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 the final 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 dedicated biomass oxy-fuel combustion, biomass combustion with CO2 capture by post-combustion carbonate looping, and dedicated biomass chemical-looping-combustion using a solid oxygen carrier.

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 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

Title	Deliverable on parameterised sub-system models, model requirements specification, modelling strategy and model user documentation
Client	Energy Technologies Institute LLP (ETI)
Reference	BwCCS PM06 D3.3, D3.4, D3.5 (T6,T7,T8)
Date	29 February 2012
Version	0.1
Authors	The TESBIC consortium:

cmcl innovations

Doosan Babcock

Drax

EDF

E4tech

Imperial College London

University of Cambridge

University of Leeds

Distribution

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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 the final three (T6, T7, T8) out of eight technology combinations.

T6 denotes dedicated biomass oxy-firing combustion

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

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

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.

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.

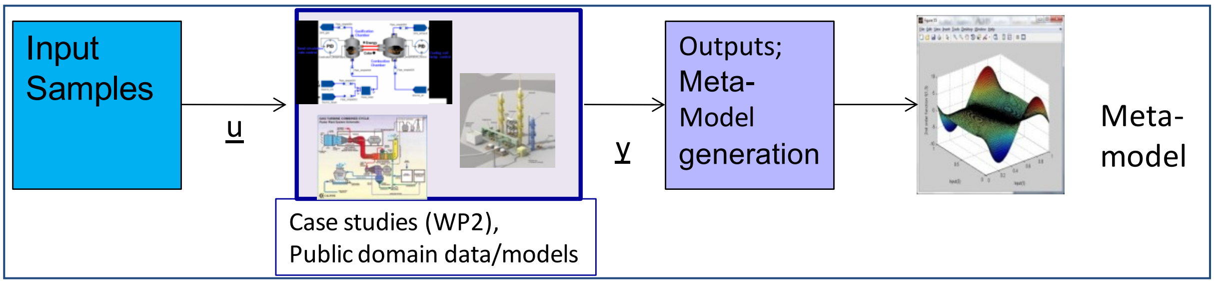

Figure 1: Overview of meta-modelling approach.

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

2. MODEL DETAILS: Dedicated biomass oxy-firing combustion [T6]

For this technology, the data was of the form (note that co-firing is not relevant):

- 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)

The data were obtained from

- The WP2 report and activities
- From internal studies and data at Doosan Power Systems
- NREL Report “A Summary of Life Cycle Assessment Studies Conducted on Biomass, Coal, and Natural Gas Systems”, Jan 2000
- NREL Report NREL/TP-510-32575, “Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics “, 2004, (http://www.nrel.gov/docs/fy04osti/32575.pdf).

The process flow diagram for the dedicated biomass oxy-firing combustion technology is presented in Figure 2.

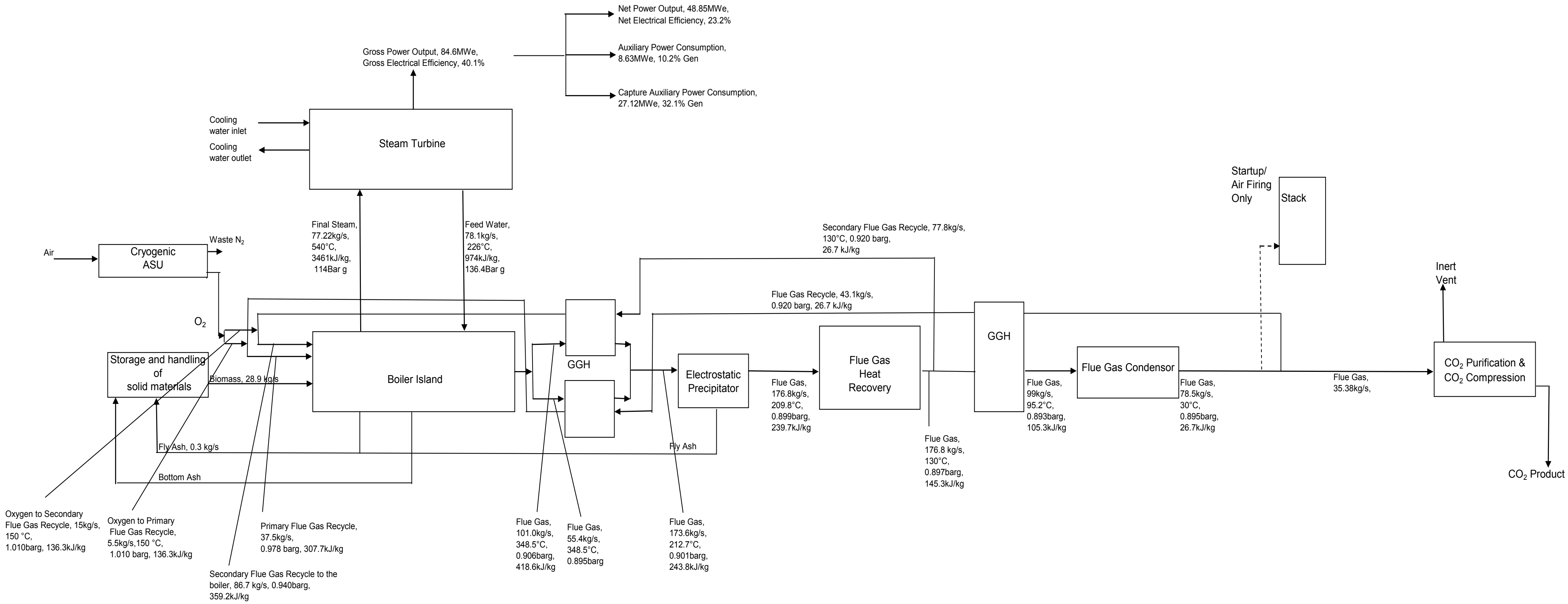

Figure 2. Process flow diagram for biomass oxy-firing combustion

3. MODEL DETAILS: Biomass combustion, with CO_2 capture by post-combustion carbonate looping [T7]

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

- Inputs (4-dimensional vector x)
  - Nameplate capacity (MWe)
  - Operating capacity (MWe)
  - Carbon capture extent (%)
  - Co-firing 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; and are summarised in Appendix 2. These data were obtained from:

- 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.

The process flow diagram for carbonate looping is presented in Figure 3.

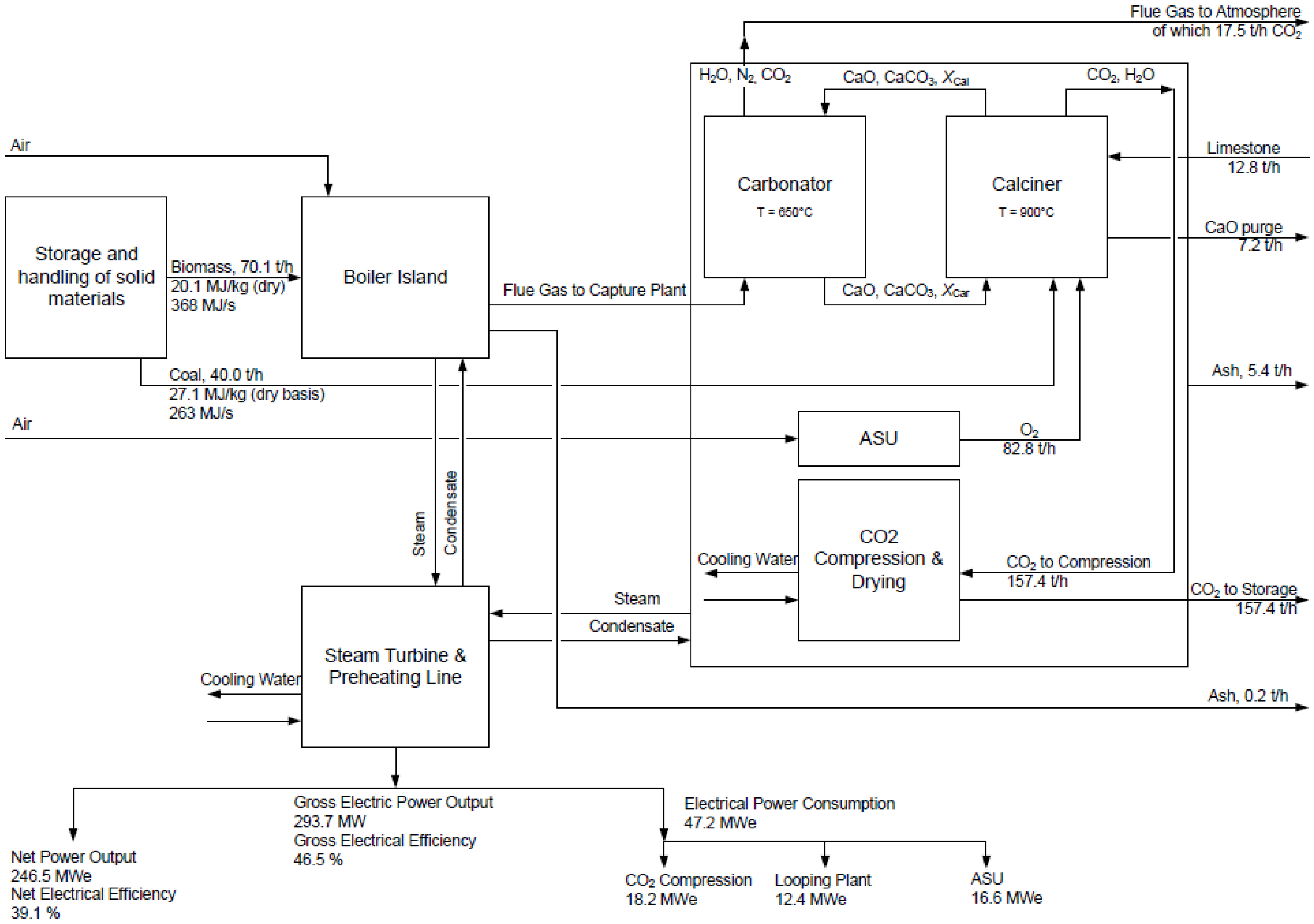

Figure 3. Process Flow Diagram for Biomass combustion, with CO_2 capture by post-combustion carbonate looping

4. MODEL DETAILS: Dedicated biomass chemical-looping-combustion using a solid oxygen carrier [T8]

Input and output data: This technology, as with T6 and T7, has the following inputs and outputs:

- 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.

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.

The process flow diagram for Tech 6 is presented in Figure 4.

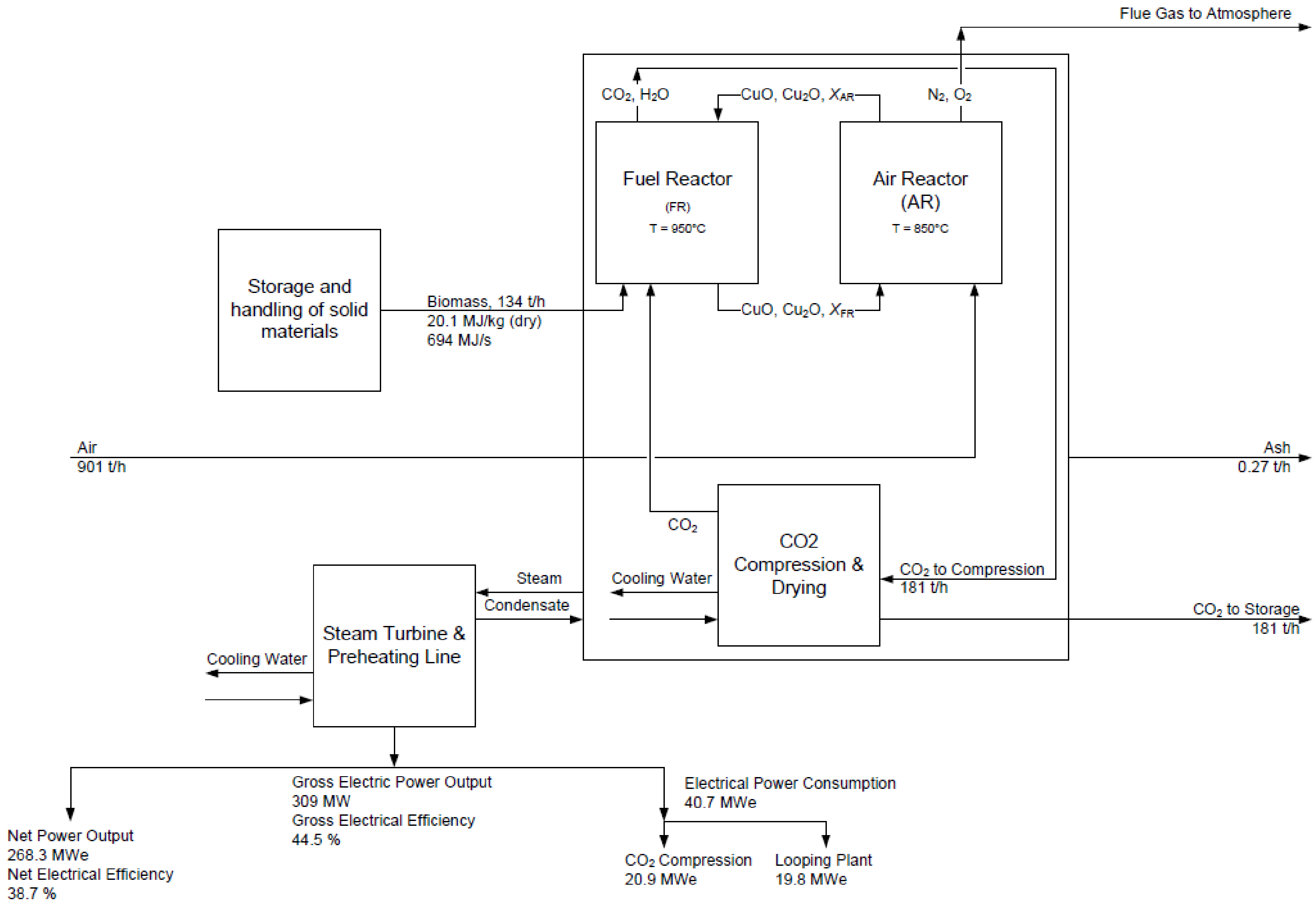

Figure 4. Process flow diagram for dedicated biomass chemical looping

5. MODEL OVERVIEW, APPLICATION RANGE AND USER-DOCUMENTATION: Biomass oxy-combustion with carbon capture

The base-delta simplified model has been developed in Microsoft Excel™. For the case of the oxy-combustion with CCS technology [T6], the applicable operation ranges of this model are presented in Table 1.

Table 1: Operating range of Biomass oxy-combustion with carbon capture (*: of actual capacity)

	Lower bound	Upper bound
Nameplate capacity (MWe)	30	100
Capacity Factor* (%)	60	100
CO_2 capture extent (%)	0	98

A screenshot of a sample model for a PC Biomass oxy-combustion with carbon capture is shown in with some explanations provided in Figure 5 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.

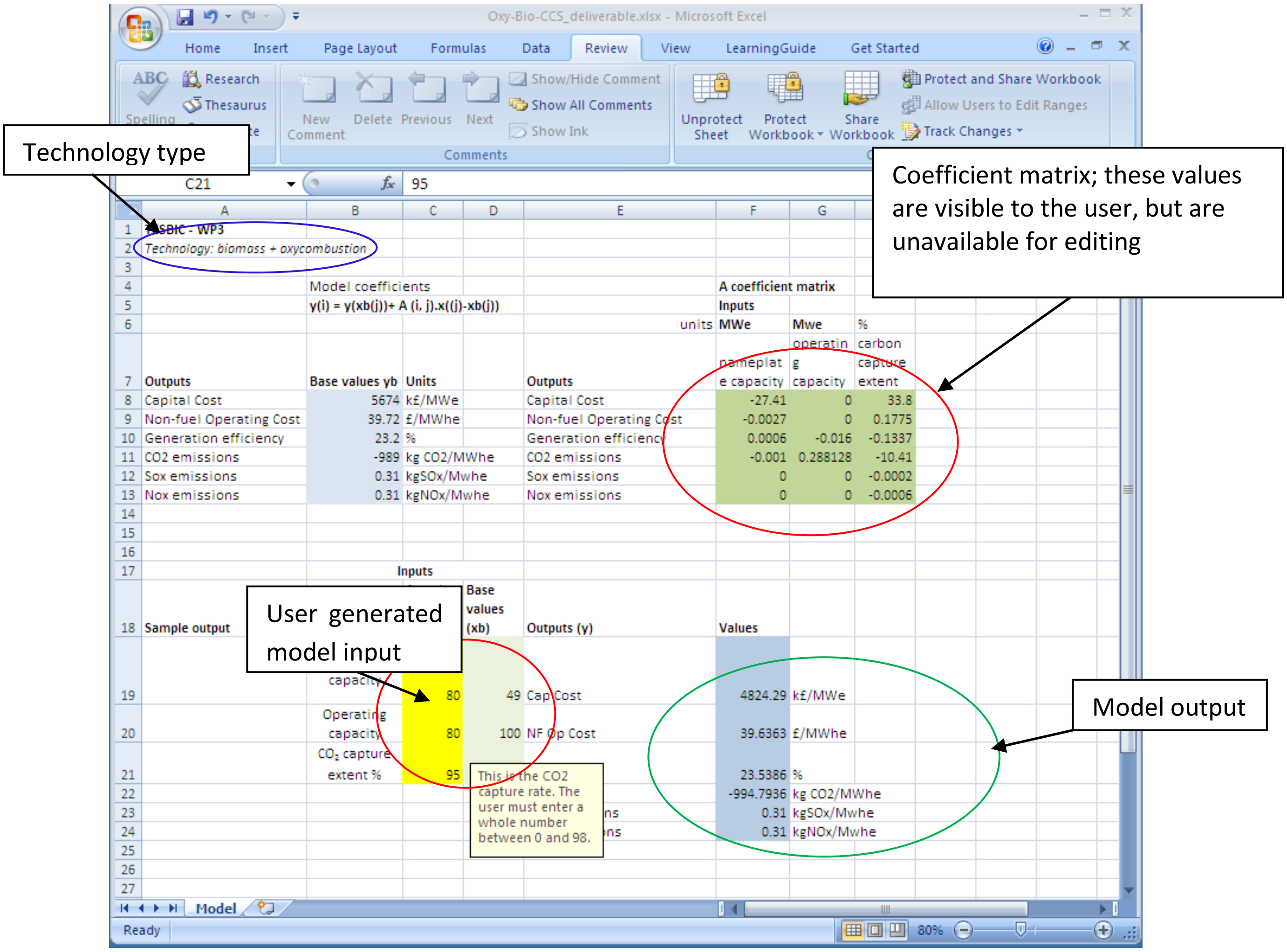

Figure 5: Screenshot of dedicated biomass with oxy-fired combustion. Required user inputs are highlighted in yellow, model parameters are highlighted in green and model outputs are highlighted in blue. Only the cells corresponding to user inputs are editable, all other cells are protected

Model Fidelity

In this section, we present an analysis of the fidelity of the proposed dedicated biomass oxy-firing model. As can be observed from Figure 6 and Figure 7, 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. Note that the CO_2 intensity is a perfect fit as it is a linear function of capture and so is not reproduced here.

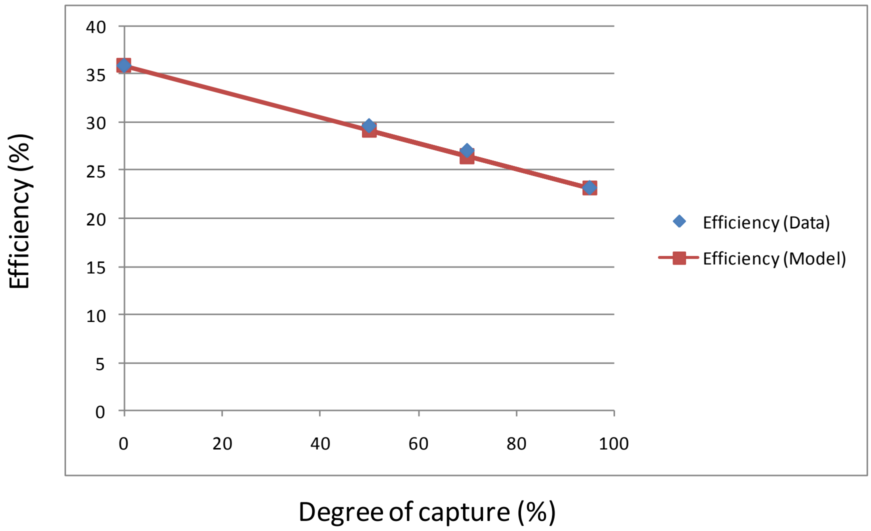

Figure 6: Efficiency data fit for biomass oxy-firing case as a function of the degree of capture

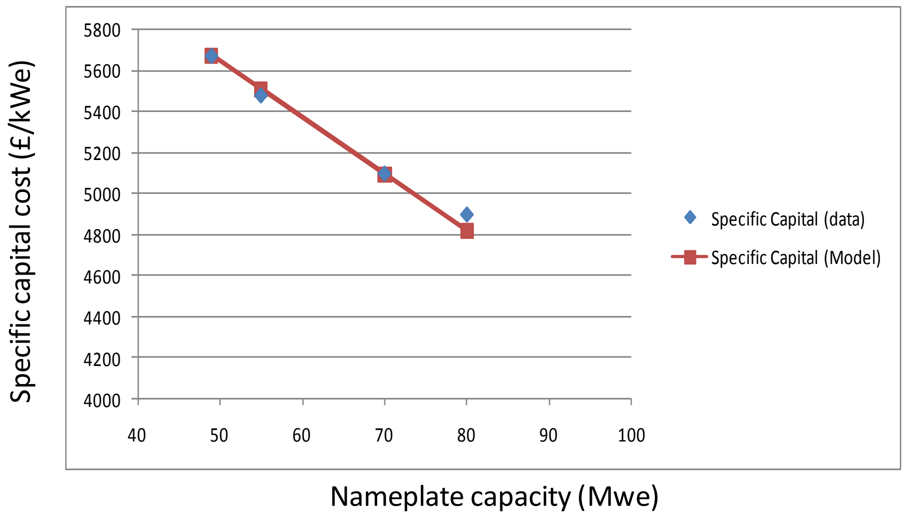

Figure 7: Data fit for biomass oxy-firing case: Relationship between specific capital cost and nameplate capacity

6. MODEL OVERVIEW, APPLICATION RANGE AND USER-DOCUMENTATION: Biomass combustion, with CO_2 capture by post-combustion carbonate looping

The base-delta model has been developed in Microsoft Excel™. For the case of biomass combustion with post-combustion carbonate looping carbon capture [T7], the applicable operation ranges of this model are presented in Table 2.

Table 2: Operating range of dedicated biomass with post-combustion carbonate looping model

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

The models will be delivered to the ETI in this format. A screenshot of the model for dedicated biomass combustion with post-combustion carbonate looping carbon capture is shown in Figure 8 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 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.

Co-fired biomass with post-combustion carbonate looping is in a way, a unique technology as compared to the seven other technology combinations assessed within the TESBiC project; in that the two input variables, i.e. the co-firing extent and the extent of carbon capture are not mutually exclusive. This is a direct consequence of the fact that coal is used in the calciner to provide the energy for the release (and thereby the capture) of CO2. From the data sources including the WP2 study that were utilised here, the most robust data-set on carbonate looping was available at around 90% carbon capture extent for a wide range of nameplate capacities (40 and 300 MWe), and capacity factors (o to 100%). To obtain a reduced extent of carbon capture, for example, to ~ 80%, the coal feed must be decreased, i.e. implying an increase in the co-firing extent. The upper and lower bounds for the two inputs discussed above were constrained around the design base case as given in Table 2.

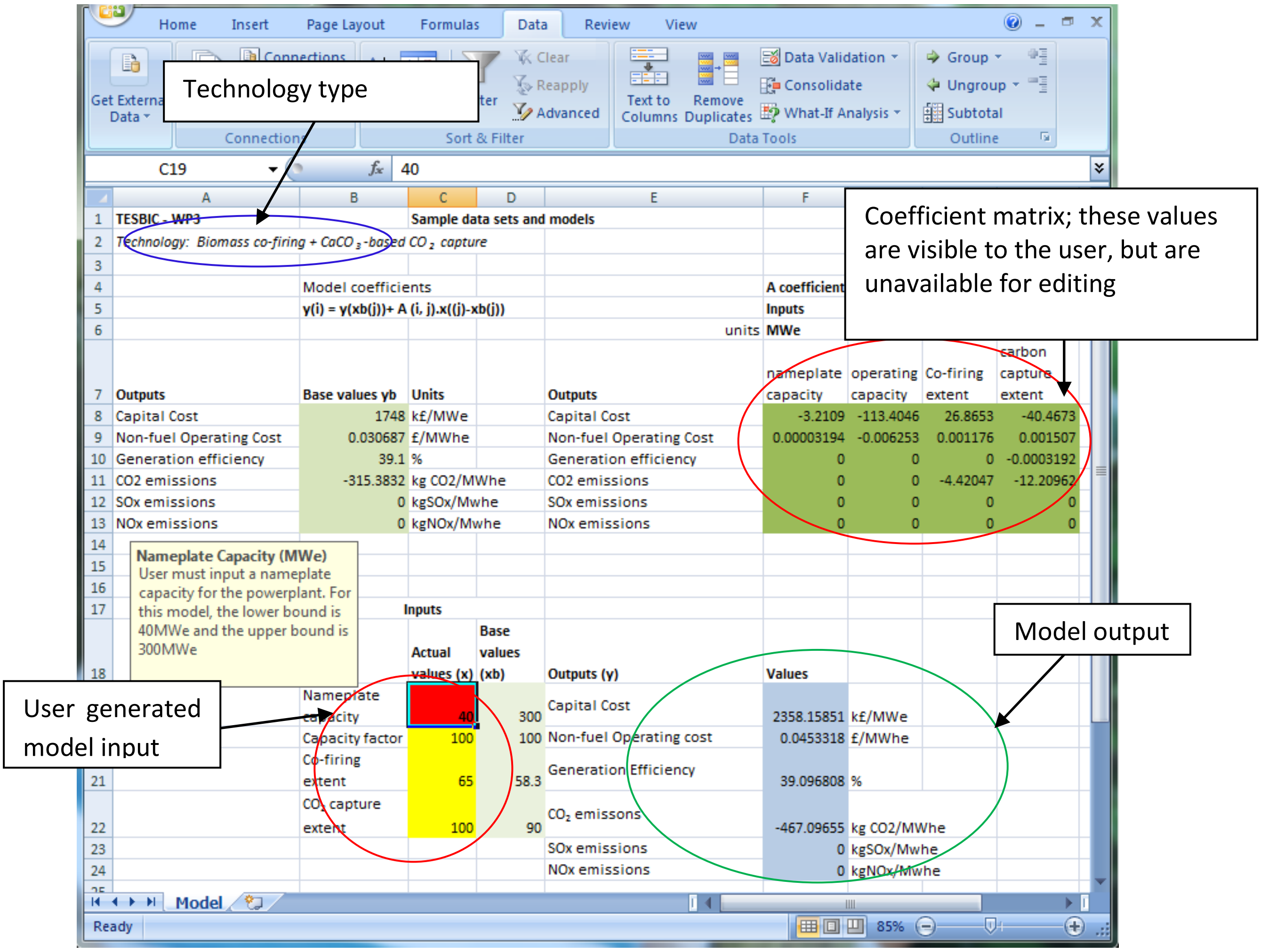

Figure 8: Screenshot of biomass combustion with post-combustion carbonate looping model. Required user inputs are highlighted in yellow, model parameters are highlighted in green and model outputs are highlighted in blue. Only the cells corresponding to user inputs are editable, all other cells are protected.

Model Fidelity

In this section, we present an analysis of the fidelity of the proposed biomass combustion with post-combustion $CaCO_3$ looping capture model. As can be observed from Figure 9, 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.

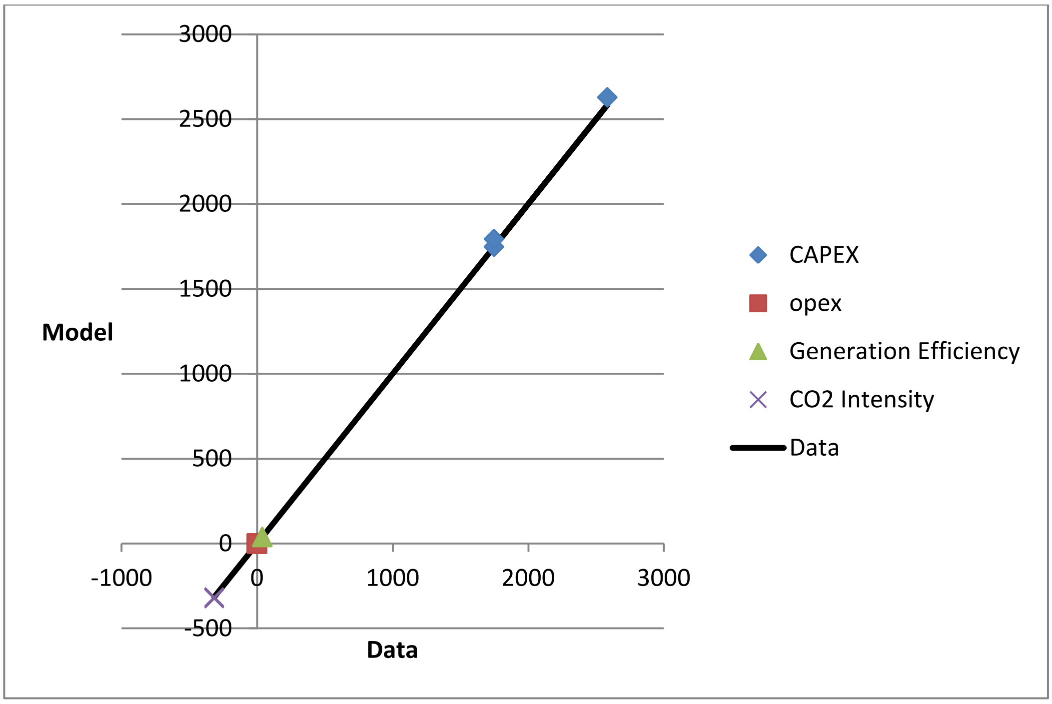

Figure 9. Deviation of post-combustion $CaCO_3$ looping model outputs from "data"

7. MODEL OVERVIEW, APPLICATION RANGE AND USER-DOCUMENTATION: Dedicated biomass chemical-looping-combustion using a solid oxygen carrier

Further, we note that in the case of the dedicated biomass with chemical looping CO_2 capture technology, the applicable operation ranges of this model are presented in Table 3.

Table 3: Operating range of dedicated biomass with chemical-looping CO_2 capture

	Lower bound	Upper bound
Nameplate capacity (MWe)	40	300
Capacity Factor (%)	0	100
CO_2 capture extent (%)	0	100

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 dedicated biomass combustion with chemical looping capture technology is shown in Figure 10.

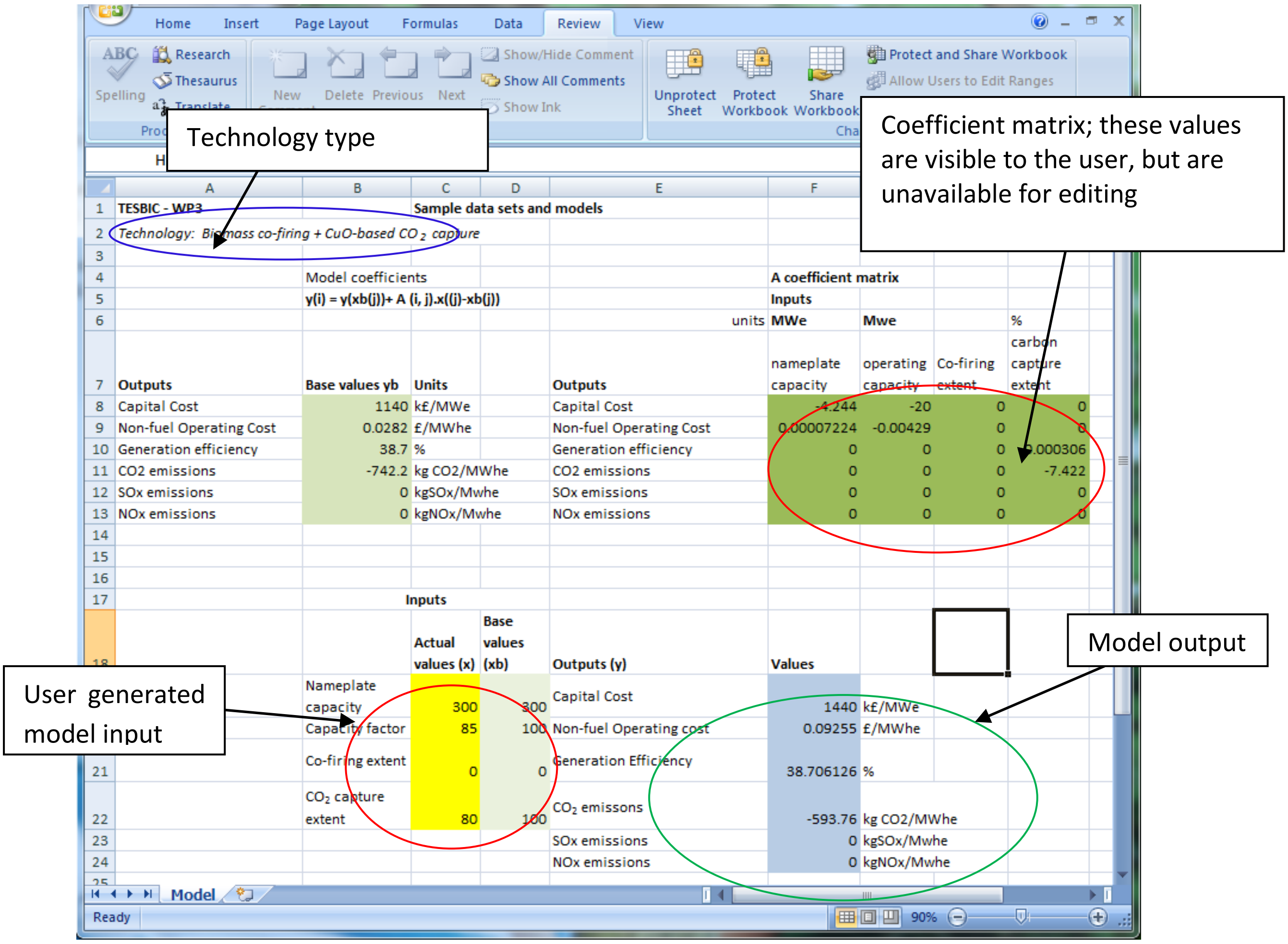

Figure 10: Screenshot of dedicated biomass with CuO CO_2 capture model. Required user inputs are highlighted in yellow, model parameters are highlighted in green and model outputs are highlighted in blue. Only the cells corresponding to user inputs are editable, all other cells are protected.

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 dedicated Biomass chemical looping combustion model. As can be observed from Figure 11, 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.

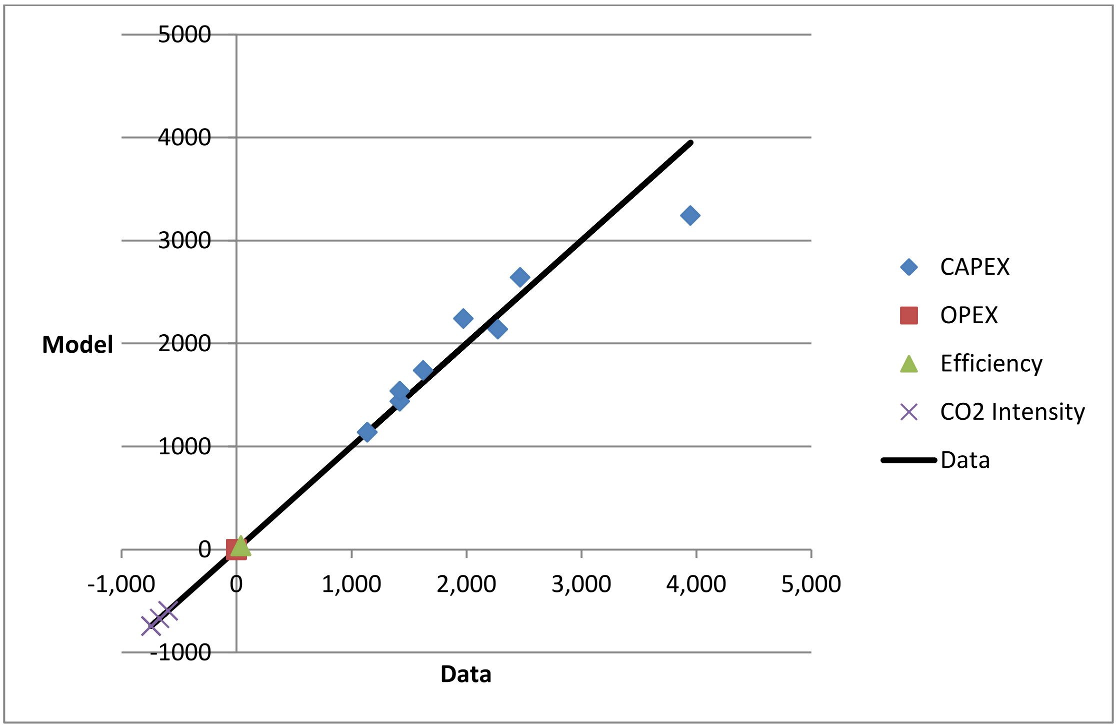

Figure 11: Deviation of dedicated Biomass chemical looping combustion model outputs from "data"

8. SUMMARY

This document has presented the modelling requirements, specification and modelling strategy, as well as associated model parameterisation and user documentation for the last three out of the total eight technology combinations within the TESBiC project. Biomass with oxycombustion [T6], co-fired biomass with carbonate looping combustion [T7] and dedicated biomass with CuO looping [T8] were the three technologies presented here.