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Deliverable 5: User guide

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The TEABPP Consortium

For the Energy Technologies Institute

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1 Executive Summary

The TEABPP consortium has prepared this user guide (Deliverable 5) in Word and pdf format explaining how to use the live process model in gPROMS prepared in the fourth Deliverable (D4).

This document provides descriptions of the important features and components of the models developed, their key assumptions and limitations, as well as step-by-step instructions for using and modifying the bioenergy supply chain models provided. This user guide does not contain an exhaustive explanation of all of the model functionalities or background theory, and focuses primarily on the most important screens in the modelling, to enable the ETI to make effective use of Deliverable 4.

1.1 Short introduction to the gPROMS model

The gPROMS® advanced process modelling platform is the powerful equation-oriented modelling and optimisation framework on which all of PSE's gPROMS family products (including gCCS) are built.

The gPROMS platform provides drag & drop flowsheeting, first-principles custom modelling, parameter estimation, physical properties integration, powerful optimisation capabilities that allow direct calculation of optimal solutions rather than by trial-and-error simulation, plus many other features. PSE provides gPROMS training courses throughout the year. Details can be found here: <https://www.psenderprise.com/services/training>. This document assumes a basic understanding of how to use gPROMS.

As part of Deliverable 4, a process model library that could be used to model bioenergy supply chains was developed in gCCS, based on the initial techno-economic results in Deliverable 2. Bioenergy chain models can be built using components from the following model libraries: TEABPP Basics, TEABPP Conversion, TEABPP Pre-processing, TEABPP Storage, TEABPP Sub-units¹, and TEABPP Transport.

In addition, 10 case studies were selected and developed in gPROMS to understand and explore the behaviour and performance of these bioenergy supply chains, the impact of feedstock characteristics and blending, transport and storage, and pre-treatment and/or improved conversion technology choices on end vector efficiency, chain costs and emissions.

Section 2 of this document describes the models developed in gCCS as part of Deliverable 4 and how to use them.

Section 2.1 describes installation instructions.

Section 2.2 describes the layout of the gCCS application and how to open the TEABPP libraries in the gCCS platform.

Section 2.3 provides a description of the model libraries developed for characterising bioenergy supply chains.

¹ It should be noted the TEABPP Sub-units library does not appear in the main palette and the models used in this library should not be used without further testing (they are used to build composite flow-sheeting models or were used for testing purposes).

Section 2.4 explain key model features of models developed including key calculations, model assumptions and limitations

Section 2.5 gives step-by-step instructions on how to develop and modify a bioenergy supply chain model.

Section 2.6 discusses how to access and understand the results generated

Section 2.7 explains how to run a 'backwards' calculation – specifying desired values for LCOE, CO₂e emissions or chain efficiencies and using gPROMS to calculate the value of the model parameters that would give such a result.

1.2 Key assumptions, limitations and glossary

Section 3 describes the key assumptions and limitations of the gPROMS tool. Section 4 provides a glossary of terms.

Appendix A sets out the relationship between key input and output parameters. Appendix B provides details of the min-max ranges of feedstock characteristics.

2 gPROMS model

2.1 Installation

A gCCS installation executable file is provided with a setup wizard for configuring installations. A number of license features are also required to run gCCS. For support on installation, contact support.gccs@psenterprise.com.

The models developed for studying bioenergy supply chains are saved as gCCS Project files. The following are provided as part of Deliverable 4:

Model Libraries

- TEABPP Basics.gPJ
- TEABPP Conversion.gPJ
- TEABPP Pre-processing.gPJ
- TEABPP Storage.gPJ
- TEABPP Transport.gPJ
- TEABPP Sub-units.gPJ

gCCS project containing the 10 Case Studies

- Preloaded_chains.gPJ

2.2 Application Start up Screen

When gCCS is opened, the last saved workspace² is displayed. If the TEABPP libraries are not present in the project tree, they can be opened by going to File → Open and choosing the path where the libraries are located. Alternatively, the user can drag and drop the libraries to the gCCS window (Figure 1). The library files may or may not be displayed on the project tree depending on whether the relevant button is Toggled off or on respectively.

² The workspace refers to the list of gCCS library, project files and case files that are automatically loaded when gCCS is launched. The first time gCCS is opened after installation, the default gCCS library files are displayed. Subsequently, the workspace is updated every time the user closes gCCS—all saved library, project and case files are automatically saved in the workspace.

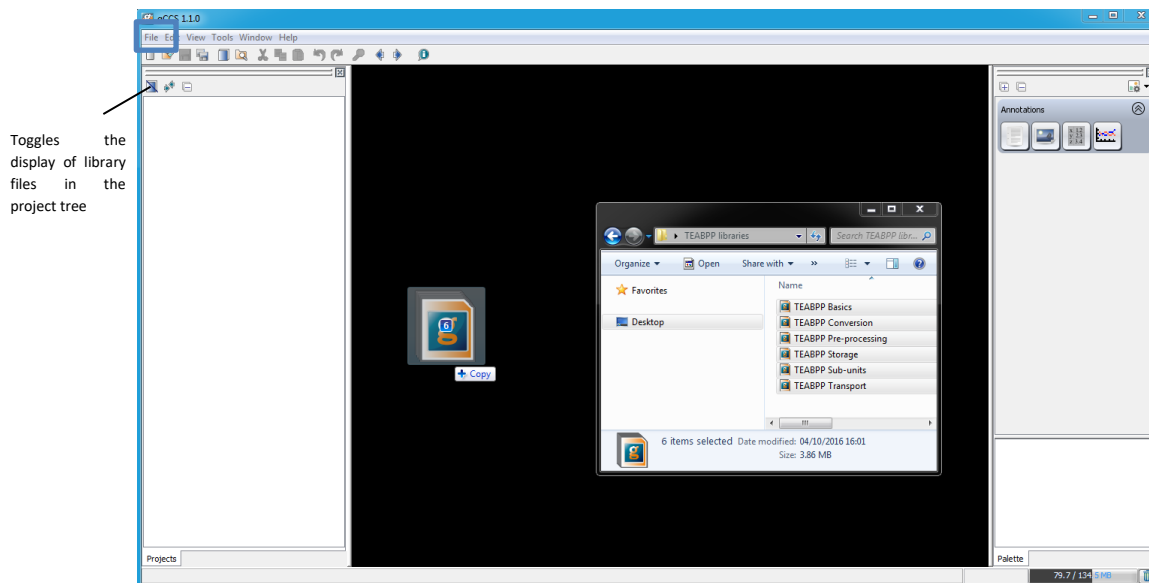


Figure 1: gCCS interface when loaded. Also represented are the TEABPP libraries being loaded to the model. They can be also opened by going to the File option (highlighted in the upper left corner)

The gCCS interface is composed by three sections, which can be seen in Figure 2:

- Project tree
- Flowsheet area
- Palette

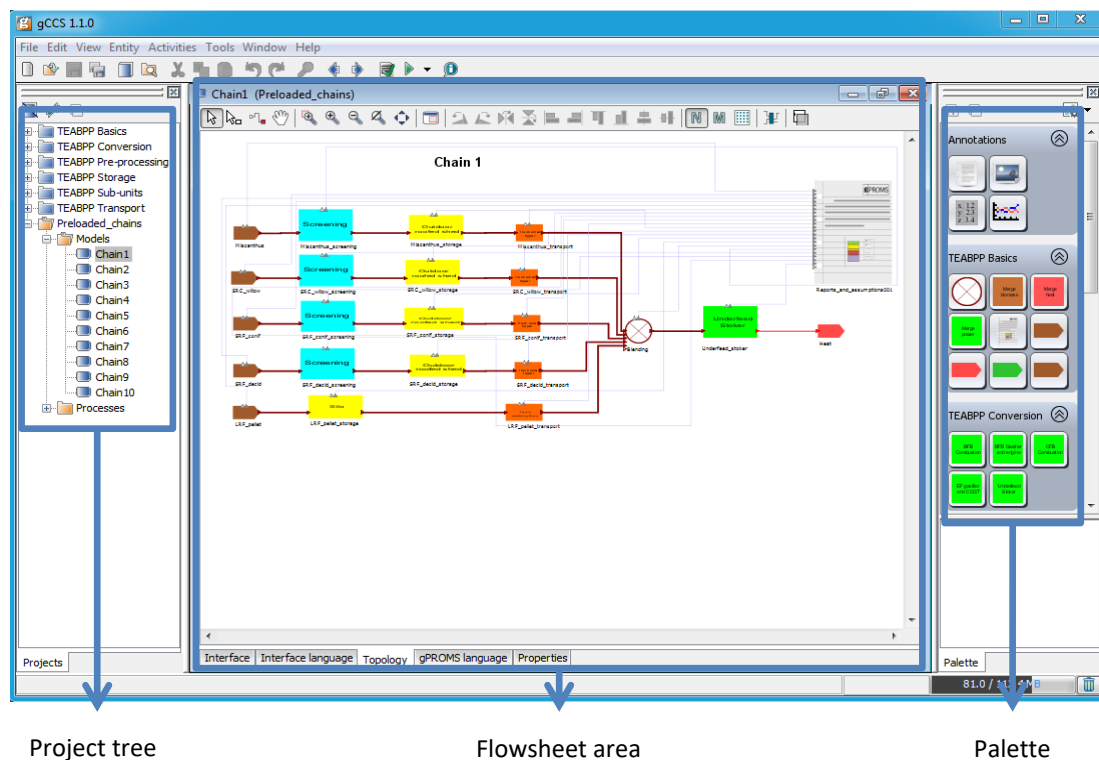


Figure 2: gCCS interface with the TEABPP libraries

The project tree is where the library and project files can be found. There, the user can see all of the entities in the libraries (such as the models, variable types, or connection types). The flowsheet area is where the user can edit the bioenergy chains, and in the Palette the user can find all the models which can be used to create/edit bioenergy chains.

2.2.1 How to reset gPROMS back to original installation settings

All the configuration specifications for the 10 case studies are saved in Preloaded_chains.gPJ. The model equations and default specifications of the bioenergy supply chain components are saved in the model library files listed above. gPROMS provides the user flexibility to modify case study flowsheets as well as model libraries. It is advisable to keep a copy of the original files provided. Some additional discussion on this topic is provided in Section 2.5.12.

Model specifications can also be reverted to the original settings by clicking the “Reset all” button in the mode interface. The default values are coloured blue, and values turn black when they are changed by the user. Further discussion on this can be found in Section 2.5.5.

It is important to note that the models used in the 10 pre-loaded chains do not always use default values (hence the need to keep a copy of the original files).

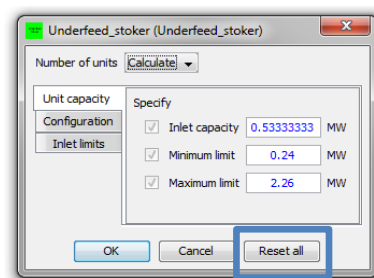


Figure 3: Dialogue box for the Underfeed_stoker model

2.3 Model libraries

The model libraries have been developed based on the results of the initial techno-economic results (Deliverable 2 of the TEABPP project). This Microsoft Excel spreadsheet was based on the techno-economic data gathered as part of Work Package 1.

For the pre-processing and conversion technologies, the formulas used within the gPROMS model were taken directly from the respective tabs in the Excel.

For the storage and transport models, the equations in the Excel are located in the Transport1/Transport2/Transport3 tabs for the storage models and the Storage1/Storage2/Storage3 tabs for the storage models.

The feedstock properties used in the model libraries were taken from the Feedstock tab in the Excel.

The TEABPP component models are provided in the following libraries and are described in the subsequent sections:

- TEABPP Basics
- TEABPP Conversion
- TEABPP Pre-processing
- TEABPP Storage
- TEABPP Transport
- TEABPP Sub-units



2.3.1 TEABPP Basics

The TEABPP Basics library contains the models used to create the bioenergy chain:

- Source_biomass
- Blending
- Merge models
- Reports_and_assumptions
- Sink models



2.3.1.1 Source_biomass

The source_biomass model is used to specify the biomass feedstock used in the chain. The user can choose between five pre-configured feedstocks or generate a custom feedstock ('Other'):

- Miscanthus
- SRC willow
- SRF coniferous (SRF conif)
- SRF deciduous (SRF decid)

- LRF pellets

The properties of these feedstocks were taken from Deliverable 2, in the Feedstock tab.

The source_biomass model has two ports, a results connection which should be linked to the Reports_and_assumptions model of the chain, as well as a biomass port.

The source model's dialog box is presented in Figure 4. There are three tabs in the model dialog – “Feedstock type”, “Composition”, “Specify”.

The dialog box 'Miscanthus (Source_biomass)' has three tabs: 'Feedstock type', 'Composition', and 'Specify'. The 'Specify' tab is active, showing pre-configured values for Miscanthus feedstock. The values are: Density (0.130725 odt / m3), LHV (17.8993 GJ / odt), Feedstock price (23.66 £ / odt), Particle size (2450 mm), and Emissions (CO2e 45.8571 kg/odt). The 'Feedstock' dropdown is set to 'Miscanthus'. The 'Density', 'LHV', 'Feedstock price', and 'Particle size' fields are checked. The 'Emissions' field is also checked. The 'OK', 'Cancel', and 'Reset all' buttons are at the bottom.

The values in these fields cannot be changed for the pre-configured feedstocks

Figure 4: Dialog box for the Source_biomass model with pre-configured feedstock

In the Feedstock type tab the user inputs the feedstock to be used. If a pre-configured feedstock is chosen, all the specifications in the “Feedstock type” and “Composition” tabs are automatically filled out and cannot be changed.

Alternatively, the user can specify the Source_biomass model as a custom feedstock. To do this, the user should choose the “Other” option in the “Feedstock” drop-down menu specification on the “Feedstock type” tab.

The dialog box 'Miscanthus (Source_biomass)' has three tabs: 'Feedstock type', 'Composition', and 'Specify'. The 'Specify' tab is active, showing custom values for an 'Other' feedstock. The values are: Density (0.12 odt / m3), LHV (13.889 GJ / odt), Feedstock price (44.3676 £ / odt), Particle size (38 mm), and Emissions (CO2e kg/odt). The 'Feedstock' dropdown is set to 'Other'. The 'Feedstock form' dropdown is set to 'Bales'. The 'Density', 'LHV', 'Feedstock price', and 'Particle size' fields are checked. The 'Emissions' field is also checked. The 'OK', 'Cancel', and 'Reset all' buttons are at the bottom.

Custom values can be provided in these fields

Figure 5: Dialog box for the Source_biomass model for “Other” feedstocks

With “Other” feedstocks, the user can provide custom values for feedstock form, density, lower heating value (LHV), feedstock price, particle size and emissions on the “Feedstock type” tab as well as the moisture content, stone and soil contamination, and composition on the “Composition” tab. It should be noted that the composition should be provided on the basis of the kilograms of the elemental form per kilogram of dry biomass, not on the basis of the oxide % of ash. A separate Excel sheet is provided to allow easy translation between the two bases.

Finally, in the “Specify” tab, the user can specify the mass flow rate or input fuel energy of the biomass by selecting the corresponding option on the “Specify” drop-down menu. The user can also choose to not specify the mass flow rate, and specify other inputs in the bioenergy chain elsewhere (such as the produced energy). Section 2.5.3 contains further discussion on when to specify the mass flowrate.

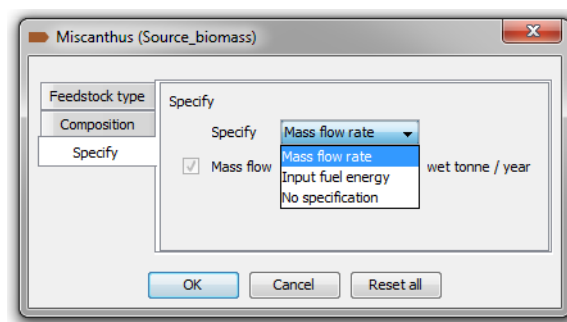


Figure 6: Specifications which can be selected in the "Specify" tab

2.3.1.2 Blending

The blending model was developed independently from the Deliverable 2 Excel, and is used to blend (mix) two or more biomass streams, allowing the consideration of different processing options and different feedstocks in one chain. This model accounts for the costs involved in blending.



Figure 7: Blending model icon

The blending model has a dynamic inlet biomass port (allowing the user to connect two or more biomass streams) and a single outlet biomass port. The model also has a Results port which must be connected to the Reports_and_assumptions model.

The blending model's dialog box is presented in Figure 8, where the user can choose whether or not to specify the blending split fractions for each stream. These fractions are then normalised if they do not sum to 1.

Further details on the assumptions used in the blending model can be found in Section 3.4.

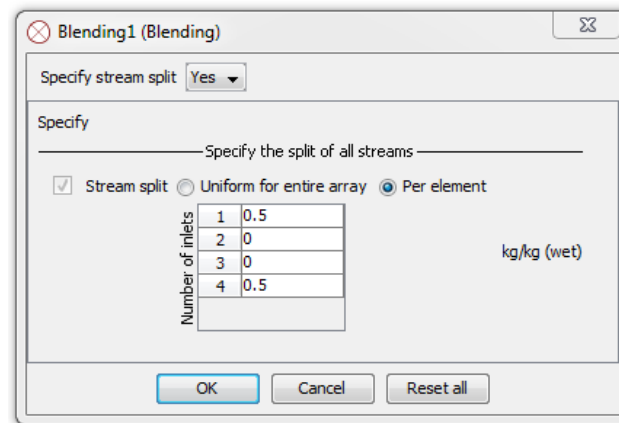


Figure 8: Dialog box for the blending model with four inlet streams

2.3.1.3 Merge models

There are currently three merge models implemented:

- Merge_biomass
- Merge_heat
- Merge_power

These models are used to connect two or more streams of biomass, heat, or power respectively.

Merge_biomass

The merge_biomass model is used to merge different biomass streams. This model differs from the blending model in the following ways:

- CAPEX and OPEX calculations are not performed in this model
- Outlet particle size is averaged in this model

The Merge_biomass model has a dynamic biomass inlet port (allowing the user to connect two or more biomass streams) and a single outlet port. Unlike the blending model there is no Results connection port in this model, as this model is provided for convenience only and does not account for the costs of such a unit.

The dialog box for this model is represented in Figure 9. In it you can specify the split fraction for the different streams.

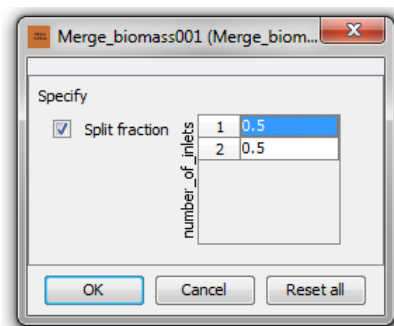


Figure 9: Dialog box for the merge_biomass model

Merge_heat

The Merge_heat model is used to merge different heat sources, which allows chains with more than one conversion unit.

The Merge_heat model has a dynamic heat inlet port (allowing the user to connect two or more heat streams) and a single outlet heat port.

This model's specification allows the user to set the inlet heat streams split fraction (Figure 10).

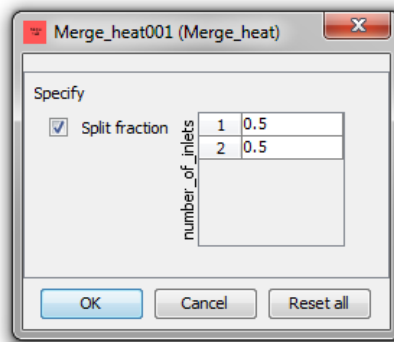


Figure 10: Dialog box for the merge_heat model

Merge_power

The Merge_power model is used in the same manner as the Merge_heat model, only to merge different power sources.

The Merge_power model has a dynamic power inlet port (allowing the user to connect two or more power streams) and a single outlet port.

This model's specification allows the user to set the inlet power streams split fraction (Figure 11).

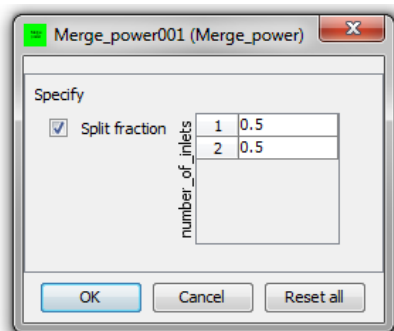


Figure 11: Dialog box for the merge_power model

2.3.1.4 Reports_and_assumptions

The reports and assumption model is where the chain model's global assumption can be reviewed and modified. The global assumptions include technical and economic parameters for all biomass processing models available in the TEABPP model library.

The model also collects and collates the results from all units and generates a report of the main results of the chain. These results include the chain efficiency, economic results (CAPEX, OPEX and LCOE), and greenhouse gas emissions.

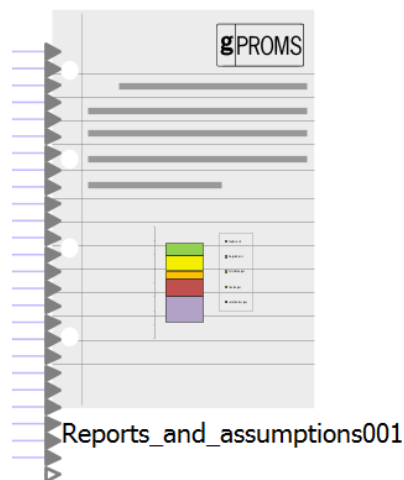


Figure 12: Icon of the Reports_and_assumptions model

The Reports_and_assumptions model has a dynamic inlet port (allowing the user to connect two or more Results connections), to which all the models (excluding the Sink model) present in the chain **must** be connected.

There are seven specification tabs in the model dialog:

- Input across boundary tab: contains the pricing and other properties of inputs required for different biomass processing units (e.g. the cost of the binder used in pelleting)
- Output across boundary tab: cost of treating waste products and value of any co-produced heat and electricity
- Transportation tab: parameters used in the transport models
- Storage tab: parameters used in the storage models
- Finance tab: discount rate and insurance cost (as fraction of total CAPEX costs)
- Unit conversions
- Currencies

Item	Value	Unit
<input checked="" type="checkbox"/> Diesel cost	44.67	£/MWh
<input checked="" type="checkbox"/> Diesel LHV	8051917277	GJ/tonne
<input checked="" type="checkbox"/> Diesel density	2320819113	tonne/m3
<input checked="" type="checkbox"/> Electricity cost	91.5	£/MWh
<input checked="" type="checkbox"/> Front end loader energy	0.002875191	MWh/odt
<input checked="" type="checkbox"/> Heavy fuel cost	34.5	£/MWh
<input checked="" type="checkbox"/> Heavy fuel LHV	40.7	GJ/tonne
<input checked="" type="checkbox"/> Natural gas cost	25.55	£/MWh
<input checked="" type="checkbox"/> Natural gas LHV	47.89	GJ/tonne
<input checked="" type="checkbox"/> Water cost	1.128320	£/tonne
<input checked="" type="checkbox"/> Urea cost	176.63	£/tonne
<input checked="" type="checkbox"/> Lime cost	217	£/tonne
<input checked="" type="checkbox"/> Binder cost	323.5	£/tonne
<input checked="" type="checkbox"/> Lipids and organics cost	0.75722	£/tonne
<input checked="" type="checkbox"/> Nitrogen cost	0.38420	£/tonne
<input checked="" type="checkbox"/> Ammonium acetate cost	316.1	£/tonne
<input checked="" type="checkbox"/> Hydrochloric acid cost	383.176	£/tonne

Figure 13: Dialog box for the Reports_and_assumptions model

2.3.1.5 Sink models

The sink models allow the user to specify the end vector production of the bioenergy chain. Currently three sinks are available:

- Sink_biomass
- Sink_heat
- Sink_power

Sink biomass

The sink biomass model allows the user to specify a biomass stream as an end product. This model can be used for testing the performance of a particular model, or to just analyse the biomass pre-processing section. This model is not used in the pre-loaded 10 case study chains.

It should be noted that when this model is used, since there is no conversion, the energy of this biomass will not be counted towards the end vector, and consequently it will not be accounted for in the chain efficiency calculation.

This model has only one inlet biomass port connection, and does not require to be connected to the Reports_and_assumptions model.

The dialog box of the sink biomass model (Figure 14) allows the user to specify the total biomass as the mass flowrate (wet tonne/year) or fuel energy (MWh/year). Alternatively, the user can choose to not specify anything on the sink model, specifying the biomass flowrate elsewhere.

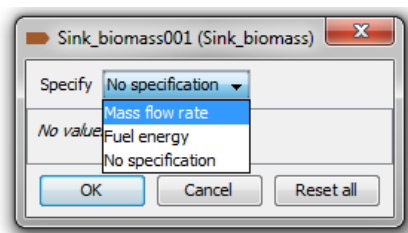


Figure 14: Dialog box for the Sink_biomass model

Sink_heat

The sink heat model allows the user to specify a heat stream as the end product of a bioenergy chain. This model can be connected to the underfeed_stoker conversion model to specify the produced energy, or alternatively it can be connected to a Merge_heat model.

This model has only one inlet heat port connection, and does not require to be connected to the Reports_and_assumptions model.

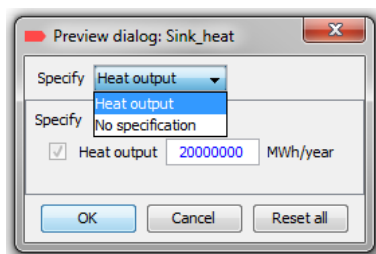


Figure 15: Dialog box for the Sink_heat model

Sink_power

The sink heat model allows the user to specify the power produced as the end product of a bioenergy chain. This model can be connected to the conversion units which produce power as an end vector to specify the produced energy, or alternatively it can be connected to a Merge_power model.

This model has only one inlet power port connection, and does not require to be connected to the Reports_and_assumptions model.

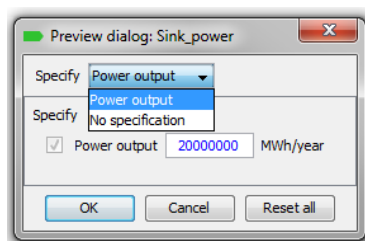
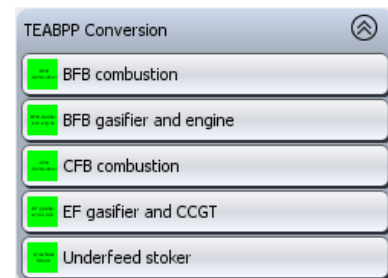


Figure 16: Dialog box for the Sink_power model

2.3.2 TEABPP Conversion

The conversion library contains the conversion units parameterised in gPROMS. The following conversion units are present:

- BFB_combustion (not used in the 10 pre-loaded chains, but included due to prior testing). No pre-processing included on-site, biomass handling into boiler, with steam turbine and flue gas clean-up.
- BFB_gasifier_and_engine. No resizing included on-site, but biomass drying (using waste heat) occurs before handling into gasifier, with syngas clean-up and syngas engine, and final flue gas clean-up.
- CFB_combustion. No pre-processing included on site, biomass handling into boiler, with steam turbine and flue gas clean-up.
- EF_gasifier_and_CCGT. Biomass drying (using waste heat) occurs before grinding and feeding at pressure into gasifier, with significant syngas clean-up, then syngas gas turbine and steam turbine, and final flue gas clean-up.
- Underfeed_stoker. No pre-processing included on site, biomass handling into boiler, with hot water extracted and flue gas clean-up.



For full technology descriptions, please see the Deliverable 1: Review and benchmarking report. The models for BFB combustion, CFB combustion, BFB gasifier and engine, and EF gasifier and CCGT are available for power production only and the Underfeed stoker model is available for heat generation.

2.3.2.1 Simple models - BFB combustion, CFB combustion and the Underfeed stoker models

The BFB combustion, CFB combustion, and Underfeed stoker models are composed of only a single model. The underlying equations used in these models can be found on their respective tabs in the Deliverable 2 Excel.

For these simpler models the dialog box has three tabs – "Unit capacity", "Configuration" and "Inlet limits" (as shown for the CFB_combustion model in Figure 17)

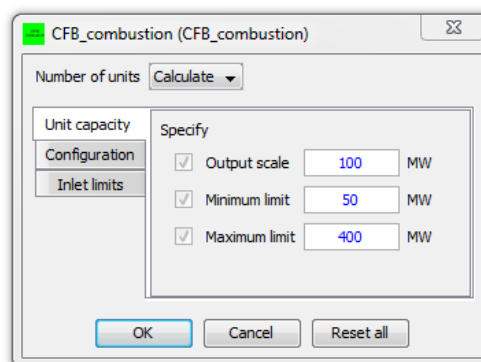


Figure 17: Dialog box for the CFB_combustion model

In the Unit capacity tab, the user inputs the size of the plant, as well as the minimum and maximum limits for this size, which are used for activating warning flags. For the BFB_combustion and CFB_combustion models, the unit size is given by the amount of energy produced (Output scale), and the Underfeed_stoker unit size is given by the inlet capacity.

The "Configuration" tab contains the main parameters for cost (total installed costs, labour maintenance, labour operations, parts and maintenance) as well as the base availability and lifetime. In this tab the user can also specify the number of units, if the drop-down menu specification of "Number of units" is changed from "Calculate" to "Specify". Section 2.4.3.1 provides further detail on how the cost parameters are used to calculate total installed cost.

Finally the "Inlet limits" tab contains the minimum and maximum allowable feedstock properties.

2.3.2.2 Composite models - BFB_gasifier_and_engine and EF_gasifier_and_CCGT models

The BFB Gasifier and engine and EF gasifier and CCGT are composite models composed of a gasifier model, a syngas cleanup, and a model which converts the syngas to energy, as shown in Figure 18. Note that the biomass does not flow into the syngas cleanup, rather information about the chlorine and sulphur content of the biomass is provided in order to calculate the syngas cleanup costs.

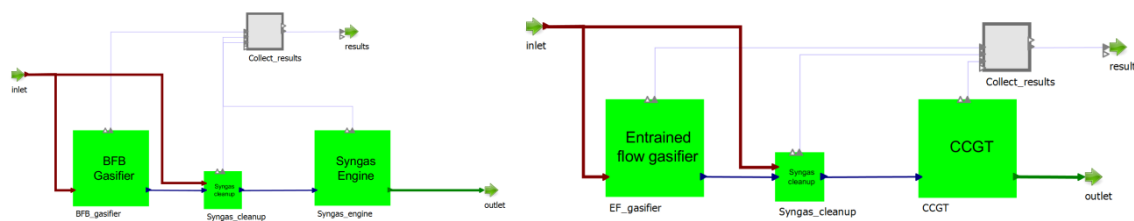


Figure 18: Topology view of the BFB_gasifier_and_engine model (left) and EF_gasifier_and_CCGT (right)

The composite models have dialog boxes with six tabs – "Unit configuration", "Inlet limits", "Number of units", and three other tabs, one which corresponds to the conversion unit, the "Syngas cleaning" which relates to the Syngas_cleanup model, and one tab related to the engine used to produce power (Figure 19).

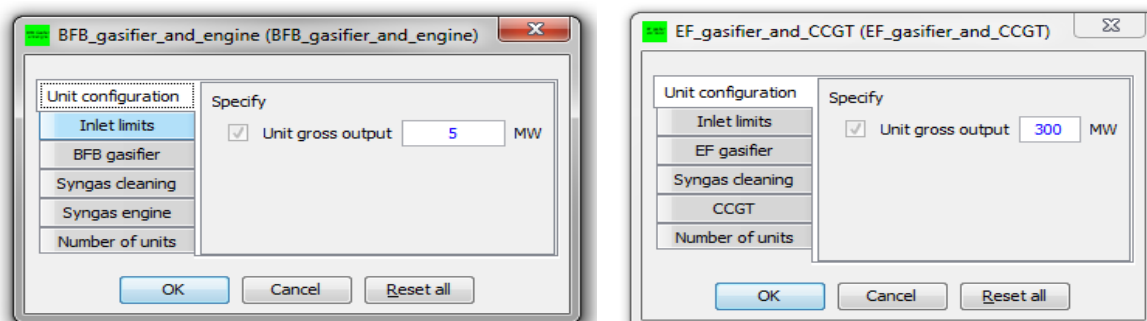


Figure 19: Dialog boxes for the BFB_gasifier_and_engine model (left) and the EF_gasifier_and_CCGT (right)

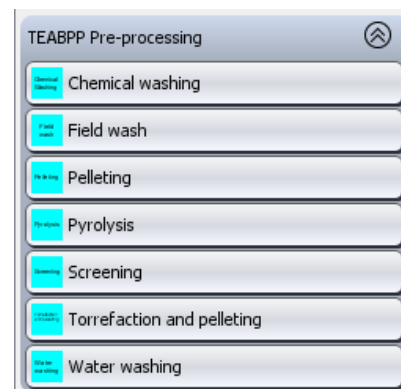
In the Unit configuration tab the gross output for the unit (either the BFB or entrained flow gasifier) is specified. The inlet limits of the feedstock for these units are specified in the Inlet limits, and the number of units can be specified on the Number of units tab.

For the “Syngas cleaning” tab the user can specify the cleaning efficiency. For the tabs relating to the conversion technologies (“BFB gasifier” and “EF gasifier”), the user can specify the main costing parameters for these units, as well as the base availability, lifetime, and inlet mass flow. For the Syngas engine and CCGT tabs, the user specifies the same cost parameters, as well as availability and lifetime, as well as the output scale for these units.

2.3.3 TEABPP Pre-processing

The conversion library contains the biomass pre-processing steps parametrised in gPROMS. The following units are present:

- Water washing. Contains screening to remove stones, chipping, magnetic screening to remove metals, water washing and filtering.
- Chemical washing. Contains screening to remove stones, chipping, magnetic screening to remove metals, water washing, chemical washing and filtering.
- Field wash. Comprises a single water washing tank, with no additional pre-processing.
- Pelleting. Contains chipping, screening, drying, grinding, conditioning, pelleting and cooling.
- Pyrolysis. Contains drying, chipping, grinding, fast pyrolysis, char separation and liquid recovery.
- Screening. Contains chipping and screening.
- Torrefaction and pelleting. Contains chipping, screening, drying, torrefaction, grinding, pelleting and cooling.



For full technology descriptions, please see the Deliverable 1: Review and benchmarking report. The underlying equations used in these models can be found on their respective tabs in the Deliverable 2 Excel.

There are three specification tabs in all pre-processing units' dialog box – “Unit capacity”, “Specification”, and “Inlet limits”.

In the “Unit capacity” tab the user provides the desired unit capacity, as well as the minimum and maximum capacity. It is important to note that some technologies measure this in wet tonne/yr while others use odt/yr.

In the “Specification” tab, the user can specify the main cost parameters (total installed costs, labour maintenance, labour operations, parts and maintenance) as well as the base availability and lifetime. Section 2.4.3.1 provides further detail on how the cost parameters are used to calculate total installed cost. The user also has to specify some operational parameters, which vary according to the pre-processing technology, as described in Table 1. Finally, the “Inlet limits” tab contains the minimum and maximum inlet feedstock properties.

Above the three specification tabs, the user has to specify whether the inlet biomass has been pre-washed or not, as it is currently not possible to propagate the existence of washing in earlier parts of the chain (as pointed out in section 3.5). If the user selects that the biomass is not prewashed, a fraction of the soil and stone contamination specified in the Source_biomass model is removed by the pre-processing model (the fraction removed is stated in the pre-processing model dialogue box). The removal of soil and stones is taken into account in the output ash content and LHV. However, if the user selects that the input biomass has been prewashed, no further soil or stone will be removed in the pre-processing model (as all the soil and stone contamination is assumed to have been removed by washing beforehand). The user can also decide whether to specify the number of units or if it should be calculated based on the inlet biomass and the defined capacity (for more information on these options, refer to section 2.5.3).

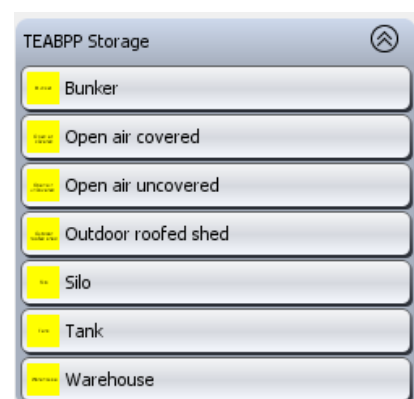
Table 1: Operational parameters for the pre-processing units provided in the “Specification” tab

Parameter	Description	Unit
Chips custom feedstock density	Density of the chips of a custom feedstock. This is necessary to calculate this unit’s outlet density. If no custom feedstock is used this value will not be relevant in the calculations	Chemical Washing Screening Water washing
Inerts screening	Amount of inert particles removed in the screening process. This value is used to calculate the reject costs	Pelleting Pyrolysis Screening Torrefaction and pelleting
Removed soil fraction	Fraction of soil and grit removed in the screening process	Pelleting Pyrolysis Screening Torrefaction and pelleting
Pelleting density	-	Pelleting
Pelleting moisture content	-	Pelleting
Torrefied pellet density	-	Torrefaction and pelleting
Torrefied pellet moisture content	-	Torrefaction and pelleting

2.3.4 TEABPP Storage

The storage library contains the model representation of different types of storage units:

- **Open_air_uncovered.** Open air storage on a concrete slab, uncovered to the elements. Biomass unloaded and recollected using a tractor, pick-up or tipper trailer.
- **Open_air_covered.** Open air storage on a concrete slab, but biomass piles covered by a plastic tarpaulin. Biomass unloaded and recollected using a tractor, pick-up or tipper trailer.
- **Outdoor_roofed_shed.** Open air storage on a concrete slab, with a corrugated iron roof constructed over the



top of the pile, and no walls. Biomass unloaded and recollected using a tractor, pick-up or tipper trailer.

- Warehouse. Biomass piles left on a concrete floor, with four brick walls, doors and a corrugated iron roof. Biomass unloaded and recollected using a tractor, pick-up or tipper trailer.
- Bunker. Rectangular shaped concrete structure buried in the ground. The top is at ground level and it would usually have a retractable cover. Unloading directly into the bunker is straightforward, and a live-bottom is used to remove the biomass.
- Silo. Usually a vertical cylinder with height to diameter ratio of ~2 to 2.5. Generally made of steel if diameters are less than 12 metres and from concrete above that figure. Provides a large amount of storage with a small footprint. Conveyors feed biomass into silos, unloading from base of silo straight into a truck or train.
- Tank (for pyrolysis oil only). Pyrolysis oil can be stored in steel or concrete tanks (either underground or mounted on a concrete slab), similar to those used for heavy fuel oil. They may need to be heated in winter. Acidity is an issue for tanks, hoses and valves.

The underlying equations for these models can be found in the Deliverable 2 Excel, in the Storage1, Storage2, or Storage3 tabs.

There are two specification tabs in all storage units dialog box – “Unit capacity” and “Configuration”. An example dialog box is shown below in Figure 20.

In the “Unit capacity” tab the user is asked to specify the desired unit capacity, as well as the minimum and maximum capacity.

In the “Configuration” tab the user has to specify the storage time in weeks, and can also set the storage unit’s lifetime, availability, CAPEX multiplier, and moisture equilibrium. Moisture equilibrium is the moisture content achieved by a sufficiently long storage time, due to average UK air humidity and the storage type. With longer storage times, biomass moisture content will approach the equilibrium level, i.e. wet biomass will lose moisture, and dry biomass will gain moisture.

The monthly degradation (dry matter loss) of the biomass in storage is calculated automatically based on the storage type, the input feedstock form (relative surface area to volume), and the input feedstock moisture content. Uncovered storage of wet chips outdoors will have the highest degradation losses, whilst silo storage of dry torrefied pellets will have the lowest losses. Tank storage of pyrolysis oil is assumed to have no degradation losses.

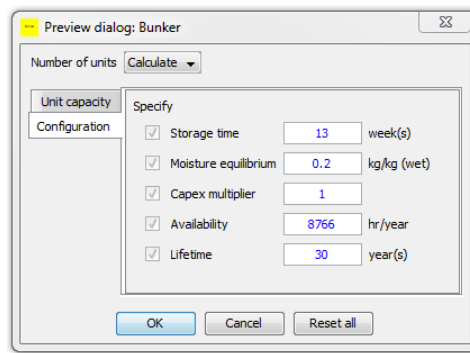
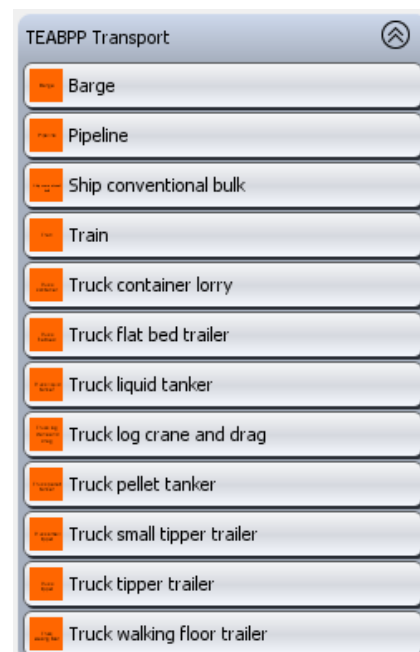


Figure 20: Dialog box for the Bunker model

2.3.5 TEABPP Transport

The transport library contains the model representation of different types of units that may be used to transport biomass:

- Barge. Can be used to convey bales, chips or pellets on inland waterways. Capacities can be 500-4000 tonnes.
- Pipeline. Thick steel pipeline for horizontal flow of liquids at pressure, often underground. Only used for pyrolysis oil transport, as not suitable for transport of solids.
- Ship_conventional_bulk. Capacities vary widely e.g. from 4,000 to 200,000 tonnes. Used for import of LRF pellets, but could also convey chips.
- Train. Can be used to convey pellets in bulk, or containers of chips or pellets, on the rail network. Several freight trains have been retrofitted in the UK to increase their pellet carrying capacity. Capacities of around 1,000 tonnes.
- Truck_small_tipper_trailer. Typically carry 5-12 tonnes. Loaded by a front loader, unloads by hydraulically tipping their load out in bulk.
- Truck_tipper_trailer. As above, but typically carry 12-20 tonnes.
- Truck_walking_floor_trailer. Equipped with a live floor that hydraulically “walks” the load from the truck and allows one person to unload within 10 minutes. Usually carry up to 28 tonnes.
- Truck_flat_bed_trailer. These do not tip and are usually unloaded by driving a small frontend loader into the trailer, using ramps at the loading dock. Some US sites have hydraulic lifting pens that can tip the whole truck over sideways (if canvas sides), or upwards, flowing the biomass directly into bunkers. Usually carry up to 28 tonnes.



- **Truck_container_lorry.** This carries generic intermodal containers, which can also be carried by ship and rail. Unloaded as above for a flatbed truck, or by crane. Usually carry up to 28 tonnes.
- **Truck_log_crane_and_drag.** Articulated log truck with draw bar trailer, used in forestry operations to take whole trunks to aggregation centres. Usually carry 15-20 tonnes.
- **Truck_pellet_tanker.** Dedicated trucks that minimise fines, and have pneumatic conveying in/out of storage. Typically carry 7-15 tonnes.
- **Truck_liquid_tanker.** Similar to a diesel tanker, involving pumping hose and tank. Needs upgraded steel linings to deal with pyrolysis oil acidity. Not suitable for transport of solids. Can carry up to 30 tonnes.

The underlying equations for these models can be found in the Deliverable 2 Excel, in the Transport1, Transport2, Transport3, or Transport4 tabs. These tabs contain the same information, only relating to different possible locations of the transport step.

For the transport models that are not trucks, the dialog box is simplified, as can be seen in Figure 21.

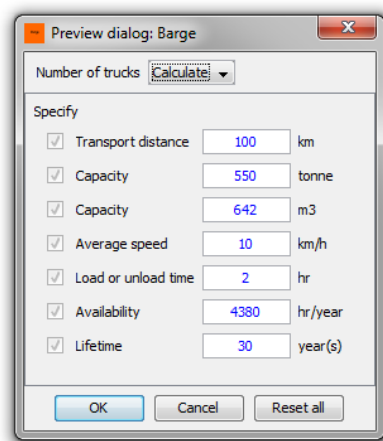


Figure 21: Dialog box for the Barge model

For the truck models, there are four tabs in the dialog box – “Configuration”, “Wages”, “CAPEX”, and “Non-fuel costs”.

In the “Configuration” tab, besides the specifications that can be seen in Figure 21, the user can also specify the truck fuel consumption. In the “Wages” tab, the user specifies the driver costs. In the “CAPEX” tab the truck costs are specified, and the “Non-fuel costs” contains the other operational costs (licenses and insurance, and tyres repairs and maintenance). These costs are not borne directly by the TEABPP chains, but rather used to calculate a likely lease hire cost for the transport step, and hence only shown as variable OPEX in the gPROMS results. The lease hire per tonne-km cost is calculated as the sum of the yearly cost of the capex (based on the depreciation period of the vehicle), fuel costs, non-fuel costs and wages, divided by the annual tonnage-km driven (which is based on the vehicle, capacity, trip distance, loading/unloading times and average speed).

2.3.6 TEABPP Sub-units

The sub-units library contains the following models:

- BFB_gasifier
- CCGT
- Collect_results
- Entrained_flow_gasifier
- Merge_syngas
- Sink_syngas
- Source_syngas
- Split_biomass
- Syngas_cleanup
- Syngas_engine

These models are not used in the Topology section to build the bioenergy chains, and consequently don't appear in the Palette. Instead, models such as BFB_gasifier, CCGT, Collect_results, Entrained_flow_gasifier, Syngas_cleanup, and Syngas_engine were used to build the composite flowsheeting models BFB_gasifier_and_engine and EF_gasifier_and_CCGT. The following models were only used for testing purposes - Merge_syngas, Sink_syngas, Source_syngas, and Split_biomass.

The models present in this library should not be used without further testing.

2.4 Model features

2.4.1 Connection types

In gPROMS, flowsheets can be built by connecting component models in the "Topology" tab.

Connections between different units in a flowsheet are associated with a connection type which defines the type of information conveyed by the connection. Five connection types were implemented in the TEABPP libraries:

- Biomass (brown)
- Heat (red)
- Power (green)
- Results (grey)
- Syngas (blue)

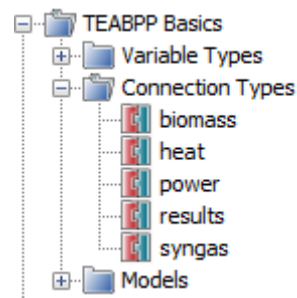


Figure 22: Connection types implemented for the TEABPP libraries

2.4.1.1 Biomass

The biomass connection type is used to link the source biomass model, pre-processing, transport, storage, and conversion units. This connection represents the biomass streams entering and leaving the units.

The biomass properties passed in this connection include the following:

Table 2: Variables in the biomass connection type

Variable	Unit	Description
LHV	GJ/wet tonne	Lower heating value
mass_flow	Wet tonne/year	Total biomass mass flow
density	Wet tonne/m ³	Biomass wet density
fuel_energy	MW	Total biomass energy available
energy_to_produce_1MWh_output	-	MWh of biomass energy required to produce 1MWh of the total output for the chain
composition	kg/kg	Elemental composition of the biomass (dry basis)
moisture_content	kg/kg	Moisture content of the biomass (wet basis)
particle_size	mm	Particle size
soil_stone_contamination	% (kg/kg)	Soil and stone contamination of the biomass (dry basis)
fuel_energy_MWh_per_year	MWh/year	Total biomass energy available
fraction_miscanthus	kg/kg	Fraction of Miscanthus in the biomass (wet basis)
fraction_SRCwillow	kg/kg	Fraction of SRC willow in the biomass (wet basis)
fraction_SRFconif	kg/kg	Fraction of SRF coniferous in the biomass (wet basis)
fraction_SRFdecid	kg/kg	Fraction of SRF deciduous in the biomass (wet basis)
fraction_other	kg/kg	Fraction of other feedstocks in the biomass (LRF pellets or when a custom feedstock is selected) (wet basis)

2.4.1.2 Heat

The heat connection type is used to represent the heat produced in the conversion models (only the Underfeed_stoker model produces heat as output). The heat connection passes the following results:

Table 3: Variables in the heat connection type

Variable	Unit	Description
output	MW	Total energy produced
energy_to_produce_1MWh_output	-	MWh of heat energy required to produce 1MWh of the total output for the chain

2.4.1.3 Power

The power connection type is used to represent the electric power produced in the conversion models. The power connection passes the following results:

Table 4: Variables in the heat connection type

Variable	Unit	Description
output	MW	Total energy produced
energy_to_produce_1MWh_output	-	MWh of electrical energy required to produce 1MWh of the total output for the chain

2.4.1.4 Results

The results connection type is used to link the unit models with the Reports_and_assumptions model. All pre-processing, conversion, transport, and storage models need to be connected with the Reports_and_assumptions model as the connection provides the main chain assumptions to the models and receives the results to be reported in the Reports_and_assumptions model.

The variables passed in this connection are the following:

Table 5: Variables in the results connection type

Variable	Unit	Description
CAPEX	£	Unit CAPEX
OPEX_variable	£/year	Unit variable OPEX
OPEX_fixed	£/year	Unit fixed OPEX
Feedstock	£/year	Cost of the feedstock (applicable only for the Source_biomass model)
Coproducts	£/year	Value of the Coproducts
LCOE_CAPEX	£/MWh	CAPEX fraction of the LCOE. Value per MWh of end vector produced energy
LCOE_OPEX_variable	£/MWh	Variable OPEX fraction of the LCOE. Value per MWh of end vector produced energy
LCOE_OPEX_fixed	£/MWh	Fixed OPEX fraction of the LCOE. Value per MWh of end vector produced energy
LCOE_Feedstock	£/MWh	Feedstock fraction of the LCOE. Value per MWh of end vector produced energy
LCOE_Coproducts	£/MWh	Coproducts fraction of the LCOE. Value per MWh of end vector produced energy
Emissions_inputs	tonne/year	Total emissions of the input materials or energy requirements to the unit (e.g. emissions of the pellet binder required in the pelleting unit)
Emissions_outputs	tonne/year	Total emissions of the output materials or energy requirements to the unit (e.g. emissions required for the treatment of waste water)

Variable	Unit	Description
Emissions_net	tonne/year	Total emissions from this unit
Emissions_feedstock	tonne/year	Total feedstock emissions (applicable only for the Source_biomass model)
energy_output	MW	Outlet biomass energy
mass_output	wet tonne/year	Outlet biomass flowrate
energy_inputs	MW	Total energy input to the unit (electricity, natural gas, diesel, and/or heavy oil)
energy_outputs	MW	Total energy output of the unit (electricity, heat)
coproducts_output	MW	Total energy of the co-products
number_trips_total	Number of trips/ MWh vector output	Total number of trips per MWh of energy produced (applicable only for the transport models)

2.4.1.5 Syngas

The syngas connection type is used to represent the syngas produced in conversion units such as the Entrained_flow_gasifier model. At the moment, only sub-models use this connection type, and this model is not used in any of the models present in the palette.

The syngas connection passes the following results:

Table 6: Variables in the syngas connection type

Variable	Unit	Description
fuel_energy	MW	Total energy of the syngas
energy_to_produce_1MWh_output	-	MWh of syngas energy required to produce 1MWh of the total output for the chain

2.4.2 Inlet property limits

The pre-processing and conversion technologies have some limitations regarding the minimum quality of the feedstock. Default values have been provided for all models; however these values can be changed in the user interface.

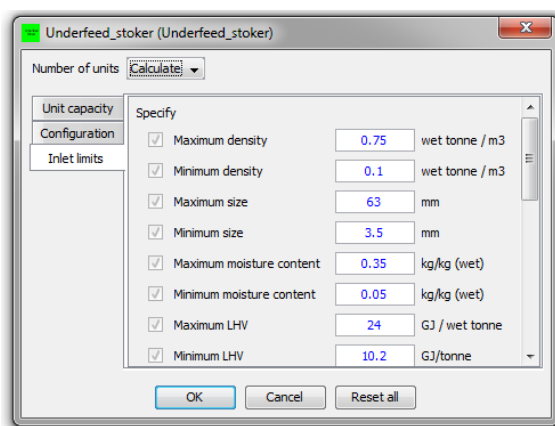


Figure 23: Inlet limits for the feedstock fed to the underfeed_stoker model

If these limits are exceeded (or the min or max scale limits are exceeded) the simulation still runs and provides the results. However, in the case file, the icon of the model will display a red exclamation point in the top right corner (Figure 24) to warn the user of the violation. Analysing the model report will show the biomass property over/under its bound, as well as the bound's value (Figure 25).

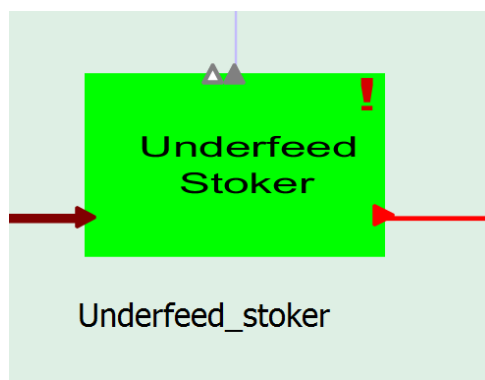


Figure 24: Underfeed_stoker model with the red exclamation point on the right hand corner. This means one of the inlet feedstock limits has been violated

Warning

Inlet ash content above maximum limit.

	Value at time 0.00000	Units
Composition	0.0140390	kg/kg (dry)
Maximum ash content	0.0120000	kg/kg (dry)

Figure 25: Warning in the report tab of the underfeed_stoker model. Inlet feedstock ash content is greater than the maximum allowed (1.2%)

2.4.3 Key model calculations

The main calculations of the TEABPP libraries for a bioenergy chain are the cost calculations, GHG emissions, and the chain efficiency.

2.4.3.1 Cost calculations

For the cost calculations, the model calculates the CAPEX, variable OPEX, and fixed OPEX. They are calculated for each unit and afterwards the LCOE for each chain is also calculated. These are calculated based on the formulas present in the Deliverable 2 Excel spreadsheet.

The total CAPEX is the sum of the installation cost, operations and utilities, civils and land, project development, and contingency. The installation cost is typically calculated with the following equation:

$$\text{Installation cost} = \text{Multiplier} \times \text{Capacity}^{\text{scaling factor}}$$

Where the capacity for the unit is either the inlet capacity (inlet mass flow, inlet energy) or the outlet capacity (outlet mass flow, outlet energy). The other CAPEX items comprising the total

investment cost (such as utilities, civils & land, project development and contingency) are based on fractions of the installation cost.

The total fixed OPEX is the sum of the insurance, parts maintenance, and labour maintenance costs. The insurance and parts maintenance costs are calculated based on the CAPEX costs.

The variable OPEX is different for each technology and is usually calculated based on some pricing multipliers and the inputs required for each technology (e.g. the pellet binder for the pelleting units). There are also labour operation costs which are based on multiplying the unit's capacity by availability and a multiplier.

The CAPEX (£), fixed OPEX (£/yr) and variable OPEX (£/yr) are calculated for an individual unit and for the necessary number of units (Chain contribution CAPEX and OPEX). For further explanation these calculations are available in the Deliverable 2 Excel 'Results' tab.

The levelised cost of energy (LCOE) in £/MWh output is calculated for each unit using the OPEX components and the unit availability, added to the levelised CAPEX (calculated using the unit lifetime, discount rate and availability). This LCOE result for each unit is then multiplied by the MWh component/MWh end vector to give the chain contribution of that unit (£/MWh end vector). There is therefore no whole chain lifetime assumption, since storage buffers make this irrelevant (the pre-processing plant and conversion plant can operate independently, at different availabilities, and hence are costed separately).

Within the Reports_and_assumptions module, the total chain LCOE (£/MWh end vector) is then calculated by adding all the chain contributions, plus the feedstock cost (converted to £/MWh end vector).

It is important to note that efficiency values (MWh component/MWh end vector) include the feedstock blending fractions, otherwise it would be breaking the laws of physics to say that e.g. 0.18 MWh of Miscanthus produces 1.00 MWh heat. Similarly, the LCOE chain contribution (in £/MWh end vector) includes blending fraction multipliers, so values for e.g. the Miscanthus storage step might be much smaller than you would expect for a 100% Miscanthus chain, but this is because Miscanthus only comprises 15% of the total feedstock used, and hence this component cost is the contribution of the Miscanthus share to the overall LCOE.

2.4.3.2 GHG emissions

The calculations of the greenhouse gas (GHG) emissions performed in the model are related to CO₂ equivalent (CO₂e) only. The conversions used for non-CO₂ species are in Table 7 – these use 100 year global warming potential factors from the IPCC^{3,4}.

Table 7: Global warming potential for different greenhouse gases

Component	GWP (kg CO ₂ e/kg)
CO	1.9
CH ₄	25

³ IPCC, "IPCC Fourth Assessment Report: Climate Change," 2007. Available at: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-3-2.html. [Accessed 12 October 2016]

⁴ IPCC, "Working group I contribution to the IPCC fifth assessment report: The physical science basis," 7 June 2013. Available at: www.climatechange2013.org/images/uploads/WGIAR5_WGI-12Doc2b_FinalDraft_All.pdf. [Accessed 12 October 2016]

Component	GWP (kg CO ₂ e/kg)
N ₂ O	298

This approach means the emissions of specific species (such as CO₂, CO, CH₄, N₂O, PM) from the conversion and pre-processing units are not being explicitly modelled. They will however be within legal limits, due to the use of urea and lime if required, plus the technology feedstock limits being obeyed (with warning flags raised if not – e.g. biomass that is too wet for the boiler design to handle can lead to higher PM due to incomplete burn-out). Note that no biogenic emissions of CO₂ from feedstock (or syngas) combustion are included in the final emissions, as these are assumed to be net neutral (drawn down by the biomass when growing).

In the model, beside the feedstock cultivation and harvesting GHG emissions, there is also a calculation for the input and output emissions along the chain. These correspond to the plant inputs and outputs, where the input emissions are the emissions of different material and energy inputs for the different biomass units (e.g. the emissions of the transport fuel and electricity or the emissions related to the production of the pellet binder used in the pelleting unit) and the output emissions relate to the outputs of the different units (e.g. the emissions required for the treatment of waste water, or disposing of ash). There is also no sale of the end vector, which means there will not be any GHG credit from the end vector. Input and output emissions are handled at the unit level (kgCO₂e/MWh output), with the emissions for each unit then multiplied by the MWh component/MWh end vector to give the chain contribution of that unit (kgCO₂e/MWh end vector).

Within the Reports_and_assumptions module, the net chain GHG emissions (kgCO₂e/MWh end vector) are then calculated by adding all the chain contributions, plus the feedstock GHG emissions:

$$\text{Net emissions (tonne/year)} = \text{Feedstock emissions} + \text{Input emissions} + \text{Output emissions}$$

This calculation is used to then calculate the total emission per vector output (kgCO₂e/MWh end vector).

2.4.3.3 Chain efficiency

The chain efficiency is calculated in the Reports_and_assumptions model. There are two efficiencies calculated, the gross chain efficiency and the net chain efficiency.

The gross chain efficiency is the total energy produced (the end vector production plus the energy produced from any coproducts) divided by the total feedstock energy:

$$\text{Gross chain efficiency (\%)} = \frac{\text{MWh end vector} + \text{MWh coproducts}}{\text{MWh feedstock}}$$

The net chain efficiency is defined similarly, however the other energy required for the different chain units (e.g. transport fuel, electricity required for chemical washing) is also accounted for:

$$\text{Net chain efficiency (\%)} = \frac{\text{MWh end vector} + \text{MWh coproducts} - \text{MWh other inputs}}{\text{MWh feedstock}}$$

2.5 Develop or modify a chain

The TEABPP libraries include a project file with 10 previously built chains.

This section explains how a user can build a bioenergy chain like the pre-configured chains using gPROMS drag-and-drop functionality and how to remove, add, or switch different technologies. A discussion is provided on how to add or remove different feedstocks using the blending model as well as modifying technology and feedstock parameters. Further information on blending can also be found in sections 3.3 and 3.4.

2.5.1 Connecting library models

The different library models can be connected by its ports. The ports are associated to one of the connection types (more information on the connections types of the TEABPP libraries is provided in section 2.4.1).

The model ports can be inlet or outlet ports. An outlet port can only be connected to an inlet port from the same connection type (Figure 26 and Figure 27).

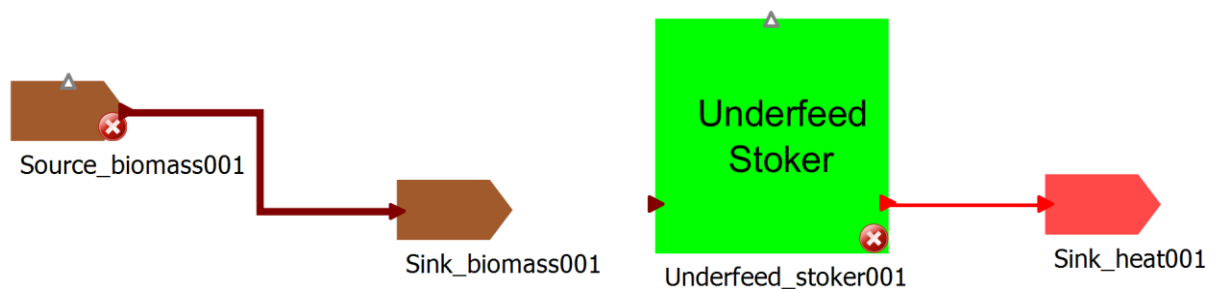


Figure 26: Examples of how to link models through the ports

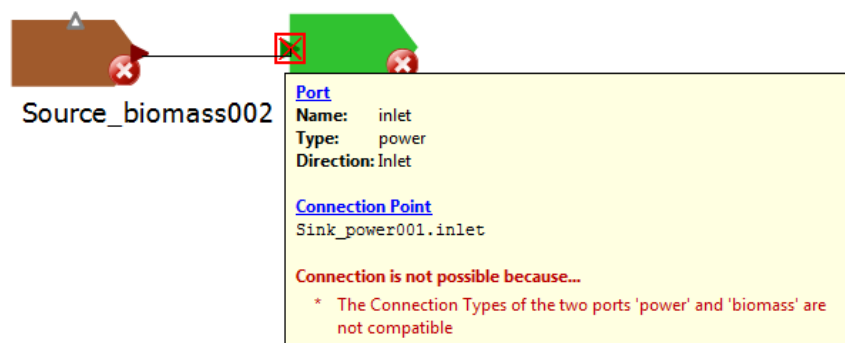


Figure 27: Error message while trying to connect two incompatible ports (Source_biomass' biomass port and Sink_power's power port)

2.5.2 Creating a bioenergy chain

Creating a bioenergy chain starts with creating a new model on a project file (Figure 28). The user can then add the units which make up the bioenergy chain using the drag-and-drop functionality from the palette (Figure 29).

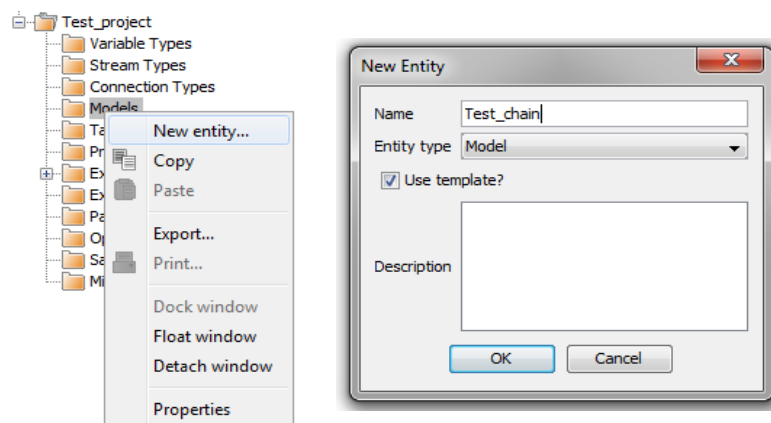


Figure 28: Creating a new model chain

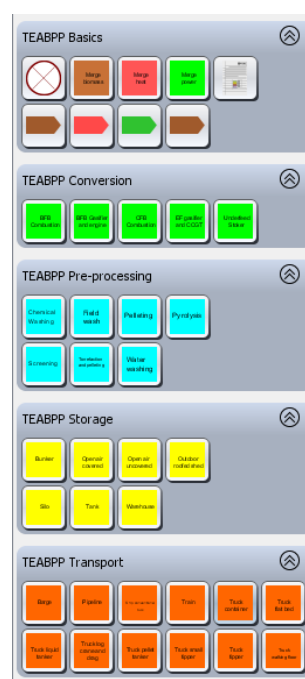


Figure 29: Palette with the TEABPP libraries open

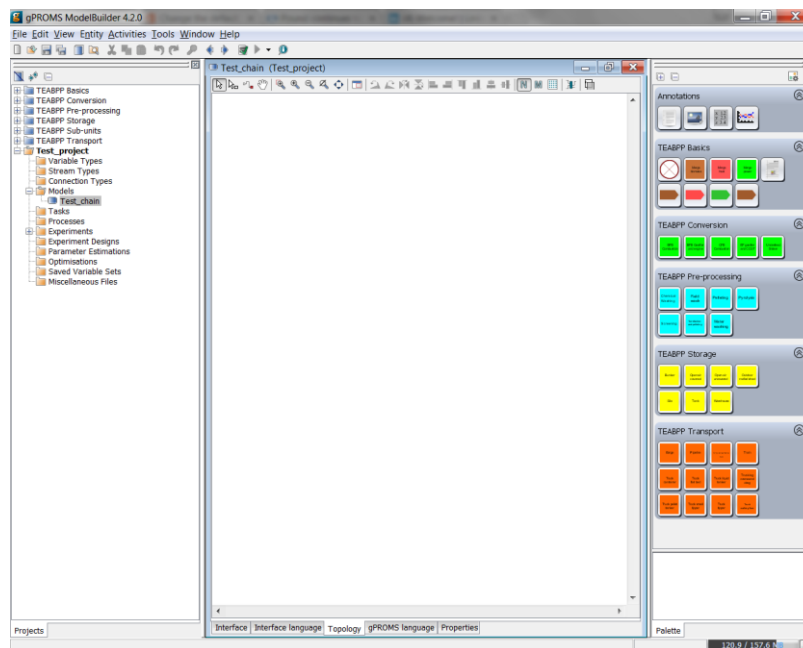


Figure 30: New chain model showing the Topology window

Firstly, a Reports_and_assumptions model is required. All models (except for the Sink model) have to be connected to the Reports_and_assumptions model via the grey port at the top of each model icon. Drag and drop the Reports_and_assumptions model into the Topology window (accessed by clicking the Topology tab of the new model as shown in Figure 30). Double-clicking the Reports_and_assumptions icon in the Topology tab opens a dialog box where the user can specify the global model parameters.

After the Reports_and_assumptions model has been fully specified, a feedstock should be defined using a Source_biomass model. When these models are first dragged from the palette to the Topology window, an error message appears stating that the relevant ports need to be connected (Figure 31). On the bottom of the Topology window the user can see a "Description" of these errors.

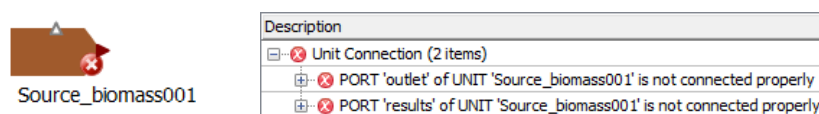


Figure 31: Source_biomass errors because the model is not connected

Next, the name of the models can be changed to a more descriptive one (for example, changing the "Source_biomass001" model to the corresponding name of the feedstock used). To do this, right click the model icon and select the "Rename" option.

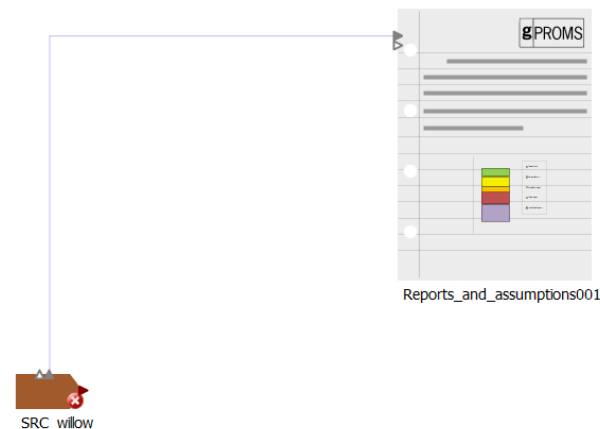


Figure 32: Topology view of the chain in progress. The name of the Source_biomass model has been changed to SRC_willow

The user can then add the other units required to finish the chain. A sample chain is presented in Figure 33, where the Source_biomass model is connected to an open air storage (Open_air_uncovered model) which is then linked to a transportation model (Truck_small_tipper), a pelleting plant, a walking floor truck (Truck_walking_floor), an entrained flow gasifier coupled with a CCGT unit (EF_gasifier_and_CCGT) and finally a Sink_power model. As it can be seen in the figure, all models (except sink power) are connected to the Reports_and_assumptions model.

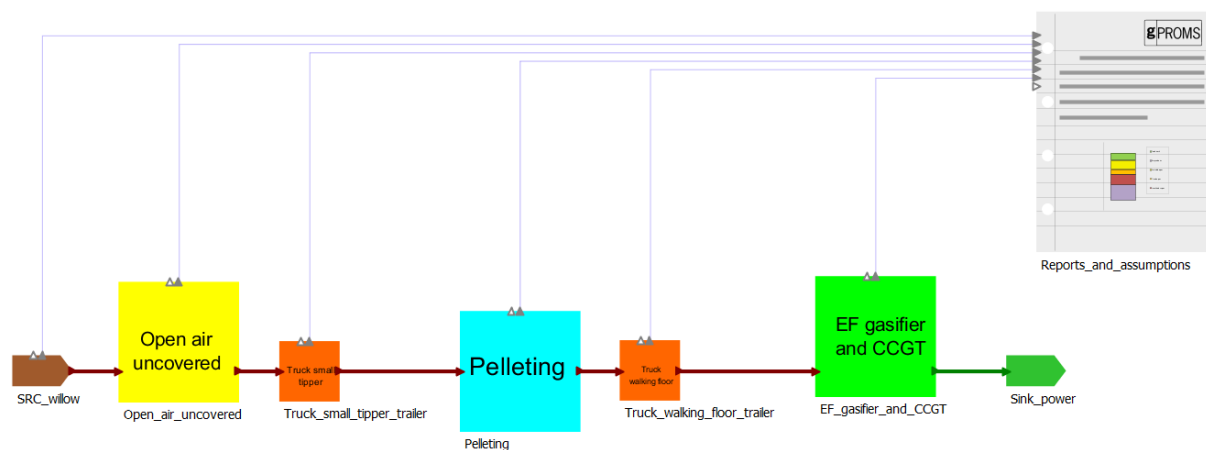


Figure 33: Sample chain

After the bioenergy chain model is finished, a process entity must be created in the project file in order to run the model. This can be done by right-clicking the model and choosing the “Edit PROCESS” option.

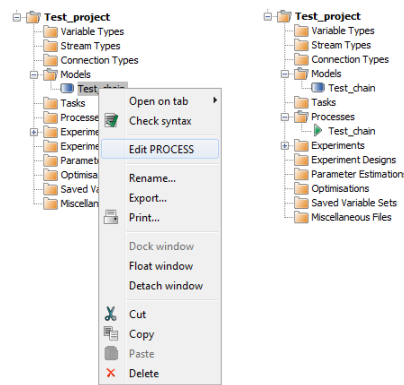


Figure 34: Dialog box to Edit a PROCESS (left) and the created PROCESS entity (right)

2.5.3 Scale of chain

Before running the simulation for the bioenergy chain, the chain size has to be specified. This can be done in three different (and mutually exclusive) ways:

- Specifying the biomass mass flowrate/biomass input fuel energy in the Source_biomass model
- Specifying the energy output in the Sink model used (Sink_biomass, Sink_heat, or Sink_power models)
- Specifying the number of units of a model

If the biomass flowrate or fuel energy is specified, the energy end vector produced is calculated based on the different units' efficiency and should not be specified. In addition, the number of units is calculated based on the inlet biomass flowrate and the unit capacity, therefore the number of units should not be specified either.

If the user specifies the produced output energy in the sink model, the biomass flowrate and the number of units should not be specified. The number of units is calculated based on the unit capacity, and the biomass flowrate will be the required amount of biomass feedstock to produce the specified amount of energy.

Finally, the number of units of a certain technology can be specified. It should be noted that for a chain, only one technology should have the number of units specified. The biomass flowrate and the produced energy are then calculated based on the scale of the unit that was specified in the dialog box (the capacity of the unit will be the specified capacity, and in this case the minimum and maximum limits will not be used in the calculations).

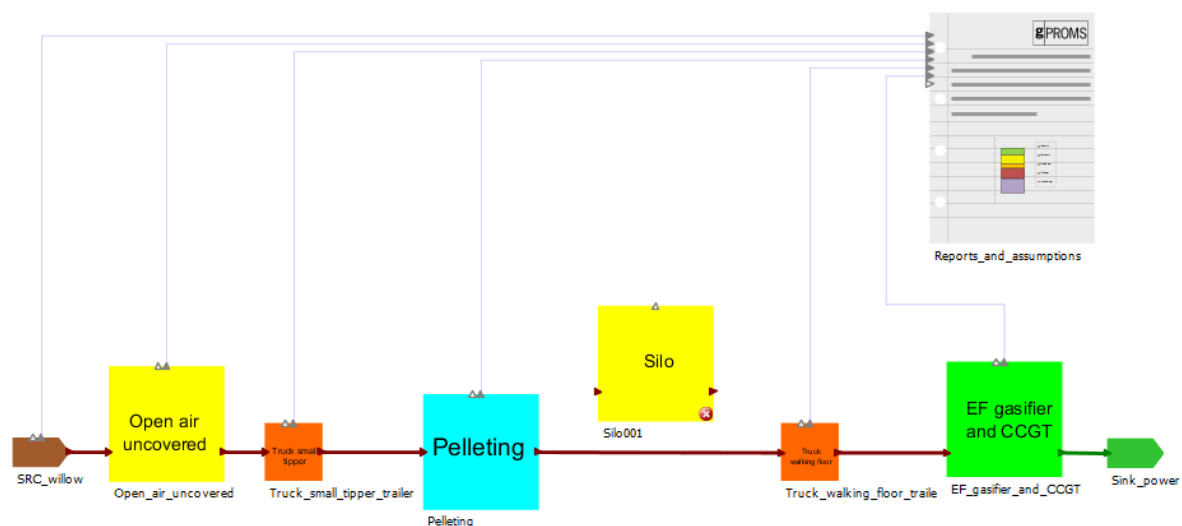
In summary, the following calculation options are available:

Table 8: Calculation options of the biomass chains

Calculation options	Biomass feed flowrate	Scale of unit	Number of units	Output vector
1	Specified	An estimate is specified. An exact value is calculated within the min and max limits. This value is estimated to ensure the number of units is an integer. The number of units is rounded to the nearest integer	Calculated	Calculated
2	Calculated	An estimate is specified. An exact value is calculated within the min and max limits. This value is estimated to ensure the number of units is an integer. The number of units is rounded to the nearest integer	Calculated	Specified
3	Calculated	Specified	Specified	Calculated

2.5.4 Adding extra units

Even after the flowsheet is complete, the user can always add or remove extra units, such as extra transport and/or storage steps. Looking at the chain developed in Figure 33, for example, the user might want to add a storage unit after the pelleting unit. In order to do this, the user simply has to drag the intended storage model (in this example, the Silo unit) from the Palette (Figure 35).

**Figure 35: Adding a silo unit to the previous model**

After adding the model, the user needs to delete the connection where the new unit should be placed (in this case, the connection between the Pelleting model and the Truck_walking_floor model) and add the proper connections to the new model (the user should also remember to always add a new model to the Reports_and_assumptions model). The updated chain is shown in Figure 36:

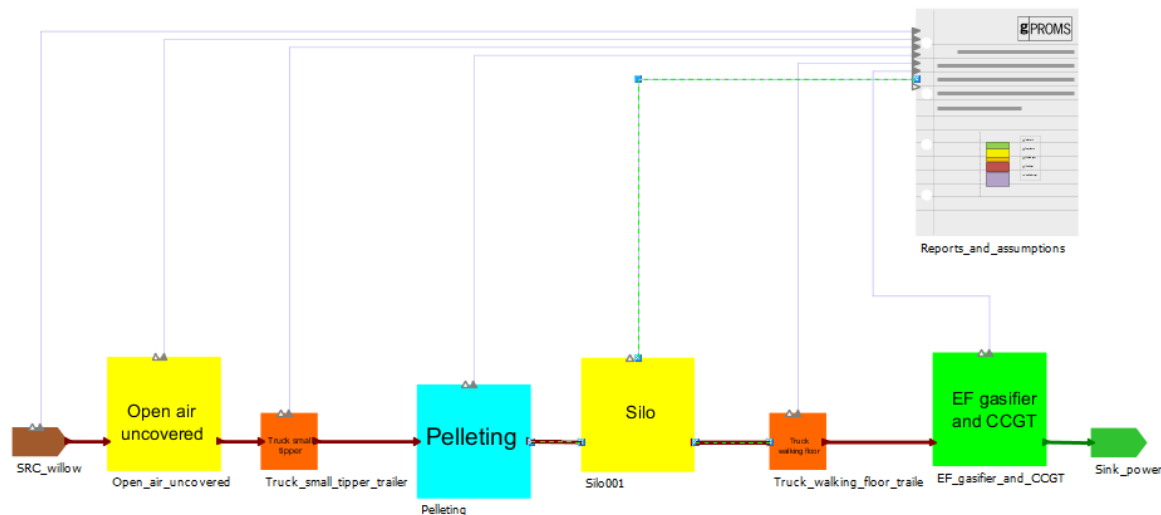


Figure 36: Updated bioenergy chain

2.5.5 Modify technology parameters

Different technology parameters can be specified by double-clicking the different models and making changes in the dialog box. Global assumptions (assumptions made throughout the chain), for example the discount rate, can be modified in the Reports_and_assumptions module.

An example showing changing a unit's specification is shown on Figure 37, where the outlet mass flow was changed from the default value of 14.29 wet tonnes per hour to 12 wet tonnes per hour. It should be noted that default values in gPROMS' dialogue boxes are given in blue, and when modified they change to a black colour.

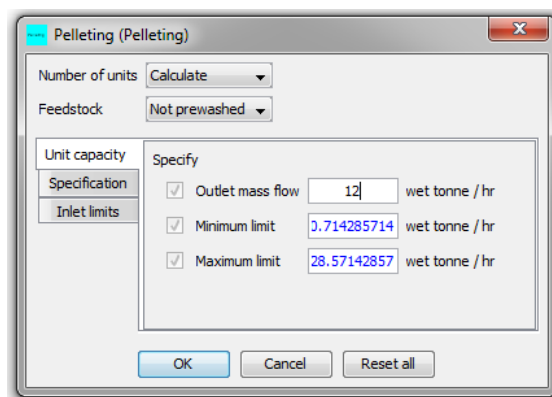


Figure 37: Example of changing the pelleting unit outlet mass flow

2.5.6 Switch between technologies

A technology can be changed by deleting the previous technology and adding the new unit using the drag-and-drop functionality, and correctly linking the new model (see Figure 39). When a technology is deleted from a chain, the user may be asked to renumber connections endpoints, due to the removal of other connections. The user should choose the "Renumber" option, as seen in Figure 38.

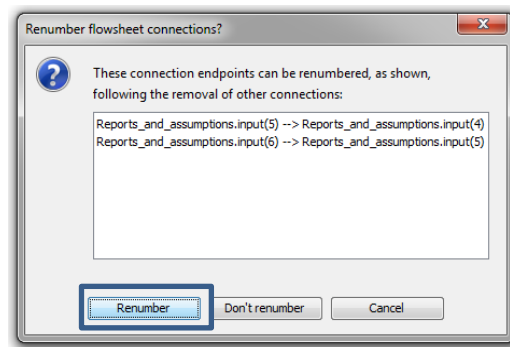


Figure 38: Dialog box to renumber the connections

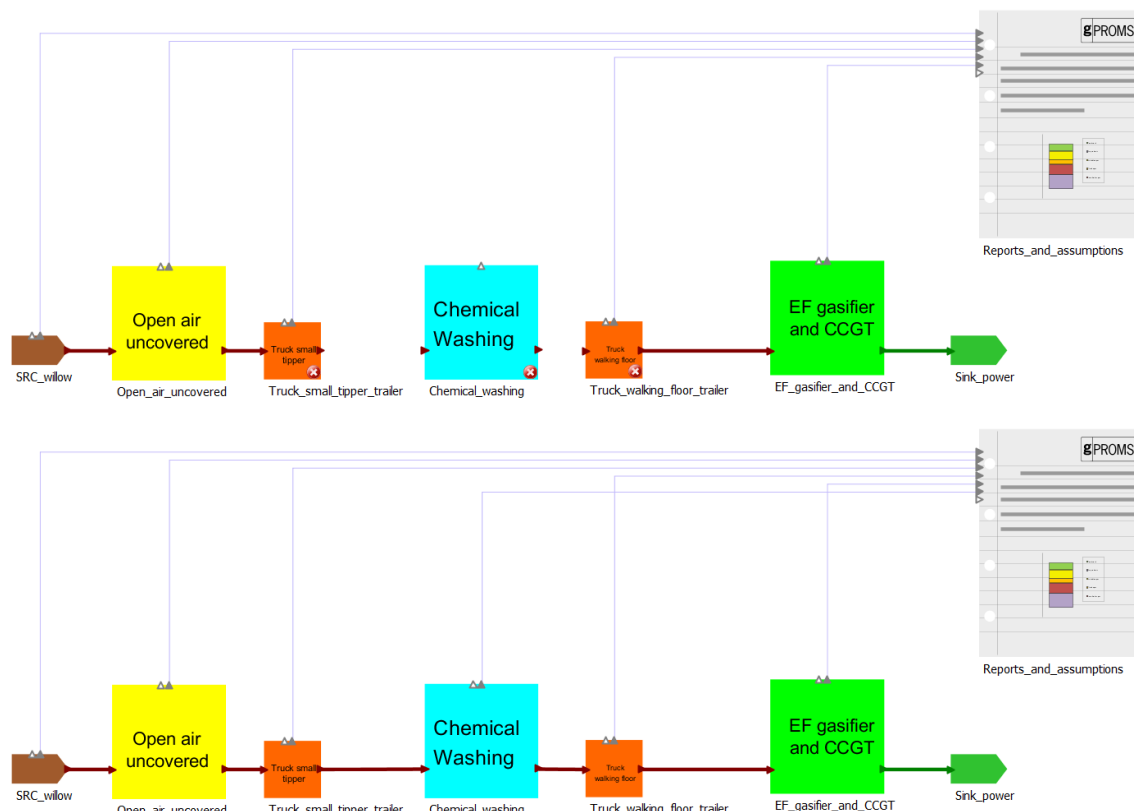


Figure 39: Changing the pre-processing unit. Deleting the Pelletting unit and adding the Chemical_Washing unit

Alternatively, the user can right-click on the model they wish to change, and select the “change MODEL...” option. The user can then choose a model with the same port structure (same inlet and outlet connections) to substitute the previous model (Figure 40, Figure 41 and Figure 42).

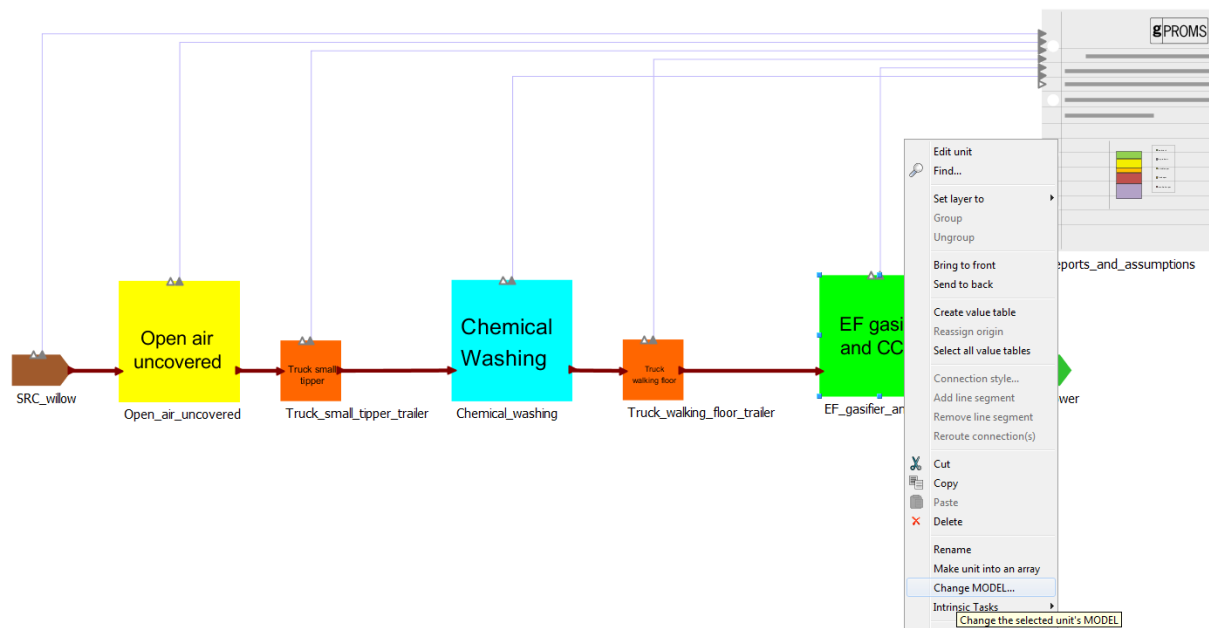


Figure 40: Changing EF_gasifier_and_CCGT model to CFB_combustion through the "Change MODEL..." option

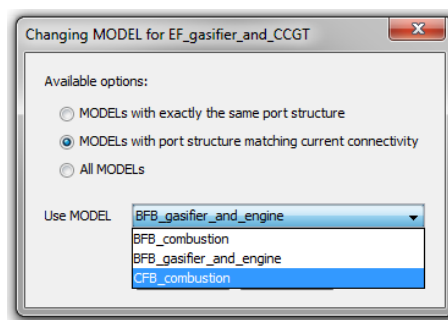


Figure 41: Changing EF_gasifier_and_CCGT model to CFB_combustion. List of MODELS with the same port structure

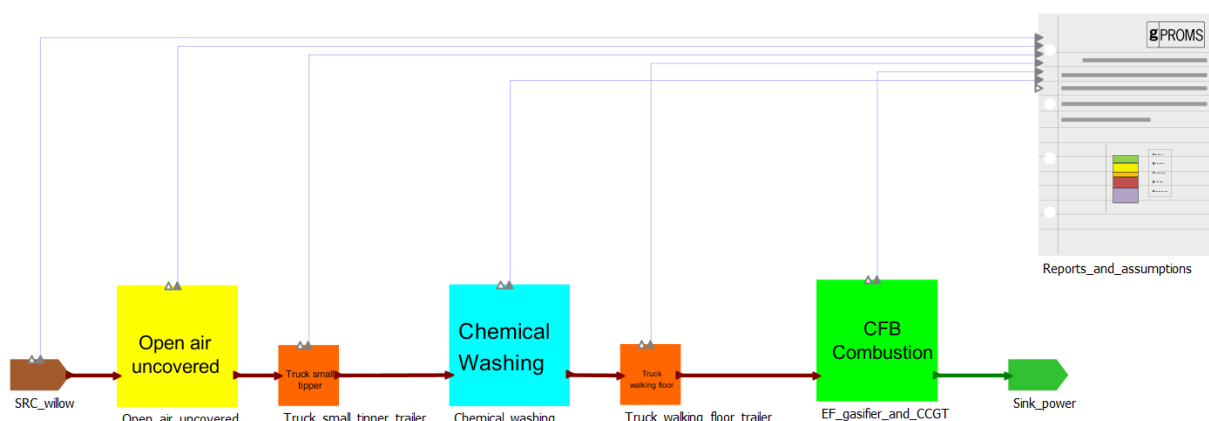


Figure 42: Changing EF_gasifier_and_CCGT model to CFB_combustion. Test_chain with the new conversion model

2.5.7 Blend two feedstocks

Different feedstocks can be blended using the Blending model. The user can add the model at any point in the chain (before the pre-processing unit or before the conversion unit, for example) and simply add and connect the new feedstock and any other units downstream. An example of adding feedstocks is seen in Figure 43, where a Miscanthus and SRF coniferous feedstocks have been added.

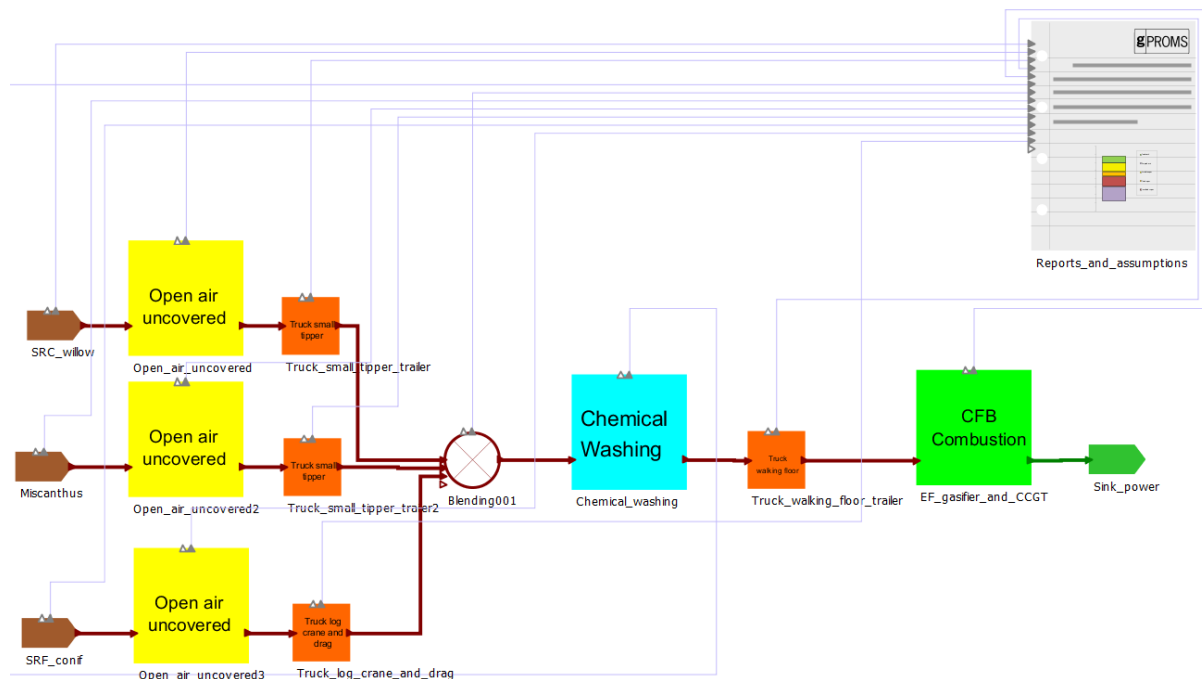


Figure 43: Test_chain with the added feedstocks, storage, and transport units

After adding a new feedstock, the user must also add an extra input:

- If the user specified the biomass flowrate/fuel energy, the user must either specify the other feedstocks' flowrate/fuel energy or the blending fractions (specified in the Blending model)
- If the user specified the energy output in the sink model, the user must specify the blending fractions
- If the user specified the number of units of a certain technology, the user must specify the blending fractions

The model with the provided information will then calculate the remaining biomass flowrates and/or the amount of energy produced in the chain.

2.5.8 Remove a feedstock

To remove a feedstock, firstly the user needs to delete the models pertaining to that feedstock. As stated in Section 2.5.6, the user will be asked whether the streams should be renumbered or not. Select the option to renumber.

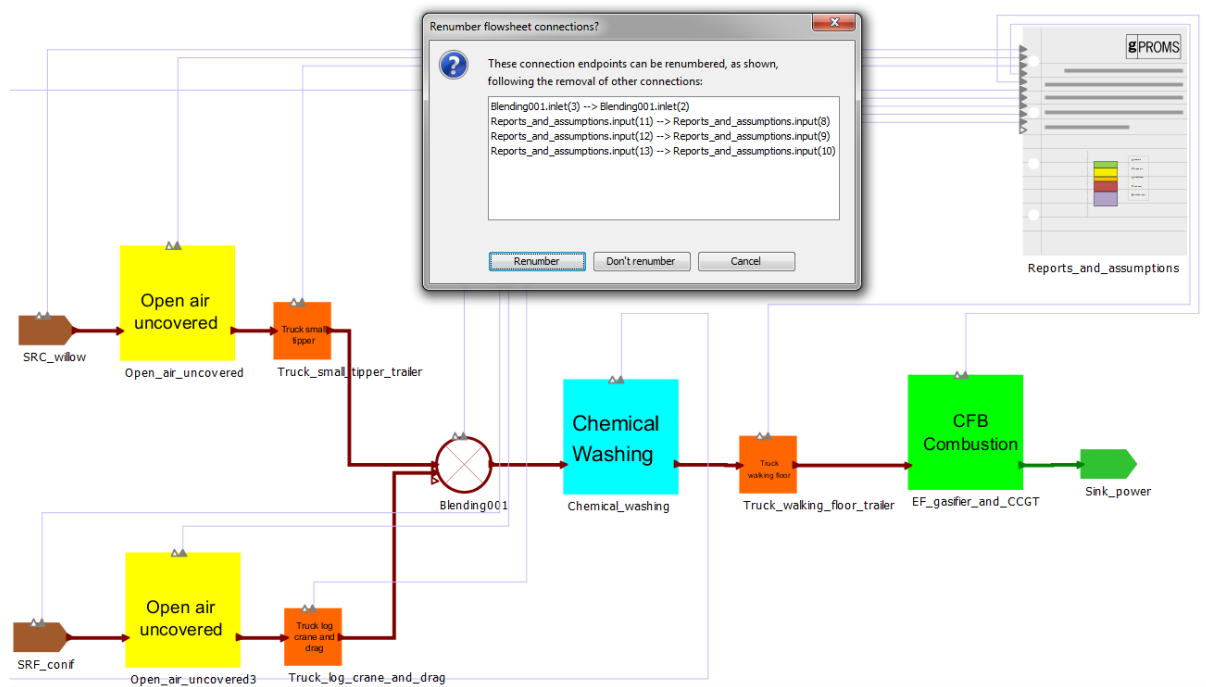


Figure 44: Removing the Miscanthus feedstock. Model requires renumbering the connection endpoints

If the split fractions were specified in a blending unit downstream, they will have to be modified – there will be an out of range split fraction specification that will have to be removed. This is illustrated in Figure 45 highlighted with the red box. Right-click that specification and select “Clear cells” or “Clear all out of range values”.

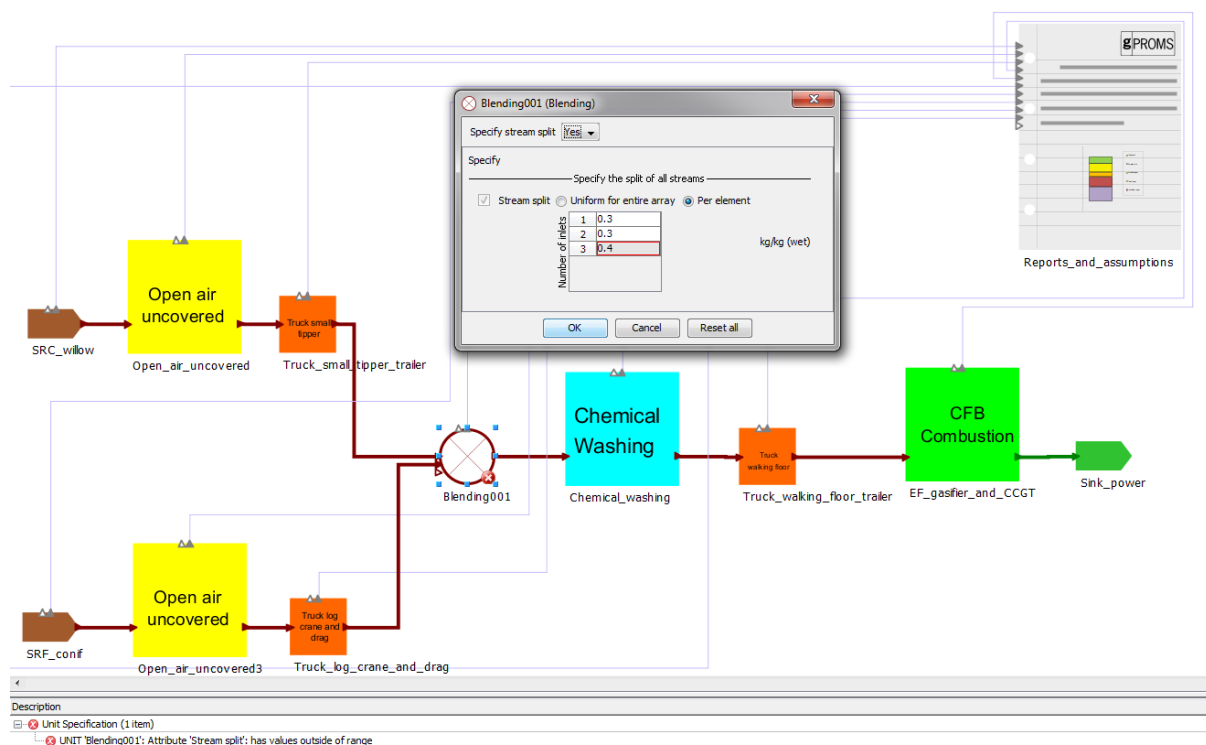


Figure 45: Error message in the blending model

2.5.9 Create and save a new feedstock

A new feedstock can be added by selecting the “Other” option in the “Feedstock” menu, as explained in Section 2.3.1, in the section related to the Source_biomass model. The user then has to populate all of the feedstock properties:

- Feedstock form
- Density
- LHV
- Price
- Particle size
- CO₂e emissions
- Moisture content
- Composition (elementary)
- Stone and soil contamination

The user can afterwards use this feedstock as they would use the pre-configured feedstocks.

After a new feedstock is created, the model instance on the flowsheet can be used in different chains simply by copying and pasting the Source_biomass model from one chain model to the other. When saving a chain with a custom feedstock, the feedstock’s properties will be saved and can be recovered simply by loading the chain model to gPROMS. The custom feedstocks’ properties are only stored on the particular instance of the Source_biomass model, and not on the TEABPP Basics library. Consequently, caution should be exercised in changing these custom feedstock properties, as they cannot be restored. This will mean a custom feedstock is only available at the flowsheet level, where the user selects its different characteristics and those will be specific only for that instance of the model. The user can then duplicate this by copying the model or by selecting the custom option in another instance and giving it the same values.

2.5.10 Modify feedstock parameters

The parameters for the pre-defined feedstocks are hard-coded in the model and cannot be directly modified. To change these parameters, the user should select the “Other” option in the “Feedstock” menu and manually fill out the all the fields with the desired properties.

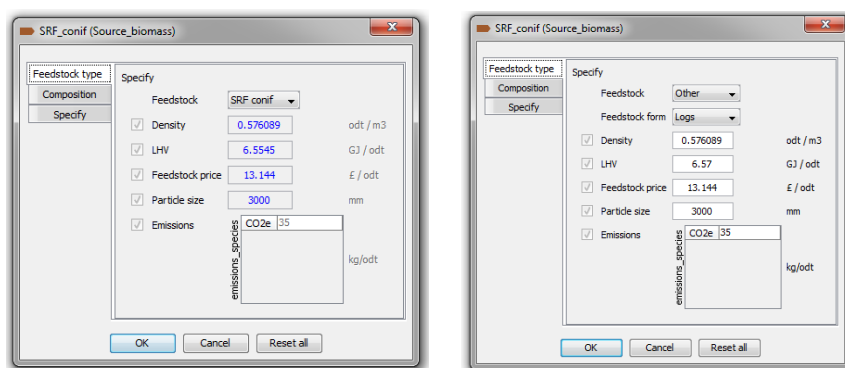


Figure 46: SRF coniferous feedstock (left) and a custom SRF coniferous feedstock with lowered LHV (right)

2.5.11 Incorporate proxy for redundancy

Adding redundancy is currently not available in the TEABPP model. Currently, relations between the number of units, total biomass and output vector have been provided. The number of units is calculated based on the scale of the unit and the total biomass. Thus, adding more units to simulate the costs of redundancy is currently not possible.

To add a proxy for redundancy, the user can increase the value of the CAPEX and OPEX multipliers. This will increase the cost of the technologies, simulating the addition of more units to each particular technology while maintaining the same availability and unit scale.

2.5.12 Reset chain back to original parameters/reload chain

When modifications have been made to a chain, if the flowsheet is not saved (if the project file appears in **bold font**), all modifications made can be reversed by right-clicking on the project and selecting the option “Revert to saved” (Figure 47).

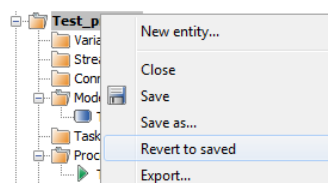


Figure 47: “Revert to saved” option to revert changes in a project file

If changes are made to a project file and saved, it is no longer possible to revert to the previous saved version as described above. It may be possible to use the “Undo” and “Redo” buttons to revert back to a previous state. It is, therefore, recommended for the user to always save a copy of the project file or at least create a duplicate the bioenergy chain flowsheet model (by selecting it on the project tree, copying it to clipboard and pasting it in the same or another project file. Copying and pasting a flowsheet model in the same project file creates duplicates which have numerated suffixes.

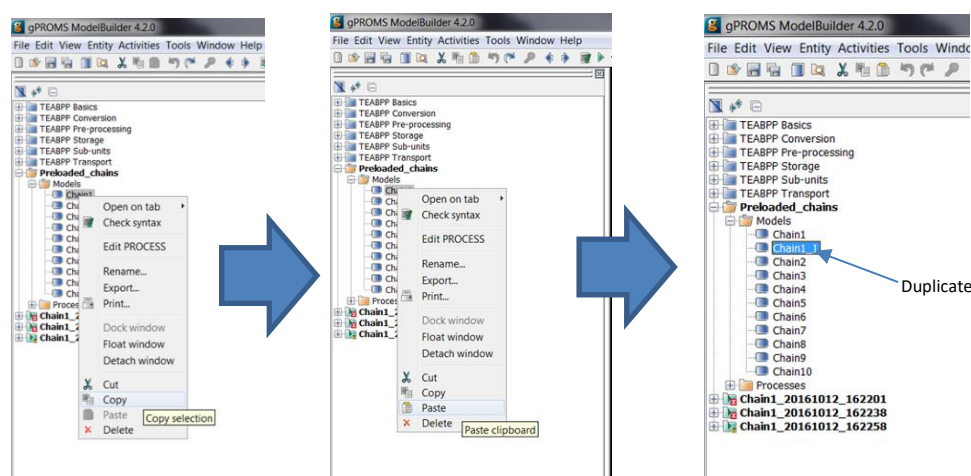


Figure 48: Creating a duplicate flowsheet model

2.6 Results

Once you have run a successful simulation, there are several ways of reviewing results.

For details on how to review the results, please refer to the gCCS Documentation. Click the Help menu and then select “Documentation” – this opens a new window. In the “Contents” area, click “gCCS Guide”, select “Viewing results”. For instance, selecting “Inspecting results for an individual variable” provides information on how to view variable results within the Cases themselves. There are also descriptions on “Viewing model reports”.

This document provides descriptions of the model reports developed in this project towards providing the user a convenient means of reviewing results.

Figure 49 shows a gCCS window after a successful bioenergy chain simulation. The case file on the Project tree is indicated. This file is generated for each simulation and contains all the results generated. In the centre of the window, the Topology window has a green background (as opposed to a white background when setting up the chains before Execution), and the model icons in the flowsheet can be double-clicked to view its model reports.

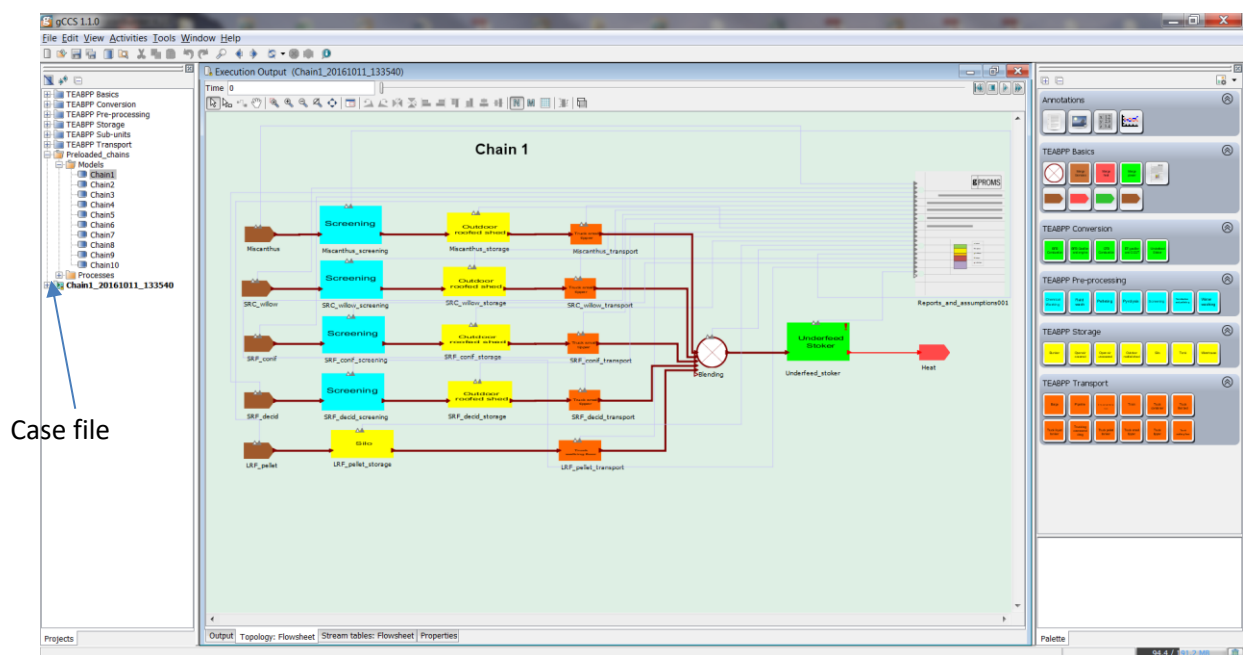


Figure 49: View of application window after successful simulation

2.6.1 Module results

Technical and economic results can be found for each unit, as well as inlet and outlet stream properties (Figure 50). The levelised cost of electricity (LCOE) of the whole chain is shown in two graphs in the “Topology” tab of the Reports_and_assumptions model report (Figure 51), and further results of the whole chain are available in the “Reports” tab.

In Figure 51, the chart on the left contains the net total chain LCOE (black dot) broken down into feedstock costs, variable and fixed OPEX, CAPEX, plus any co-product revenues. The chart on the right has the same breakdown of LCOE, but for each stage of the bioenergy chain. Rather than

having 3-15 different transport and storage steps for the various chain branches/different feedstocks, all the storage module costs are combined within storage, and all transport costs are combined within transport. If required, the results are split into much more detail by component in the Reports tabs, or else by clicking on the individual modules in the chain. Note that transport costs are all variable OPEX (i.e. a hired vehicle fleet, not bought and operated). This is explained in further detail in section 2.3.5.

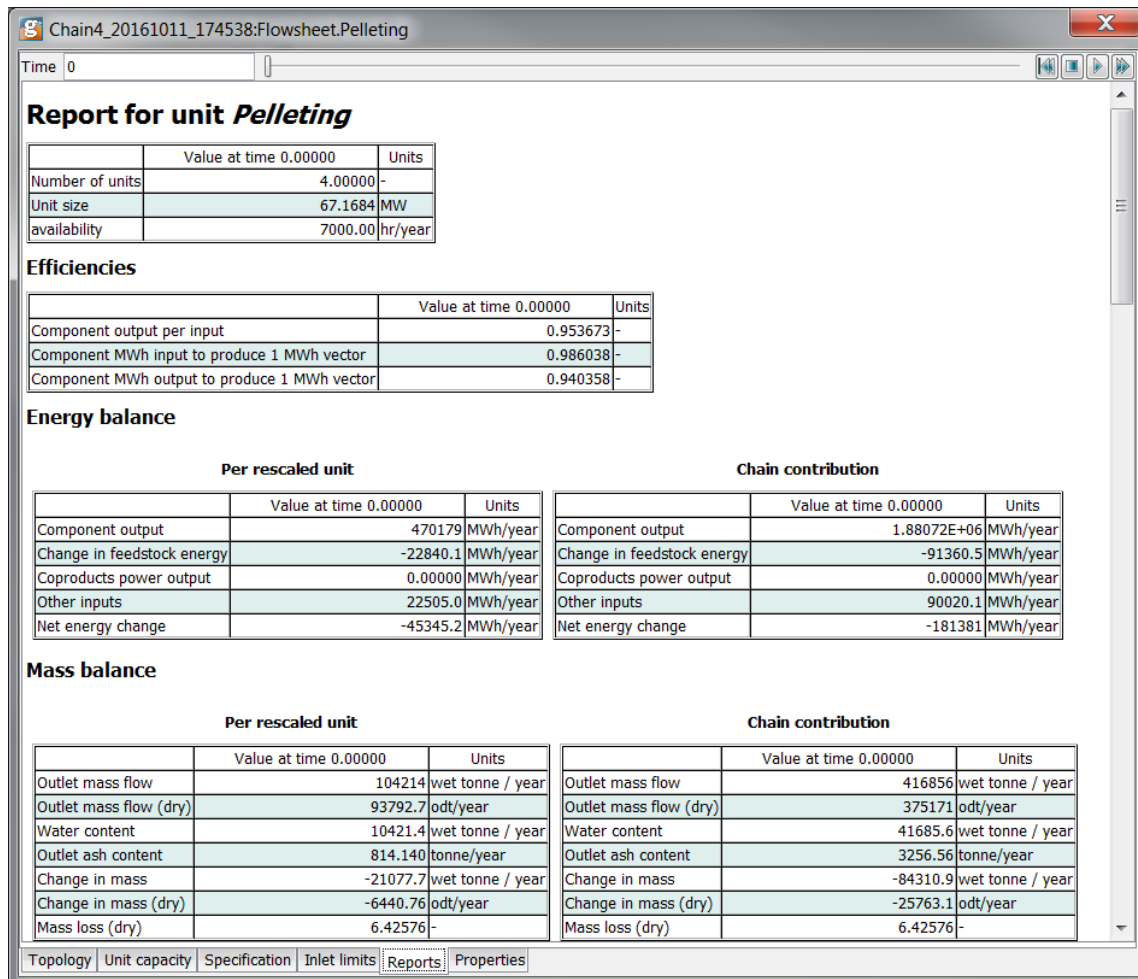


Figure 50: Model report of the Pelleting model

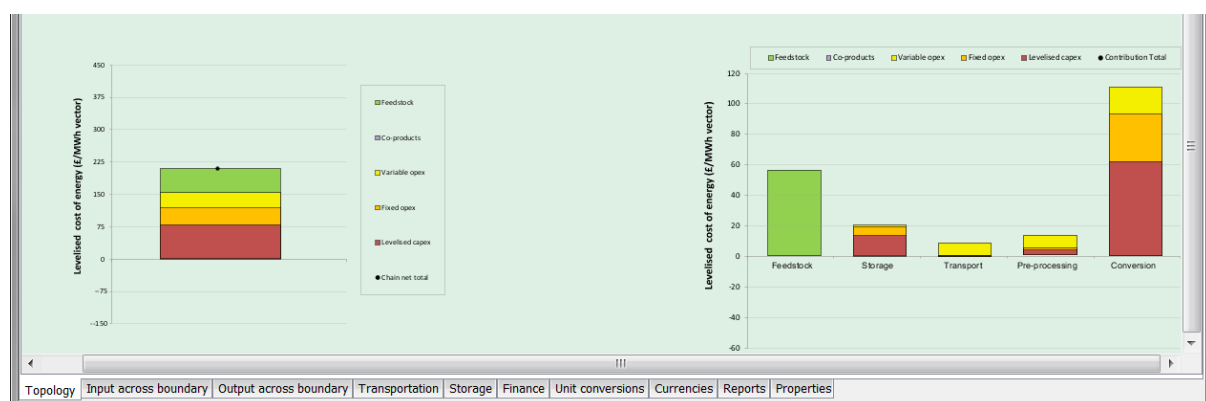


Figure 51: LCOE of the whole chain (left) and broken down into chain stages (right)

2.6.2 Warning flag when parameter value outside range

If there is a violation of an inlet property limit, a warning flag is displayed on the model icon in the Results flowsheet. In addition, on double-clicking the model review, the user can review what limits were violated. The warning messages have headings with red text. This is shown in Figure 52.

This warning also appears when the biomass flow or output energy vector production or number of units is set too low or too high (see section 2.4.2), and the technology unit scale required therefore lies outside of the permissible minimum or maximum values. The biomass flow, vector production or number of units should be adjusted to get the unit scale within allowable bounds.

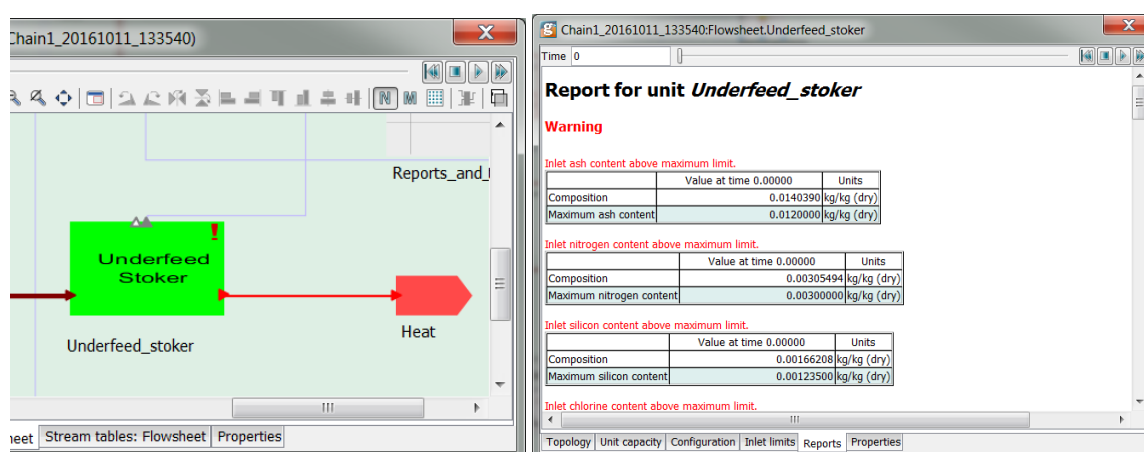


Figure 52: Underfeed_stoker model icon with a warning flag (left); model report with warning messages (right)

2.6.3 Save and print results

To save the results, right click the Case file shown in Figure 49 and select “Save” or “Save as...”. For details on how to print results, please refer to the gCCS Documentation. Click the Help menu and then select “Documentation” – this opens a new window. In the “Contents” area, click “gCCS Guide”, select “Miscellaneous Utilities” and then “Printing”. Under the “Miscellaneous Utilities” heading, there are discussions about “Exporting Data to CSV files”.

To export pdf reports, open the relevant report, click on the “File” menu and select “Print”. Click on the “Print...” button and change the Printer Name drop-down menu to an option that converts to pdf.

2.7 Backwards calculation

While developing the model, it was considered the user would be mainly interested in “forward” calculation, which involves specifying relevant model parameters. The only “backward” calculation that was fully implemented in the model was to set the energy production at the end of the chain. More information on this implementation is in section 2.5.3.

Other possible “backward” calculations may involve specifying desired values for LCOE, CO₂e emissions or chain efficiencies and using gPROMS to calculate the value of the model parameters that would give such a result. However, these “backward” calculations require only one upstream degree of freedom to be relaxed, which is highly complicated given the choice of 300+ parameters involved, and require expert knowledge of the feasible output and input ranges.

If the user wants to run these “backward” calculations, it is advisable that the user first runs a simulation as specified in section 2.5.3 (specifying the power output, biomass flowrate or number of units). The user can thus get a good initial guess of the model results that are feasible for this chain.

For example, Figure 53 shows Chain 1 of the pre-prepared bioenergy chains. By running the simulation considering an end vector production of 2,000,000 MWh per year and a biomass blend of 70% LRF pellets, 15% miscanthus, and 15% SRF deciduous, the calculated LCOE is 62.4 £/MWh (Figure 54).

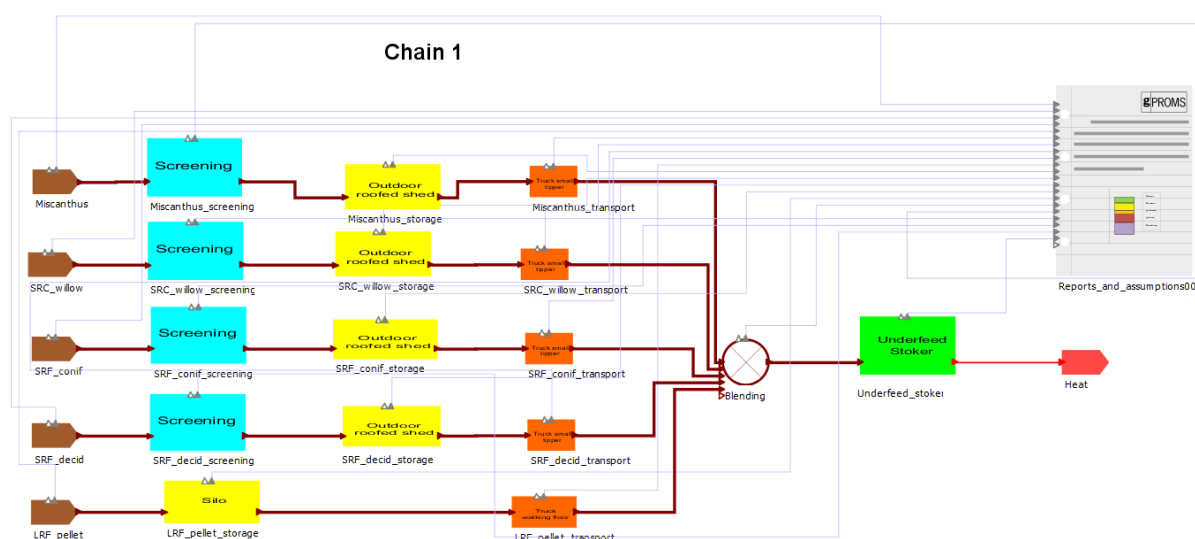


Figure 53: Flowsheet configuration for Chain 1

Chain total LCOE

		Units
CAPEX	28.9365	£/MWh vector output
Fixed OPEX	7.31609	£/MWh vector output
Variable OPEX	5.82438	£/MWh vector output
Coproducts	0.00000	£/MWh vector output
Feedstock	20.3670	£/MWh vector output
Net total	62.4439	£/MWh vector output

Figure 54: Chain LCOE results for Chain 1

After getting a good initial guess of the LCOE, the user can run a simulation where the one of the main input variables is replaced by the value of LCOE the user desires. This can be done by going to the PROCESS section of the flowsheet (Figure 55) and adding the lines of code shown in Figure 56 in the SCHEDULE section:

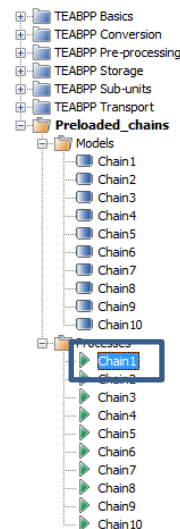


Figure 55: Location of the PROCESS for the bioenergy chains

```
SCHEDULE
SEQUENCE
  REPLACE Flowsheet.Blending.split(1) WITH Flowsheet.Reports_and_assumptions001.LCOE_net_total := 61 ; END
END
```

Figure 56: Additional text added to the PROCESS of Chain 1. Replacing the assignment of the blending fraction of Miscanthus for the total LCOE

In the example in Figure 56, the blending fraction of Miscanthus (Flowsheet.Blending.split(1)) is being changed in order to lower the LCOE net total to 61 £/MWh (Flowsheet.Reports_and_assumptions001.LCOE_net_total). The SCHEDULE section is always added in the bottom of the PROCESS code.

By running a new simulation with this specification, the blending split is now calculated instead of being specified.

There are, however, limitations to this approach:

- Only variables can be replaced. To choose from the variables which have been assigned, the user should look at the ASSIGN section in the PROCESS. In the base case for Chain 1, the only variables assigned which are sensitive to LCOE, for example, are the blending fractions and the yearly power output (Figure 57).

```
ASSIGN
# Start Unit Specifications
WITHIN Flowsheet DO
  WITHIN Blending DO
    split(1) := 0.5 ; # 0.5 "kg/kg (wet)"
    split(2) := 0 ; # 0 "kg/kg (wet)"
    split(3) := 0 ; # 0 "kg/kg (wet)"
    split(4) := 0.5 ; # 0.5 "kg/kg (wet)"
    split(5) := 0 ; # 0 "kg/kg (wet)"
  END # WITHIN Blending
  WITHIN Heat DO
    yearly_output := 20000000 ; # 20000000 "MWh/year"
  END # WITHIN Heat
```

Figure 57: ASSIGN section of the PROCESS of Chain 1

- The values of the variable that you want to assign (in this case, the LCOE) should not be very different from their initial result. This will primarily avoid a situation where the user chooses an unfeasible output value, however the model may also not be able to calculate from a very different value.
- The chosen input variable must be sensitive to the output variable.
- The user must know the path of the output variable they want to assign. The path can be found by searching the trajectories of a case file from that flowsheet and looking for the name of the variable the user wishes to assign.

3 Key assumptions and limitations

3.1 Modelling dependent on input data quality

The parameterisation of the different units in gPROMS relies on the data sets generated during Work Package 1 and during the development of Deliverable 2. This data has subsequently been through several major iterations and review cycles, such as:

- Switching pelleting over to biomass-dried
- Adding further relationships between impurities and conversion plant efficiency, availability and OPEX
- Adding further relationships for the degradation and drying of stored biomass
- New inlet limits / warning flags
- Addition of field washing technology

The tables in Appendix A set out which input parameters influence the output parameters of capex (£), opex (£/yr), efficiency (% LHV) and availability (hr/yr), for each of the conversion and pre-processing technologies in the 10 TEABPP chains.

3.2 TEABPP libraries

The gPROMS libraries contain the following limitations and assumptions:

- The model library is fixed in time, since all technical and economic parameters are fixed values and validated at the time of development. As a consequence, the results, especially the economic results, are generated based on 2015 (calendar year) costs.
- Due to assumptions in the Blending model, only biomass streams with similar properties should be mixed. Particularly, blending of pre-processed feedstocks (e.g. in the form of pellets) with untreated feedstocks should be avoided.
 - Particle size is considered as the maximum particle size of all the blends. This is currently only used for the warning flags for the pre-processing and conversion units. However, if feedstocks with very different particle sizes are blended the particle size reported by the model may not be representative of the particle size of the blend in reality.
 - The feedstock density is calculated as a weighted average of the inlet feedstocks. This is a reasonable assumption for similar feedstocks, however if feedstocks have quite different shapes, this may not apply in reality (for example, if smaller particles can fit between the spaces of much larger particles, increasing the density of the blended feedstock).
 - In Chain 10, pyrolysis oil would not be blended with LRF pellets before entering the conversion plant – the pyrolysis oil would instead be blended with the ground

pellets just before feeding into the entrained flow gasifier. An example of a similar EF gasifier technology would be the Texaco gasifier⁵, which can process coal, coke and heavy fuel oil. The location of the Chain 10 blending module would therefore in reality be within the plant boundary, not upstream, but as gPROMS needs to calculate the blended biomass properties before gasification, and factor in the two handling systems, this blending module would still be required. However, it is important to note that the TEABPP project sensitivity analysis will not be using or blending any imported LRF pellets, so no ground pellets will be mixed with the pyrolysis oil.

- Several parameters are not used in calculating outputs, but are included for information. These include volatile content, fixed carbon, carbon, hydrogen, silicon, bromine, fluorine, aluminium, calcium.
- Model uses elemental percentages, not the percentage of an oxide in the ash. There is therefore a separate Microsoft Excel spreadsheet sheet to convert from one to the other.
- The availabilities and data are all annual – there are no seasons.
- Unit numbers are set by the base scale (capacity of the different technologies, e.g. inlet flowrate in tonnes/yr or energy output in MW_e), not by the numbers of other units within the chain. This is a slightly different assumption to the D2 Excel, which for some chains allowed some matching between the number of storage units and the number of pre-processing units (e.g. D2 could choose that each pelleting plant always had one warehouse, or that each chemical washing plant had one pelleting plant onsite, and resize accordingly). However, in gPROMS, the number of units cannot be passed on through the chains, because there are an infinite number of different arrangements of modules and chain lengths possible in gPROMS, unlike the simple, rigid architecture in D2. gPROMS unit numbers are therefore set by the base scale; for example, in gPROMS chain 7, you might have 24 chemical washing plants then 102 warehouses leading into 13 pellet plants. However, unit numbers can be manually adjusted within gPROMS, e.g. the user can set 13 chemical washing units and 13 warehouses so that their scales increase to match the 13 pelleting plants.

3.3 Blending fraction base case

Regarding the pre-loaded chains, all chains consider the possibility of having any (or all) of the five pre-configured feedstocks. This is done by including blending units before the conversion unit and/or before the pre-processing stage.

For chains 1 to 3, the blending model is placed before the conversion unit, due to short, small-scale supply chains that are unlikely to be aggregated centrally before distribution to the conversion plant – forest/field direct to plant is much more likely. For the rest of the chains, two blending models are present. Firstly, the local feedstocks (Miscanthus, SRC willow, SRF deciduous and SRF coniferous) are

⁵ Texaco (1999) "Enhancing Refinery Profitability by Gasification, Hydroprocessing & Power Generation", Available at: <http://www.gasification-syngas.org/uploads/eventLibrary/GTC99270.pdf> [Accessed 17th November 2016]

blended before the pre-processing stage, and the resulting biomass stream is afterwards blended with a LRF pellet feedstock at the conversion plant.

Since blending all five different feedstocks is highly unlikely in reality, it was considered that only two feedstocks would be blended in the base case (the blending fraction for the other feedstocks to be set as 0 in the base case).

SRF deciduous feedstock was selected instead of a SRF coniferous. This is because the SRF deciduous feedstock contains a higher ash and alkali index, providing a suitable contrast to the cleaner LRF pellets.

Finally, since the SRC willow is not significantly different from the SRF deciduous feedstock (fairly similar ash content, alkali index, and chlorine and nitrogen content), it was decided that picking it would not offer significantly different insights. Instead, the Miscanthus feedstock was chosen. Its higher chlorine content, as well as slightly higher alkali index and ash makes it the potentially least chemically attractive feedstock. This will provide the greatest impact on the conversion plant, and hence potentially the greatest benefits of pre-processing.

With the reasoning above, the base case blending fraction was assumed for all chains as 50% SRF deciduous logs and 50% Miscanthus bales, keeping the five blending chain architecture, so that SRC willow, SRC coniferous and LRF pellets can also be added by the user.

Given that the subsequent sensitivity and cross-analysis analysis is being conducted using a generic woody feedstock (with min-max ranges wide enough to encompass SRC willow, SRF coniferous and SRC deciduous feedstocks), we have provided further detail regarding the min-max limits of each of the three component feedstocks and the new generic woody feedstock in Appendix B.

3.4 Blending costs and impacts

The blending model contains the following assumptions:

- Outlet composition, soil and stone contamination, moisture, density, and LHV are the weight averaged values of the inlet stream's properties.
- Outlet maximum particle size is assumed to be the maximum of the inlet particle sizes.
- CAPEX and OPEX costs are calculated from a fixed price in pounds per oven dried tonne (£/odt) of inlet biomass:
 - Total cost (CAPEX, fixed OPEX and variable OPEX) is based on the costs for bulk storage with hopper (0.20 \$/short ton oven) and a conveying/mixing system (0.60 \$/short ton oven)⁶.
 - Breakdown of the total cost to CAPEX, fixed and variable costs is provided in the Deliverable 2 Excel in the storage tabs (cells K115:N129). Variable OPEX is calculated based on the hopper storage (£0.075/odt) and conveying/mixing power costs (£0.100/odt). CAPEX is calculated based on the discount rate and considering a

⁶ Idaho National Laboratory, "Feedstock Supply System Design and Economics for Conversion of Lignocellulosic Biomass to Hydrocarbon Fuels," January 2014. [Online]. Available: <https://inldigitallibrary.inl.gov/sti/6038147.pdf>. [Accessed 07 October 2016].

lifetime of 30 years (£0.284/odt). And Fixed OPEX (in £/MW/year) is considered as 5% of the total CAPEX (in £/MW), which results in the cost of £0.134/odt.

- Blending costs increase per number of streams of “active” streams (with non-zero flowrate), so that the price multiplies by the number of streams being mixed:

$$\text{Capex per odt (£/odt)} = 0.284 \text{ (£/odt)} \times (\text{number active streams} - 1)$$

$$\text{Fixed OPEX per odt (£/odt)} = 0.134 \text{ (£/odt)} \times (\text{number active streams} - 1)$$

$$\text{Variable OPEX per odt (£/odt)} = 0.176 \text{ (£/odt)} \times (\text{number active streams} - 1)$$

3.5 General limitations

- System has become highly complex – the chains have many elements and parameters, plus multiple branches, hence when interpreting results, the blending fractions have to always be borne in mind.
- Key parameters that are propagated are biomass parameters, but it is not currently possible to flow through the numbers of units or the status of other parts of the chain.
- Need to link each module to results, which means manual process if want to remove a feedstock (i.e. set to 0% blending).

4 Glossary of terms

This section is useful as a quick reference guide to understand some of the terminology used.

BFB = Bubbling fluidised bed

CAPEX = Total investment costs

CCGT = Combined cycle gas turbine

CH₄ = Methane

CO = Carbon Monoxide

CO₂ = Carbon Dioxide

CO₂e = Carbon Dioxide equivalent (based on IPCC 100 year global warming potentials, 5th Assessment Report)

CSV = Comma separated values

EF = Entrained flow

End vector = Model output of electricity or heat

gCCS = PSE's system modelling toolkit for CCS systems (www.psenderprise.com/products/gccs)

gPROMS = PSE's software platform for all its application software

GHG = Greenhouse gas

GJ = Gigajoule

Gross chain efficiency = (MWh end vector + MWh coproducts)/MWh feedstocks

GUI = Graphical User Interface

GWP = Global warming potential

HP = Horsepower

IPCC = Intergovernmental Panel on Climate Change

kg = Kilogram

LCOE = Levelised cost of energy

LHV = Lower heating value

LRF = Long Rotation Forestry

m³ = cubic metre

MBtu = Million British Thermal Unit (a unit of heat)

mm = Millimetre

MW = Megawatt

MWh = Megawatt hour

N₂O = Nitrous oxide

Net chain efficiency = (MWh end vector + MWh coproducts – MWh other inputs)/MWh feedstocks

Net emissions = input emissions + output emissions + feedstock emissions

OPEX = Annual operating costs

PM = Particulate matter

RHI = Renewable Heat Incentive

Short ton = 907.18kg (or 2000 pounds (lb))

SRC = Short Rotation Coppice

SRF = Short Rotation Forestry

Tonne (metric) = 1000 kg

5 Appendix A - Input and output parameter relationships

The following tables set out which input parameters influence the output parameters of capex (£), opex (£/yr), efficiency (% LHV) and availability (hr/yr), for each of the conversion and pre-processing technologies in the 10 TEABPP chains. A “✓” signifies a parameterised relationship (either directly, or indirectly via other parameters – e.g. capacity often influences capex, which then influences fixed opex – but the fixed opex formulae themselves do not include capacity parameters).

Underfired combustion boiler for heating	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture			✓	
Ash		✓	✓	✓
Alkali Index		✓	✓	✓
N				
S			✓	
Cl		✓	✓	✓
CFB combustion boiler + steam turbine for power	Capex	Opex	Efficiency	Availability
Capacity	✓	✓	✓	
Moisture			✓	
Ash		✓	✓	✓
Alkali Index		✓	✓	✓
N	✓	✓		
S	✓	✓	✓	
Cl	✓	✓	✓	✓
BFB gasifier + syngas clean-up + gas engine for power	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
Ash		✓		✓
Alkali Index		✓		✓
N		✓		
S	✓	✓		
Cl	✓	✓		✓
EF gasifier + syngas clean-up + CCGT for power	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
Ash		✓		✓
Alkali Index		✓		✓
N		✓		
S	✓	✓		
Cl	✓	✓		✓

Screening	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Soil contamination		✓	✓	
Chipping	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Pelleting	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
Soil contamination		✓	✓	
LHV		✓	✓	
(if Miscanthus)		+ binder		
Torrefaction + pelleting	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
Soil contamination		✓		
LHV		✓	✓	
Ash		✓		
(if Miscanthus)		+ binder		
Pyrolysis	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
Soil contamination		✓		
LHV		✓	✓	
Ash		✓	✓	
N		✓		
S		✓		
Cl		✓		
Field wash	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
Soil contamination		✓	✓	
LHV		✓	✓	
Water washing	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
LHV		✓	✓	
Ash		✓	✓	
Chemical washing	Capex	Opex	Efficiency	Availability
Capacity	✓	✓		
Moisture		✓	✓	
LHV		✓	✓	
Ash		✓	✓	

6 Appendix B – Feedstock min-max limits

The table below shows the Base case feedstock values pre-loaded into the gPROMS model, along with the Min and Max range limits used in the sensitivity analysis. The ranges for SRC willow, SRF coniferous and SRF deciduous species have been merged into a single “Generic woody feedstock” in the sensitivity analysis (with the Base case using SRF decid data), and so the % differences between the three component woody base cases are shown in the final columns.

			Miscanthus					SRC willow					SRF conif					SRF decid			Generic woody feedstock			Woody base delta from:		
Name	Δ min to base	Δ max to base	Min	Base	Max	Δ min to base	Δ max to base	Min	Base	Max	Δ min to base	Δ max to base	Min	Base	Max	Δ min to base	Δ max to base	Min	Base	Max	Min	Base	Max	SRC willow	SRF conif	SRF decid
Form			Bales	Bales	Bales			Chips	Chips	Chips			Logs	Logs	Logs			Logs	Logs	Logs	Chips	Logs	Logs			
Bulk density (wet tonne/m3)	-20%	20%	0.123	0.153	0.184	-20%	20%	0.283	0.354	0.425	-20%	10%	0.461	0.576	0.634	-20%	10%	0.524	0.655	0.720	0.283	0.655	0.720	-46%	-12%	0%
Size (mm)	-20%	20%	1,960	2,450	2,940	-20%	20%	50	63	76	-20%	20%	2,400	3,000	3,600	-20%	20%	2,400	3,000	3,600	50	3,000	3,600	-98%	0%	0%
Soil contamination (% dry)			0.00%	1.00%	2.00%			0.00%	0.50%	2.00%			0.00%	0.20%	2.00%			0.00%	0.20%	2.00%	0.00%	0.20%	2.00%	150%	0%	0%
Production cost (£/wet tonne)	-30%	30%	14.1	20.2	26.2	-30%	30%	7.5	10.7	13.9	-30%	30%	9.2	13.1	17.1	-30%	30%	9.6	13.7	17.9	7.5	13.7	17.9	-22%	-4%	0%
GHG emissions (kgCO2e/odt)	-60%	60%	18.3	45.9	73.4	-60%	60%	12.9	32.2	51.5	-60%	60%	14.0	35.0	56.0	-60%	60%	14.0	35.0	56.0	12.9	35.0	56.0	-8%	0%	0%
	Δ min to COF min	Δ max to COF max				Δ min to COF min	Δ max to COF max				Δ min to COF min	Δ max to COF max				Δ min to COF min	Δ max to COF max									
Moisture content (% wet)	0%	0%	8.4%	14.8%	21.8%	0%	0%	48.1%	52.6%	65.1%	0%	0%	53.0%	58.3%	64.8%	0%	0%	49.4%	56.5%	61.4%	48.1%	56.5%	65.1%	-7%	3%	0%
LHV dry (GJ/odt), no soil	0%	0%	17.61	17.89	18.12	0%	0%	18.22	18.29	18.55	0%	0%	18.91	19.15	19.52	0%	0%	17.93	18.20	18.42	17.93	18.20	19.52	0%	5%	0%
LHV (GJ/wet tonne), no soil	0%	0%	13.39	14.89	16.26	0%	0%	4.89	7.39	8.43	0%	0%	5.16	6.55	7.76	0%	0%	5.56	654.6%	8.02	4.89	6.55	8.43	13%	0%	0%
Ash fusion temperature (deg C)	0%	0%	815	1,091	1,500	0%	0%	1,100	1,447	1,500	0%	0%	1,187	1,455	1,500	0%	0%	1,447	1,492	1,500	1,100	1,492	1,500	-3%	-2%	0%
Ash content (% dry), no soil	-100%	30%	0.00%	2.27%	4.29%	-100%	30%	0.00%	2.22%	3.77%	-100%	30%	0.00%	1.40%	2.41%	-100%	30%	0.00%	2.20%	3.67%	0.00%	2.20%	3.77%	1%	-36%	0%
Total halides (% dry)	-100%	30%	0.000%	0.116%	0.313%	-100%	30%	0.000%	0.015%	0.053%	-100%	30%	0.000%	0.021%	0.065%	-100%	30%	0.000%	0.0%	0.044%	0.00%	0.013%	0.065%	13%	63%	0%
Total alkali metal (% dry)	-100%	30%	0.00%	0.30%	0.81%	-100%	30%	0.00%	0.22%	0.49%	-100%	30%	0.00%	0.16%	0.42%	-100%	30%	0.00%	0.25%	0.53%	0.00%	0.25%	0.53%	-12%	-36%	0%
Alkali index (kg/GJ)			0.00	0.22	0.57			0.00	0.15	0.33			0.00	0.10	0.27			0.00	0.17	0.37	0.00	0.17	0.37	-13%	-39%	0%
Total volatile content (% dry)	0%	0%	77.5%	80.9%	84.3%	0%	0%	77.4%	81.4%	83.8%	0%	0%	79.0%	80.5%	82.0%	0%	0%	80.7%	82.0%	83.4%	77.4%	82.0%	83.8%	-1%	-2%	0%
Fixed carbon (% dry)	0%	0%	14.0%	16.7%	19.8%	0%	0%	15.0%	16.8%	19.8%	0%	0%	17.1%	18.3%	19.6%	0%	0%	15.0%	15.9%	16.7%	15.0%	15.9%	19.8%	5%	15%	0%
Carbon content (% dry)	0%	0%	47.3%	48.5%	49.8%	0%	0%	48.0%	49.4%	51.0%	0%	0%	49.5%	51.4%	52.2%	0%	0%	48.7%	49.4%	50.6%	48.0%	49.4%	52.2%	0%	4%	0%
Hydrogen content (% dry)	0%	0%	5.8%	6.0%	6.2%	0%	0%	5.9%	6.1%	6.2%	0%	0%	6.0%	6.2%	6.4%	0%	0%	5.8%	6.0%	6.1%	5.8%	6.0%	6.4%	1%	3%	0%
Nitrogen content (% dry)	-100%	30%	0.00%	0.35%	0.78%	-100%	30%	0.00%	0.53%	1.21%	-100%	30%	0.00%	0.48%	1.06%	-100%	30%	0.00%	0.4%	0.78%	0.00%	0.40%	1.21%	32%	19%	0%
Silicon content (% dry)	-100%	30%	0.000%	0.521%	1.261%	-100%	30%	0.000%	0.033%	0.151%	-100%	30%	0.000%	0.043%	0.166%	-100%	30%	0.000%	0.0%	0.099%	0.000%	0.018%	0.166%	82%	135%	0%
Chlorine content (% dry)	-100%	30%	0.0000%	0.1155%	0.312%	-100%	30%	0.0000%	0.0143%	0.052%	-100%	30%	0.0000%	0.0210%	0.064%	-100%	30%	0.0000%	0.0%	0.044%	0.000%	0.0128%	0.064%	12%	64%	0%
Bromine content (% dry)	-100%	30%	0.00000%	0.00066%	0.00312%	-100%	30%	0.00000%	0.00020%	0.00034%	-100%	30%	0.00000%	0.00022%	0.00032%	-100%	30%	0.00000%	0.0%	0.00068%	0.00000%	0.00021%	0.00068%	-6%	5%	0%
Fluorine content (% dry)	-100%	30%	0.00000%	0.00021%	0.00052%	-100%	30%	0.00000%	0.00020%	0.00034%	-100%	30%	0.00000%	0.00021%	0.00040%	-100%	30%	0.00000%	0.0%	0.00032%	0.00000%	0.00020%	0.00040%	-1%	4%	0%
Aluminium content (% dry)	-100%	30%	0.0000%	0.0065%	0.043%	-100%	30%	0.0000%	0.0063%	0.044%	-100%	30%	0.0000%	0.0081%	0.038%	-100%	30%	0.0000%	0.0%	0.021%	0.0000%	0.0052%	0.044%	22%	57%	0%
Potassium content (% dry)	-100%	30%	0.00%	0.29%	0.79%	-100%	30%	0.00%	0.22%	0.48%	-100%	30%	0.00%	0.16%	0.41%	-100%	30%	0.00%	0.2%	0.53%	0.00%	0.25%	0.53%	-12%	-36%	0%
Sodium content (% dry)	-100%	30%	0.0000%	0.0104%	0.039%	-100%	30%	0.0000%	0.0054%	0.014%	-100%	30%	0.0000%	0.0061%	0.021%	-100%	30%	0.0000%	0.0%	0.018%	0.0000%	0.0070%	0.021%	-22%	-13%	0%
Calcium content (% dry)	-100%	30%	0.00%	0.12%	0.348%	-100%	30%	0.00%	0.42%	0.936%	-100%	30%	0.00%	0.21%	0.422%	-100%	30%	0.00%	0.5%	0.927%	0.00%	0.48%	0.936%	-13%	-56%	0%
Sulphur content (% dry)	-100%	30%	0.0000%	0.0115%	0.039%	-100%	30%	0.0000%	0.0117%	0.052%	-100%	30%	0.0000%	0.0227%	0.179%	-100%	30%	0.0000%	0.0%	0.047%	0.0000%	0.0171%	0.18%	-32%	33%	0%
Oxygen content (% dry)	0%	0%	42.6%	43.7%	44.7%	0%	0%	40.2%	42.7%	44.2%	0%	0%	39.9%	41.0%	43.4%	0%	0%	41.4%	42.5%	43.3%	39.9%	42.5%	44.2%	1%	-4%	0%

The tables below represent results from the ETI's Characterisation of Feedstock (CoF) project. The mean values shown in the table below correspond to the 'Base' feedstock characteristics in the table on the preceding page. The Max value for each chemical composition (Ash, N, Cl, K, Na, S) used in the sensitivity analysis table (above) is taken as being either 30% above the max CoF value, or the max composition given in the ECN Phyllis2 database⁷, whichever value is higher. Min values for the chemical compositions are taken as zero.

	Min						Max					
	Miscanthus	SRC Willow	SRF Conif	SRF Decid	LRF pellet	SRC Poplar	Miscanthus	SRC Willow	SRF Conif	SRF Decid	LRF pellet	SRC Poplar
Moisture content (% wet)	8.4%	48.1%	53.0%	49.4%	4.3%	51.2%	21.8%	65.1%	64.8%	61.4%	12.2%	68.5%
LHV dry (GJ/odt)	17.606	18.216	18.912	17.927	18.405	17.979	18.124	18.554	19.521	18.422	19.564	18.334
LHV (GJ/wet tonne)	13.3860	4.8850	5.1569	5.5613	16.4650	3.9900	16.2560	8.4260	7.7602	8.0174	18.3210	7.6960
Ash fusion temperature (deg C)	815	1,100	1,187	1,447	1,210	1,450	1,500	1,500	1,500	1,500	1,410	1,500
Ash content (% dry)	1.30%	1.00%	0.47%	1.43%	0.30%	2.20%	3.30%	2.90%	1.85%	2.82%	2.20%	3.50%
Total halides (% dry)	0.041%	0.010%	0.011%	0.010%	0.010%	0.010%	0.240%	0.040%	0.050%	0.034%	0.032%	0.010%
Total alkali metal (% dry)	0.12%	0.12%	0.09%	0.13%	0.03%	0.05%	0.62%	0.38%	0.32%	0.41%	0.18%	0.53%
Alkali index (kg/GJ)	0.08	0.08	0.06	0.09	0.02	0.03	0.42	0.24	0.20	0.26	0.11	0.35
Total volatile content (% dry)	77.5%	77.4%	79.0%	80.7%	80.6%	78.1%	84.3%	83.8%	82.0%	83.4%	84.9%	81.6%
Fixed carbon (% dry)	14.0%	15.0%	17.1%	15.0%	14.4%	16.4%	19.8%	19.8%	19.6%	16.7%	17.6%	18.4%
Carbon content (% dry)	47.3%	48.0%	49.5%	48.7%	48.4%	48.9%	49.8%	51.0%	52.2%	50.6%	51.4%	50.0%
Hydrogen content (% dry)	5.8%	5.9%	6.0%	5.8%	5.8%	5.9%	6.2%	6.2%	6.4%	6.1%	6.4%	6.0%
Nitrogen content (% dry)	0.22%	0.22%	0.23%	0.28%	0.21%	0.35%	0.60%	0.930%	0.815%	0.596%	0.40%	1.12%
Silicon content (% dry)	0.22%	0.00%	0.01%	0.00%	0.03%	0.00%	0.97%	0.12%	0.13%	0.08%	0.42%	0.06%
Chlorine content (% dry)	0.040%	0.010%	0.011%	0.010%	0.010%	0.010%	0.240%	0.040%	0.050%	0.034%	0.030%	0.010%
Bromine content (% dry)	0.00019%	0.00018%	0.00021%	0.00018%	0.00000%	0.00019%	0.00240%	0.00026%	0.00024%	0.00052%	0.00000%	0.00020%
Fluorine content (% dry)	0.00018%	0.00018%	0.00019%	0.00019%	0.00020%	0.00019%	0.00040%	0.00026%	0.00031%	0.00025%	0.00162%	0.00020%
Aluminium content (% dry)	0.0007%	0.0006%	0.0029%	0.0015%	0.0068%	0.0002%	0.0328%	0.0341%	0.0289%	0.0160%	0.1040%	0.0052%
Potassium content (% dry)	0.11%	0.12%	0.08%	0.12%	0.03%	0.05%	0.60%	0.37%	0.31%	0.41%	0.16%	0.52%
Sodium content (% dry)	0.0049%	0.0016%	0.0025%	0.0017%	0.0007%	0.0008%	0.0297%	0.0109%	0.0163%	0.0139%	0.0223%	0.0066%
Calcium content (% dry)	0.06%	0.22%	0.14%	0.33%	0.06%	0.07%	0.27%	0.72%	0.32%	0.71%	0.36%	0.61%
Sulphur content (% dry)	0.0100%	0.0100%	0.0100%	0.0100%	0.0100%	0.0100%	0.0300%	0.0400%	0.1379%	0.0363%	0.0300%	0.0400%
Oxygen content (% dry)	42.56%	40.16%	39.90%	41.44%	40.66%	40.65%	44.67%	44.16%	43.42%	43.31%	45.39%	41.89%

	Mean						Standard deviation					
	Miscanthus	SRC Willow	SRF Conif	SRF Decid	LRF pellet	SRC Poplar	Miscanthus	SRC Willow	SRF Conif	SRF Decid	LRF pellet	SRC Poplar
Moisture content (% wet)	14.8%	52.6%	58.3%	56.5%	6.6%	61.0%	5.5%	6.4%	2.8%	3.1%	1.1%	8.9%
LHV dry (GJ/odt)	17.893	18.387	19.193	18.241	18.978	18.180	0.171	0.147	0.157	0.119	0.199	0.182
LHV (GJ/wet tonne)	14.8891	7.4297	6.5821	6.5618	17.5593	5.6097	1.2250	1.3132	0.6366	0.6404	0.3215	1.8966
Ash fusion temperature (deg C)	1,091	1,447	1,455	1,492	1,283	1,483	99	49	86	15	67	29
Ash content (% dry)	2.27%	1.72%	1.20%	2.00%	0.93%	3.03%	0.42%	0.34%	0.29%	0.33%	0.33%	0.72%
Total halides (% dry)	0.116%	0.015%	0.021%	0.013%	0.015%	0.010%	0.049%	0.005%	0.008%	0.005%	0.007%	0.000%
Total alkali metal (% dry)	0.30%	0.22%	0.16%	0.25%	0.09%	0.27%	0.12%	0.05%	0.06%	0.08%	0.03%	0.24%
Alkali index (kg/GJ)	0.22	0.16	0.11	0.16	0.05	0.18	0.13	0.07	0.04	0.06	0.02	0.16
Total volatile content (% dry)	80.9%	81.4%	80.5%	82.0%	83.1%	79.5%	2.1%	2.5%	0.9%	0.8%	0.9%	1.8%
Fixed carbon (% dry)	16.7%	16.8%	18.3%	15.9%	15.9%	17.6%	1.8%	1.8%	0.7%	0.5%	0.7%	1.1%
Carbon content (% dry)	48.5%	49.4%	51.4%	49.4%	50.5%	49.3%	0.5%	0.5%	0.6%	0.4%	0.6%	0.6%
Hydrogen content (% dry)	6.0%	6.1%	6.2%	6.0%	6.1%	6.0%	0.1%	0.1%	0.1%	0.1%	0.2%	0.0%
Nitrogen content (% dry)	0.35%	0.53%	0.48%	0.40%	0.29%	0.79%	0.10%	0.13%	0.11%	0.08%	0.05%	0.40%
Silicon content (% dry)	0.52%	0.03%	0.04%	0.02%	0.12%	0.02%	0.15%	0.03%	0.03%	0.02%	0.08%	0.03%
Chlorine content (% dry)	0.116%	0.014%	0.021%	0.013%	0.014%	0.010%	0.049%	0.005%	0.008%	0.005%	0.006%	0.000%
Bromine content (% dry)	0.00066%	0.00020%	0.00022%	0.00021%	0.00000%	0.00020%	0.00041%	0.00001%	0.00001%	0.00009%	0.00000%	0.00000%
Fluorine content (% dry)	0.00021%	0.00020%	0.00021%	0.00020%	0.00063%	0.00020%	0.00002%	0.00001%	0.00003%	0.00002%	0.00047%	0.00000%
Aluminium content (% dry)	0.0065%	0.0063%	0.0081%	0.0052%	0.0301%	0.0029%	0.0055%	0.0066%	0.0053%	0.0036%	0.0218%	0.0025%
Potassium content (% dry)	0.29%	0.22%	0.16%	0.25%	0.08%	0.26%	0.12%	0.05%	0.06%	0.08%	0.02%	0.24%
Sodium content (% dry)	0.0104%	0.0054%	0.0061%	0.0070%	0.0085%	0.0045%	0.0033%	0.0017%	0.0030%	0.0030%	0.0052%	0.0032%
Calcium content (% dry)	0.12%	0.42%	0.21%	0.48%	0.14%	0.43%	0.05%	0.11%	0.04%	0.09%	0.07%	0.31%
Sulphur content (% dry)	0.0115%	0.0117%	0.0227%	0.0171%	0.0115%	0.0233%	0.0028%	0.0036%	0.0190%	0.0079%	0.0039%	0.0153%
Oxygen content (% dry)	43.68%	42.71%	40.98%	42.47%	42.75%	41.31%	0.60%	0.63%	0.63%	0.43%	98.95%	0.62%

⁷ ECN (2017) "Phyllis 2: Database for biomass and waste", Available at: <https://www.ecn.nl/phyllis2/> (accessed 21st September 2017)