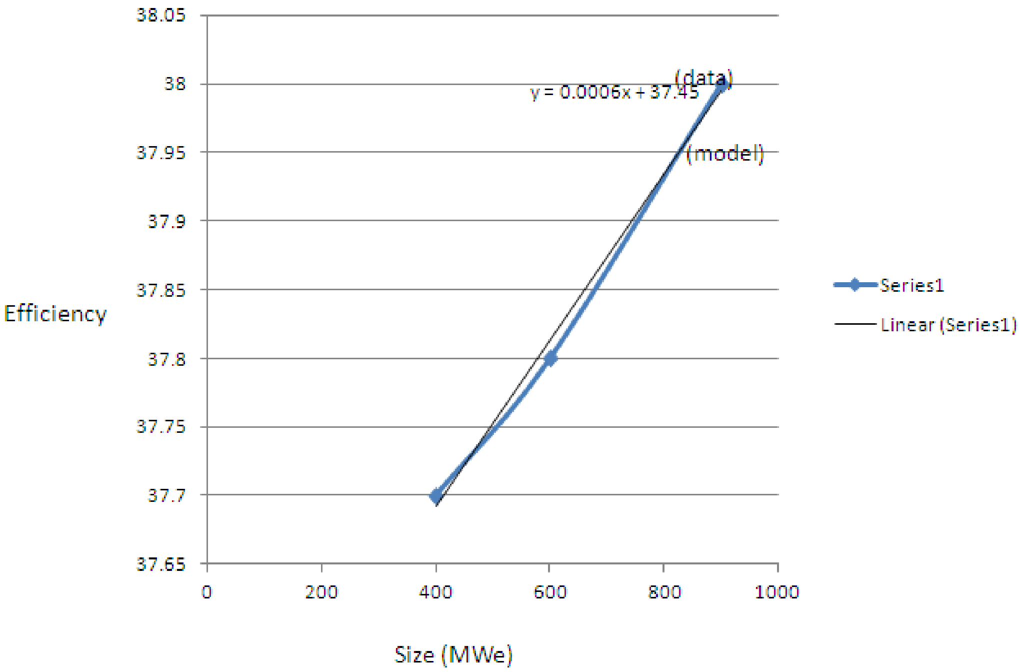

Figure 9: Efficiency data fits as a function of plant scale

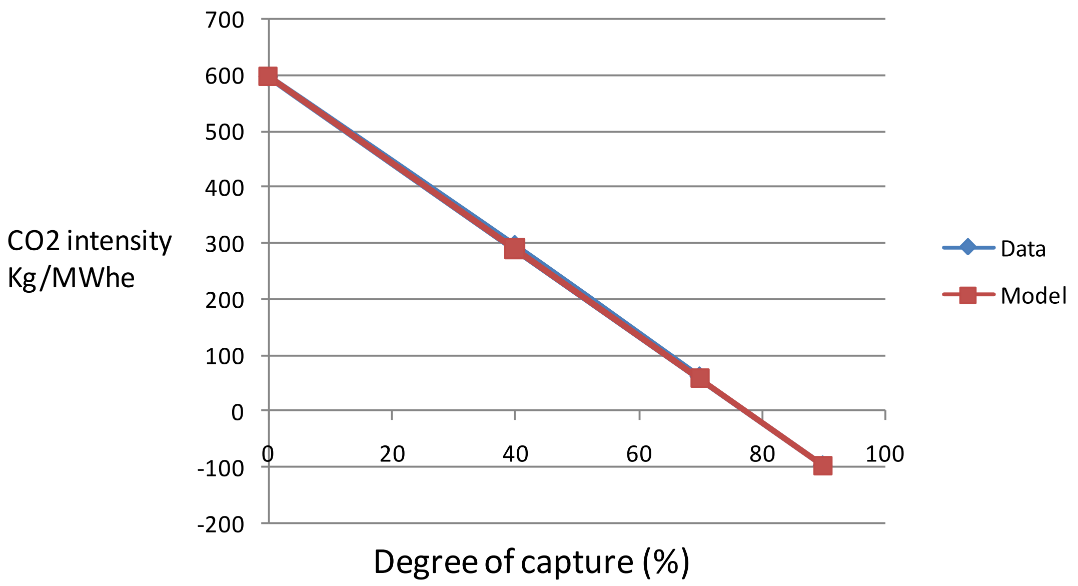

Figure 10: CO_2 intensity data fit

6. MODEL OVERVIEW, APPLICATION RANGE AND USER-DOCUMENTATION: DEDICATED BIOMASS WITH AMINE SCRUBBING

A sample model has been developed in Microsoft Excel™.

We note that in the case of the dedicated biomass with post combustion amine scrubbing based carbon capture technology [T4], the applicable operation ranges of this model are presented in Table 2.

Table 2: Operating range of dedicated biomass with amine scrubbing model

	Lower bound	Upper bound
Nameplate capacity (MWe)	20	100
Capacity Factor (%)	60	100
CO2 capture extent (%)	30	95

The models will be delivered to the ETI in this format. A screenshot of a sample model for dedicated biomass combustion with amine scrubbing based carbon capture is shown in Figure 11 with some explanations. The model has been implemented in MS Excel ™ and the worksheet has been password protected.

The required user inputs are highlighted in yellow. These are the plant nameplate capacity, its operating capacity and the extent of CO_2 capture. In the case of Biomass combustion with post-combustion capture, there is no “co-firing” variable. In order to use this model, the user must provide these inputs within the operating ranges specified in Table 2.

The model outputs are highlighted in blue. These are the plant capital cost, the non-fuel operating cost, the plant efficiency and the CO_2 emissions. These inputs and outputs can then be entered into the BVCM technology database and the ESME data sheets.

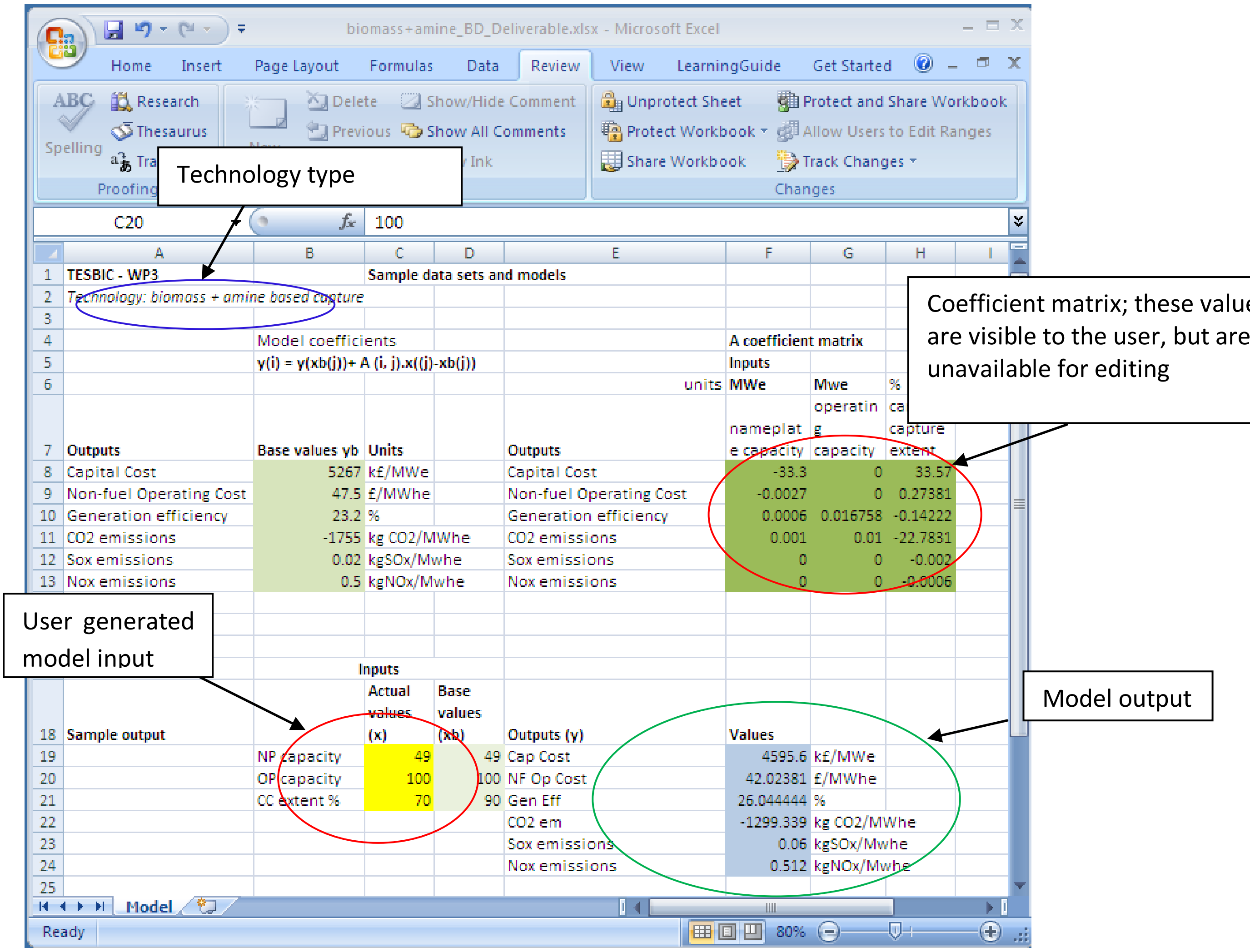

Figure 11: Screenshot of Biomass combustion with post-combustion capture model. Required user inputs are highlighted in yellow, model parameters are highlighted in green and model outputs are highlighted in blue. Only the cells corresponding to user inputs are editable, all other cells are protected.

Model Fidelity

In this section, we present an analysis of the fidelity of the proposed Biomass combustion with post-combustion capture model. As can be observed from Figure 12, the proposed model gives a quantitatively reliable description of the data available from WP2. Thus, this model is considered suitable for data generation for the BVCM and ESME teams.

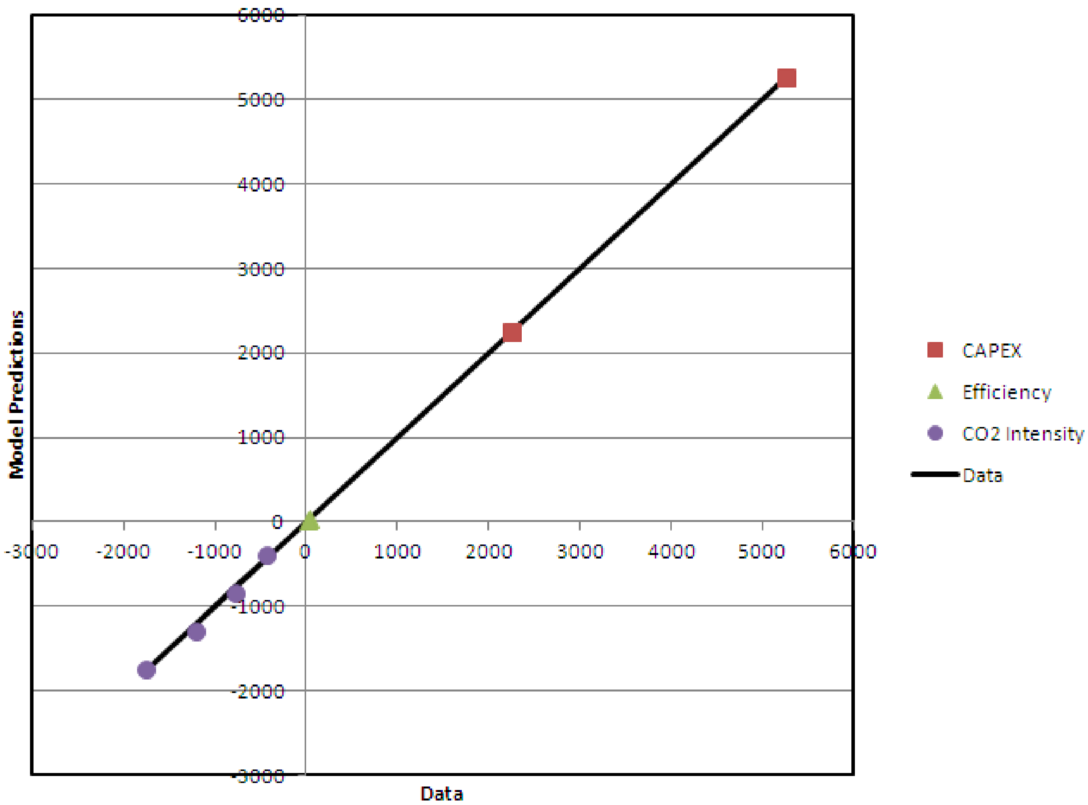

Figure 12. Deviation of dedicated biomass combustion with amine scrubbing model outputs from "experimental data"

7. MODEL OVERVIEW, APPLICATION RANGE AND USER-DOCUMENTATION: BIOMASS CO-FIRING WITH OXY-COMBUSTION

Further, we note that in the case of the Biomass oxy-combustion technology, the applicable operation ranges of this model are presented in **Table 3**.

Table 3: Operating range of co-firing biomass with oxy-combustion model

	Lower bound	Upper bound
Nameplate capacity (MWe)	300	1000
Capacity Factor (%)	60	100

Co-firing extent (%)	0	50
CO2 capture extent (%)	0	95

A sample model has been developed in Microsoft Excel™. The models will be delivered to the ETI in this format. A screenshot of a sample model for Biomass oxy-combustion is shown in Figure 13 with some explanations.

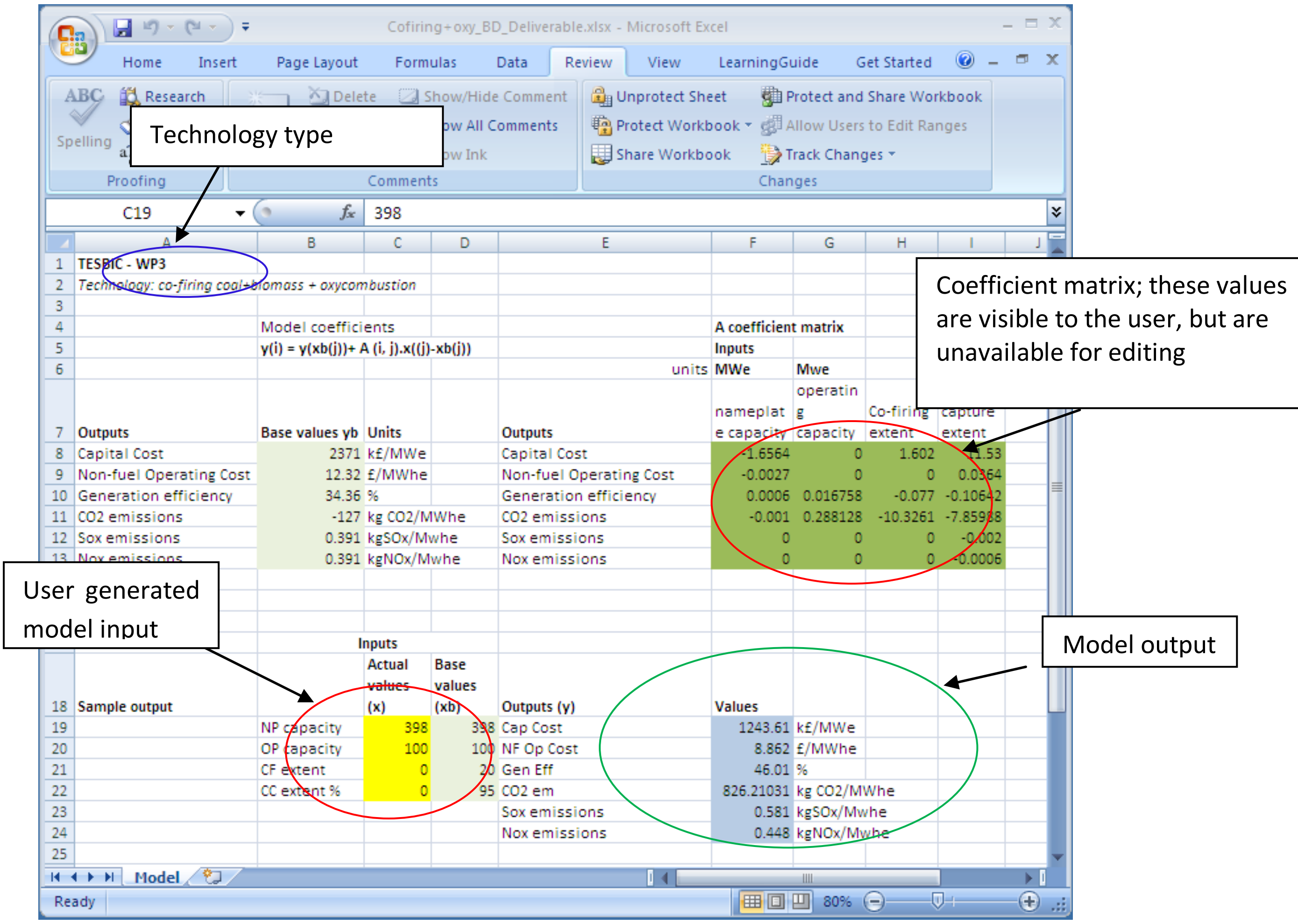

Figure 13: Screenshot of Biomass oxy-combustion model. Required user inputs are highlighted in yellow, model parameters are highlighted in green and model outputs are highlighted in blue. Only the cells corresponding to user inputs are editable, all other cells are protected.

A screen shot of the Biomass oxy-combustion model is presented in Figure 13. The model has been implemented in MS Excel ™ and the worksheet has been password protected.

The required user inputs are highlighted in yellow. These are the plant nameplate capacity, its operating capacity and the extent of CO_2 capture. In order to use this model, the user must provide these inputs within the operating ranges specified in Table 3.

The model outputs are highlighted in blue. These are the plant capital cost, the non-fuel operating cost, the plant efficiency and the CO_2 emissions. These inputs and outputs can then be entered into the BVCM technology database and the ESME data sheets

Model Fidelity

In this section, we present an analysis of the fidelity of the proposed Biomass oxy-combustion model. As can be observed from Figure 14, the proposed model gives a quantitatively reliable description of the data available from WP2. Thus, this model is considered suitable for data generation for the BVCM and ESME teams.

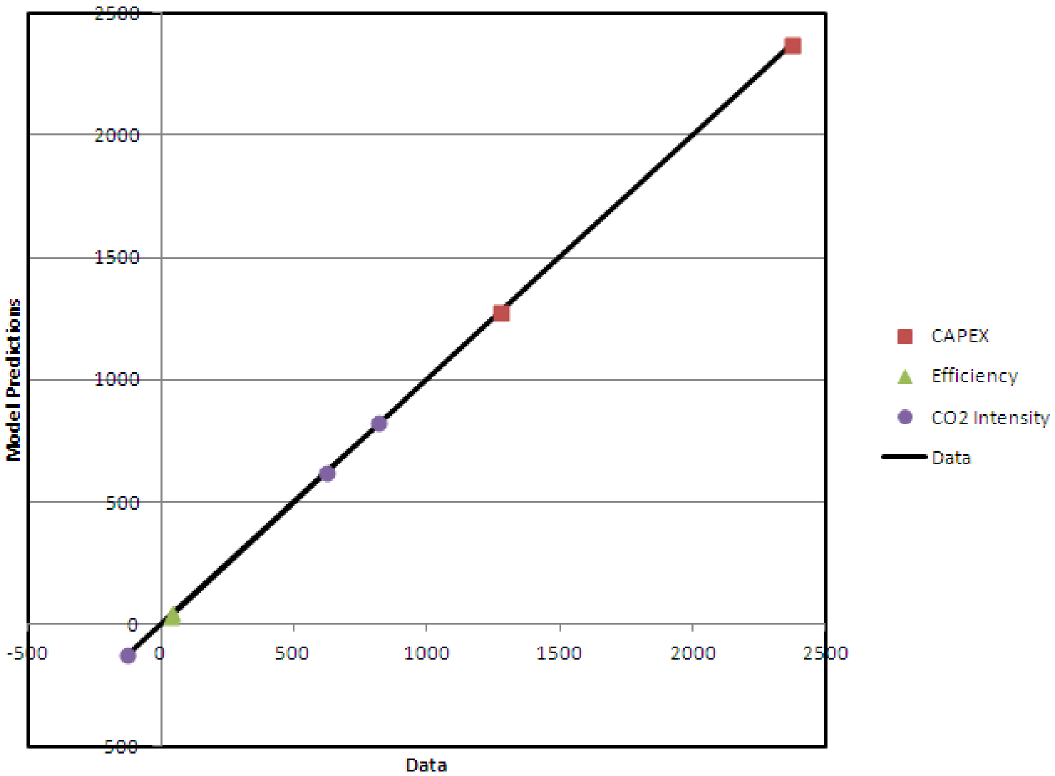

Figure 14: Deviation of Technology 3 model outputs from "experimental data"

8. SUMMARY

This document has presented the modelling requirements specification and modelling strategy, as well as associated model parameterisation and user documentation for three out of eight technology combinations within the TESBiC project. Co-fired biomass combustion with amine scrubbing [T3], dedicated biomass combustion with amine scrubbing [T4] and co-fired biomass with oxy-fuel combustion [T5] were the three technologies presented here.

APPENDIX 1: SUMMARY OF RAW DATA (DETAILED MODEL OUTPUTS) FOR T3

Case	Data name	Value	Units
1- Base	Nameplate capacity	500	MWe
(WP2)	Operating capacity	100	MWe
	co-firing %	22	%
	CO2 Capture extent %	90	%
	Capital Cost	2079	k£/MWe
	Non-fuel Operating Cost	16.57	£/MWhe
	Generation efficiency	34.5	%
	CO2 emissions	-97	kg CO2/MWhe
	SOx emissions	0.27	kg SOx/MWhe
	NOx emissions	0.27	kg NOx/MWhe
2-delta	Nameplate capacity	500	MWe
(WP2)	Operating capacity	100	MWe
	co-firing %	22	%
	CO2 Capture extent %	0	%
	Capital Cost	1280	k£/MWe
	Non-fuel Operating Cost	8.86	£/MWhe
	Generation efficiency	44.8	%
	CO2 emissions	599	kg CO2/MWhe
	SOx emissions	0.54	kg SOx/MWhe
	NOx emissions	0.324	kg NOx/MWhe

3-delta *Explore sensitivity of capital cost of capture plant to degree of capture (Rao & Rubin data)*

DoC (%)	Cap Cost
70	340
70	327
80	366
80	352
85	410
85	383
90	422
90	442
95	443
95	466

4-delta *This case explores sensitivity of system efficiency to degree of capture (Rao & Rubin data)*

	DoC (%)	Efficiency (%)
Base	90	34.5
D1	95	31.725
D2	70	35.25
D3	0	47

5-delta *This case is used to explore sensitivity of plant cost to scale (CoalPerform data)*

Size (MWe)	cost (2006$)	Spec cost 2011 k£/Mwe
400	1624527	3045.988125
600	2071959	2589.94875
900	2642629	2202.190833

5-delta *This case is used to explore sensitivity of plant cost to scale (CoalPerform data)*

Size (MWe)	efficiency (%)
400	37.7
600	37.8
900	38

6-delta *This case is used to explore sensitivity of non-fuel cost to scale (CoalPerform data)*

Size (MWe)	$/MWh	
400	6.4125	
600	5.9625	
900	5.055	k£/MWe

Emissions		
Air	1678	t/hr
assume all N2	59928.57143	kmol/hr
SOX	200	mg/Nm3
	1342400	Nm3/hr
	134.24	kg/hr
	0.26848	kgSOx/Mwe
Cross check		
SOX	0.1	lb/mm BTU (input)
	0.0454	kg/mm BTU (input)
	4.30332E-05	kg/MJ
	0.154919431	kg/MWhth
	0.387298578	kg/Mwhe

APPENDIX 2: SUMMARY OF RAW DATA (DETAILED MODEL OUTPUTS) FOR T4

Case	Data name	Value	Units
1-			
Base	Nameplate capacity	49	MWe
(WP2)	Operating capacity	100	MWe
	CO2 Capture extent %	90	%
	Capital Cost	5267	k£/MWe
	Non-fuel Operating Cost	47.5	£/MWhe
	Generation efficiency	23.2	%
	CO2 emissions	-1755	kg CO2/MWhe
	SOx emissions	0.02	kg SOx/MWhe
	NOx emissions	0.5	kg NOx/MWhe
2-			
delta	Nameplate capacity	49	MWe
(WP2)	Operating capacity	100	MWe
	CO2 Capture extent %	0	%
	Capital Cost	2246	k£/MWe
	Non-fuel Operating Cost	22.9	£/MWhe
	Generation efficiency	36	%
	CO2 emissions	0	kg CO2/MWhe
	SOx emissions	0.2	kg SOx/MWhe
	NOx emissions	0.554	kg NOx/MWhe

3-
delta *This case is used to explore sensitivity of plant cost to scale (CoalPerform data)*

Size (MWe)	Sp cost (k£/MWe)	total cost £
49	5,267	258,083
70	4,567	319,669

4-
delta *This case explores sensitivity of emissions and efficiency to degr. of capture (authors' models)*

CC extent %	efficiency %	total emissions	CO2 intensity
90	23.2	-1932.3108	-1756.646217
70	26.04	-1721.5673	-1205.097082
50	28.89	-1551.7346	-775.8672802
30	31.73	-1412.8462	-423.8538744
0			0

APPENDIX 3: SUMMARY OF RAW DATA (DETAILED MODEL OUTPUTS) FOR T5

Case	Data name	Value	Units	
1-				
Base	Nameplate capacity	398	MWe	
WP2	Operating capacity	100	%	
	co-firing %	20	%	
	CO2 Capture extent %	95	%	
	Capital Cost	2371	k£/MWe	2371
	Non-fuel Operating Cost	12.32	£/MWhe	
	Generation efficiency	34.36	%	34.36
	CO2 emissions	-127	kg CO2/MWhe	
	SOx emissions	0.391	kg SOx/MWhe	
	NOx emissions	0.391	kg NOx/MWhe	
2-delta	Nameplate capacity	518.9	MWe	
WP2	Operating capacity	100	%	
	co-firing %	20	%	
	CO2 Capture extent %	0	%	
	Capital Cost	1276	k£/MWe	
	Non-fuel Operating Cost	8.86	£/MWhe	
	Generation efficiency	44.47	%	
	CO2 emissions	619.6	kg CO2/MWhe	
	SOx emissions	0.391	kg SOx/MWhe	
	NOx emissions	0.391	kg NOx/MWhe	
3-delta	As case 2, but with no co-firing to explore carbon intensity and efficiency with 0% co-firing (authors' calcs)			
	Generation efficiency	44.8	%	
	CO2 emissions	820	kg CO2/MWhe	
4-delta	Other gradients - use sensitivity of efficiency and cost to scale as per coal PC (Chemical Process Equipment - Selection & Design, 2nd Edition, Couper et al.)			