Programme Area: Bioenergy

Project: TEA Biomass Pre-processing

Title: Down-selection and workshop report

Abstract:

This report details the selection process for the modelling phase of the TEAB project, focusing on the downselecting of ten clearly defined case studies, from amongst the thousands of possible chain choices considered within the Deliverable 2 (D2) Excel tool. These 10 case studies are grouped in to twos or threes to compare the costs, efficiencies and GHG emissions of biomass supply chains “with” and “without” significant preprocessing. This Deliverable 3 (D3) report is a summary of the chain prioritisation process, containing:

- The agreed selection criteria used;
- A write-up of the down-selection workshop discussions and decisions held;
- The further data collected and improvements made to the D2 tool; and
- Justification for the selection of the final 10 case studies – based on an assessment rating the chains against the selection criteria, highlighting particular strengths or weaknesses, and where particular criteria exclude groups of chains or chains containing particular components.

Context:

The techno-economic project will provide a greater understanding of the options available to modify or improve the physical and chemical characteristics of different types of UK-derived 2nd generation energy biomass feedstocks, that may otherwise reduce the cost-effective performance of conversion technologies.

BI2011

Techno-Economic Assessment of Biomass Pre-Processing (TEABPP)

Deliverable 3: Down-selection and workshop report

Version 2.0

The TEABPP Consortium

For the Energy Technologies Institute

11 February 2016

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Contents

1 Executive Summary

The Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project aims to compare the costs, performance and emissions of biomass supply chain configurations with and without pre-processing, and with and without conversion plant improvements. The primary objective of the Project is to establish optimal system designs for different scales, feedstock types and end uses, highlighting areas of the supply chain with greatest potential for improvement. This will develop the ETI's understanding of pre-processing activities, and show which do or do not benefit the overall levelised cost of energy of the supply chain.

There are two objectives of Work Package 2 (WP2) of the project: firstly, to conduct an initial techno-economic analysis of full supply chains, using the component pre-processing and conversion technology data from WP1, supplemented with new data on feedstocks, logistics and storage. Interaction with ETI experts led to significant enhancement of the Deliverable 2 Excel tool, with new relationships and the explicit modelling of biomass parameters, in order to capture more accurately the costs and performance of each chain.

Secondly, the thousands of possible chains were filtered using an agreed set of down-selection criteria, in order to choose 10 chains for future detailed uncertainty and sensitivity modelling in WP3 (in gPROMS + MoDS). The write-up of the selection process, workshop discussions and justifications forms this Deliverable 3 report.

The primary selection criteria considered are:

- Chain levelised cost of energy (LCOE), focusing on the cheapest conversion technology options at different scales, and most beneficial pre-processing technologies
- Chain energy efficiency, thereby excluding chains with large additional energy inputs
- Pairs of chains are required to model chains with and without pre-processing
- Variety of end vectors, conversion technologies and pre-processing options is required in order for WP3 to gain sufficient insights

Other secondary criteria such as technical readiness, data quality, and UK potential were also considered qualitatively. Based on the down-selection process described in this report, the 10 chains recommended for selection are given in the Table below. Full details of the rationale for each selection can be found in Section 5 of this report.

In 98% of all the cases considered within the D2 tool, including pre-processing within a chain is likely to add to the overall LCOE, even when considering the net benefits to the conversion technology and chain logistics. However, there are a small number of cases (49 of the 2,208 chains analysed) where densification and feedstock property benefits are likely outweigh the added costs of pre-processing, leading to a lower overall LCOE. Of the 49 chains, 32 use Miscanthus pellets, 9 use Miscanthus briquettes, 6 use Miscanthus steam exploded pellets, and 2 use dried deciduous SRF chips. Densification is particularly important for Miscanthus, to avoid the very high cost of trucking low density bales in the "Off" chains.

Crucially, the results above are only valid for the base case assumptions within D2, and the relatively clean feedstock data from the Characterisation of Feedstocks project. The conclusions will likely dramatically change if the user chooses different transport distances, storage times, technology sizes, energy prices, discount rates or less clean feedstocks. This demonstrates the value of carrying out the full process modelling in WP3 on the selected 10 chains, to investigate these key sensitivities, and the parameter ranges where pre-processing still adds value.

Summary of chains recommended for WP3 selection

End vector	Conversion	Pre-processing	Rationale	Chain
Heat	Underfed stoker combustion boiler	Natural drying + screening	"Off" chain for comparison, including screening	1
Heat		Water washing	Local sourcing and ability to investigate cheaper rudimentary washing	2
Power	BFB gasifier + syngas engine	Natural drying + screening	"Off" chain for comparison, including screening	3
Power		Water wash + pelleting	Alkali metal and ash reduction to benefit opex, densify for trucking	4
Power	CFB combustion + steam turbine	Natural drying + screening	"Off" chain for comparison, including screening	5
Power		Pelleting	Cheapest large-scale supply option	6
Power		Chemical wash + pelleting	Alkali metal and ash removal to benefit opex, densify for trucking	7
Power	Entrained flow gasifier + CCGT	Pelleting	No "Off" chain, nor chips allowed, hence pelleting is best comparison	8
Power		Torrefaction + pelleting	Slightly higher cost, but avoided grinding energy	9
Power		Pyrolysis	High cost, but novel and avoided grinding energy	10

The project team have excluded chains based on:

- Steam explosion, due the very high additional energy inputs that consistently exceed 20%
- AFEX, due to applicability only to Miscanthus and high cost
- Briquetting (and Torrefaction + briquetting), due to conversion technology size requirements and limited UK interest
- Drum and Belt drying, due to a lack of innovation potential, and the equipment already being included within pelleting plants
- Chipping, due to most of the feedstocks already being chipped
- Torrefaction only (to chips), due to low material density and high transport cost

2 Introduction

Work Package 1 (WP1) provided a report (Deliverable 1) reviewing the pre-processing, combustion and gasification conversion technologies used to transform forestry and perennial energy crop feedstocks into heat, power and syngas; and gathered techno-economic data for use in WP2 & WP3.

The objective of WP2 within the TEABPP project is to focus and prioritise the project efforts, by down-selecting 10 clearly defined case studies for input into the WP3 process modelling, from amongst the thousands of possible chain choices considered within the Deliverable 2 (D2) Excel tool.

This Deliverable 3 (D3) report is therefore a summary of the chain prioritisation process, containing:

- The agreed selection criteria used in this Work Package;
- A write-up of the down-selection workshop discussions and decisions;
- The further data collected and improvements made to the D2 tool; and
- Justification for the selection of the final 10 case studies – based on an assessment rating the chains against the selection criteria, highlighting particular strengths or weaknesses, and where particular criteria exclude groups of chains or chains containing particular components.

A single case study is defined as a fixed choice of pre-treatment technology, conversion technology and end vector. Biomass feedstock choice and other chain parameters (including the performance of pre-treatment and conversion technologies) are allowed to vary within a chain. It is important to note that removal or addition of a pre-processing technology within a chain will require creation of a new case study, since the process modelling and sensitivity analysis require continuous functions without binary variables. The 10 case studies are therefore best viewed as frozen chain structures, upon which the gPROMS and HDMR modelling is built.

2.1 Short introduction to the D2 tool

Each chain within the D2 tool contains:

- A user-defined choice of either Miscanthus, SRC willow, SRF conifer, SRF deciduous or LRF pellets, which has a starting set of characteristics
- Up to four different transport steps over user-defined distances, containing various modes (6 types of truck, plus train, barge, ship or pipeline)
- Up to three different storage steps with user-defined storage times
- Zero, one or two different pre-processing steps, with user-defined choices of drying, sizing, densification and treatment options, and their combinations
- One user-defined choice of a combustion or gasification conversion technology, for the production of a user-specified amount of electricity, hot water, combined heat and power, or syngas. Base case component scales are used to calculate number of units required within each step, although the user can set the number of units independently (provided they fall within the allowable scale range)

- The ability to turn on/off end vector revenues, vary the discount rate, and the ability for users to establish their own chains

With these inputs, the tool is then able to access and draw upon the following underlying datasets at the correct scales and input conditions:

- Techno-economic data for each pre-processing and conversion technology, from WP1. For individual references behind the technology data analysed in D2, and presented in this report, please see the revised D1 report.
- Feedstock data from the ETI’s Characterisation of Feedstocks project
- Additional data sourced in WP2 for the logistics and storage steps

After rescaling to match the requirements of the supply chain, the chain is able to calculate the costs of each unit and hence component. Then, using the combined efficiencies and inputs/outputs of each step, the tool calculates the following output metrics:

- Levelised cost of energy (LCOE), with or without revenues from the sale of the end vector
- Chain efficiency (MWh of end vector/MWh feedstock)
- Additional electricity or fossil energy inputs to the chain (MWh of additional inputs/MWh feedstock)
- Net balance = (MWh of end vector – MWh of additional inputs)/(MWh feedstock)

  = Chain efficiency – Additional energy inputs to the chain
- The detailed splits of the LCOE across the supply chain components and cost categories (levelised capex, fixed opex, variable opex, co-products, feedstock and end vector revenue) then allows the following chain charts to be plotted:
  - LCOE, by component and cost category
  - Total LCOE, by cost category
  - LCOE waterfall[1], by component totals
  - Energy production, inputs and co-products, by components
  - Energy balance, feedstock losses/gains, inputs and co-products, by components
  - Total investment costs, by component
  - Annual fixed operating, variable operating, feedstock costs, end vector and co-product revenue, by component

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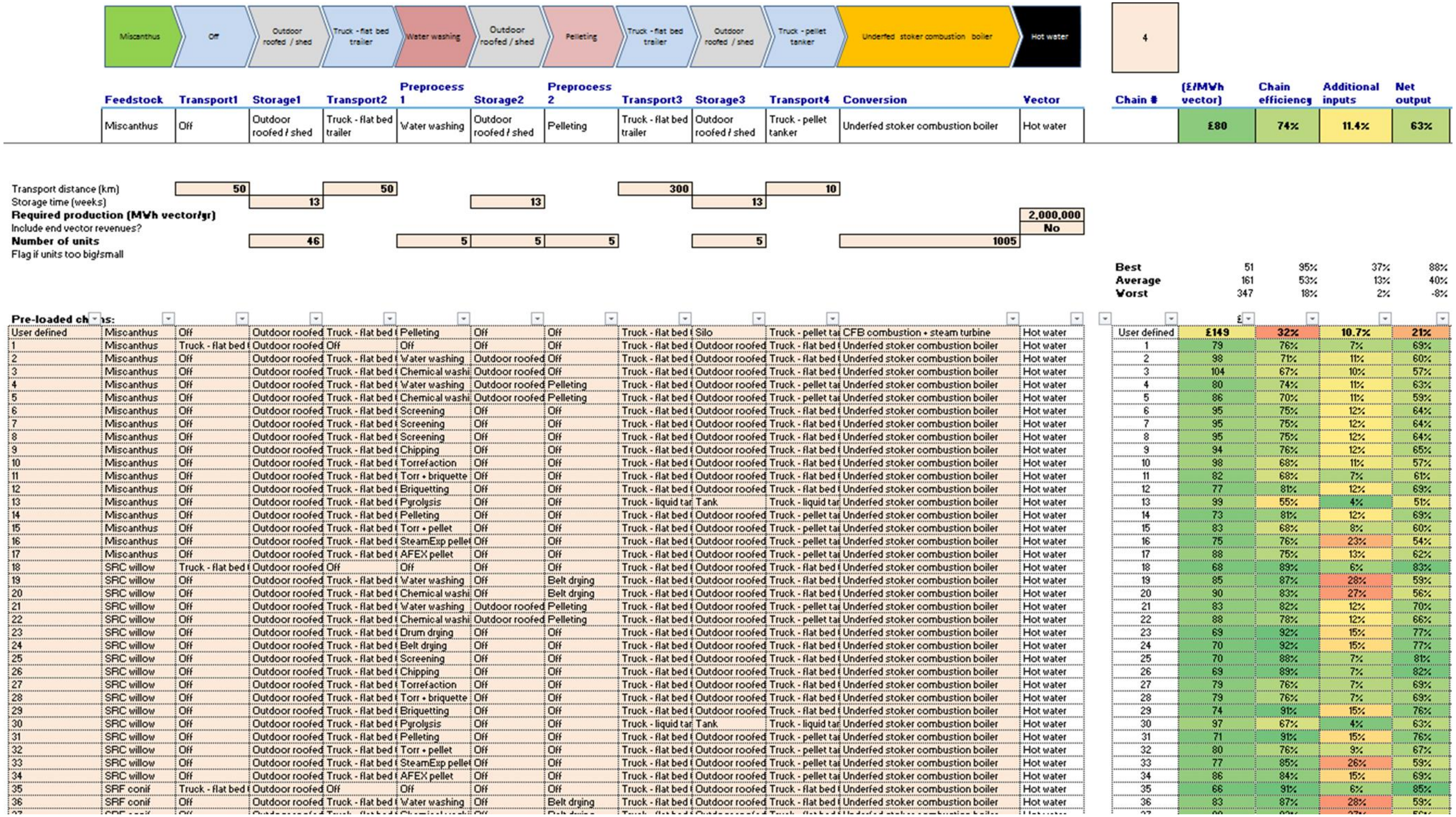
[1] A waterfall (or flying bricks) chart is a stacked cumulative column chart, but with each separate cost component spread along the x-axis



	Feedstock	Transport1	Storage1	Transport2	Preprocess 1	Storage2	Preprocess 2	Transport3	Storage3	Transport4	Conversion	Vector	Chain #	(£/MWh vector)	Chain efficiency	Additional inputs	Net output
	Miscanthus	Off	Outdoor roofed / shed	Truck - flat bed trailer	Water washing	Outdoor roofed / shed	Pelleting	Truck - flat bed trailer	Outdoor roofed / shed	Truck - pellet tanker	Underfed stoker combustion boiler	Hot water		£80	74%	11.4%	63%
Transport distance (km)		50		50				300		10							
Storage time (weeks)			13			13			13								
Required production (MWh vector/yr)												2,000,000					
Include end vector revenues?												No					
Number of units			46		5	5	5		5		1005						
Flag if units too big/small																	
													Best	51	95%	37%	88%
													Average	161	53%	13%	40%
													Worst	347	18%	2%	-8%

Pre-loaded chains:

														£			
User defined	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Pelleting	Off	Off	Truck - flat bed t	Silo	Truck - pellet ta	CFB combustion + steam turbine	Hot water	User defined	£149	32%	10.7%	21%
1	Miscanthus	Truck - flat bed t	Outdoor roofed	Off	Off	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	1	79	76%	7%	69%
2	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Water washing	Outdoor roofed	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	2	98	71%	11%	60%
3	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Chemical washi	Outdoor roofed	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	3	104	67%	10%	57%
4	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Water washing	Outdoor roofed	Pelleting	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	4	80	74%	11%	63%
5	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Chemical washi	Outdoor roofed	Pelleting	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	5	86	70%	11%	59%
6	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Screening	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	6	95	75%	12%	64%
7	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Screening	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	7	95	75%	12%	64%
8	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Screening	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	8	95	75%	12%	64%
9	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Chipping	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	9	94	76%	12%	65%
10	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Torrefaction	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	10	98	68%	11%	57%
11	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Torr + briquette	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	11	82	68%	7%	61%
12	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Briquetting	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	12	77	81%	12%	69%
13	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Pyrolysis	Off	Off	Truck - liquid tar	Tank	Truck - liquid tar	Underfed stoker combustion boiler	Hot water	13	99	55%	4%	51%
14	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Pelleting	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	14	73	81%	12%	69%
15	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	Torr + pellet	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	15	83	68%	8%	60%
16	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	SteamExp pellet	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	16	75	76%	23%	54%
17	Miscanthus	Off	Outdoor roofed	Truck - flat bed t	AFEX pellet	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	17	88	75%	13%	62%
18	SRC willow	Truck - flat bed t	Outdoor roofed	Off	Off	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	18	68	89%	6%	83%
19	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Water washing	Off	Belt drying	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	19	85	87%	28%	59%
20	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Chemical washi	Off	Belt drying	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	20	90	83%	27%	56%
21	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Water washing	Outdoor roofed	Pelleting	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	21	83	82%	12%	70%
22	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Chemical washi	Outdoor roofed	Pelleting	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	22	88	78%	12%	66%
23	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Drum drying	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	23	69	92%	15%	77%
24	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Belt drying	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	24	70	92%	15%	77%
25	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Screening	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	25	70	88%	7%	81%
26	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Chipping	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	26	69	89%	7%	82%
27	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Torrefaction	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	27	79	76%	7%	69%
28	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Torr + briquette	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	28	79	76%	7%	69%
29	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Briquetting	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	29	74	91%	15%	76%
30	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Pyrolysis	Off	Off	Truck - liquid tar	Tank	Truck - liquid tar	Underfed stoker combustion boiler	Hot water	30	97	67%	4%	63%
31	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Pelleting	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	31	71	91%	15%	76%
32	SRC willow	Off	Outdoor roofed	Truck - flat bed t	Torr + pellet	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	32	80	76%	9%	67%
33	SRC willow	Off	Outdoor roofed	Truck - flat bed t	SteamExp pellet	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	33	77	85%	26%	59%
34	SRC willow	Off	Outdoor roofed	Truck - flat bed t	AFEX pellet	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - pellet ta	Underfed stoker combustion boiler	Hot water	34	86	84%	15%	69%
35	SRF conif	Truck - flat bed t	Outdoor roofed	Off	Off	Off	Off	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	35	66	91%	6%	85%
36	SRF conif	Off	Outdoor roofed	Truck - flat bed t	Water washing	Off	Belt drying	Truck - flat bed t	Outdoor roofed	Truck - flat bed t	Underfed stoker combustion boiler	Hot water	36	83	87%	28%	59%

Figure 1: An example screenshot from the D2 Excel tool

3 Selection criteria

The selection criteria were presented and discussed in a meeting with the ETI bioSAG on 23rd September 2015, hosted at DECC. The suggested criteria resulting from the discussions were then agreed with ETI the next day. The project team note that these criteria have some minor variations from those listed in the TEABPP contract, but that with the agreement of all parties, these criteria below are the ones used within D3.

The **primary criteria** that were used to select chains for further analysis are:

- Lowest chain levelised cost of energy (LCOE) – calculated by the D2 tool. We provided the option to consider end vector revenues (sale price of electricity, hot water or syngas) within D2, but this does not alter the relative merit order of different chains within an application. Chains with pre-processing that are more than 40% above the LCOE of the "Off" chain without pre-processing will be excluded for selection, as this cost gap is judged likely to remain even with consideration of uncertainties and technical improvements.
- Lowest additional energy inputs and best overall energy balance (biomass to end vector efficiency, minus additional energy inputs) – calculated by the D2 model. Chains with the largest additional energy inputs have the greatest risk of high GHG emissions (accepting that different inputs have different carbon intensities), potentially exceeding legislated thresholds. These thresholds could tighten to 80% GHG savings in the future, so all chains with greater than 20% additional energy inputs have been excluded. As quantifying chain GHG emissions was out of scope of the D2 model, these energy metrics are the most appropriate proxy measure to use when comparing the sustainability of different chains. Given eventual fossil resource depletion in the far future, independence from fossil fuel use is also important to consider in its own right.
- The need to have (at least) pairs of chains using the same conversion technology to compare similar chains with and without pre-processing.
- Variety between chains – it was considered particularly important to aim for a spread of chains selected across different end vector types, scales, and technology types such as combustion vs. gasification. Some of the experts also suggested picking pre-processing technologies purely on this basis, to cover as many options across the technology landscape as possible, given the scope only allows 10 chains in total (of which up to half will not have a pre-processing step). This criteria became even more important in later decisions.

Other **secondary criteria** were agreed to be used if the primary criteria were not conclusive:

- Innovation – technologies at a lower Technology Readiness Level, or with potential for significant cost and performance improvement compared with that assumed in the D2 data, based on the information given in D1
- Feedstock flexibility or exclusions
- Data quality available for WP3 process modelling
- UK deployment potential and fit with the UK's wider energy strategy
- Value to the UK via IP, capabilities or activities

3.1 Data certainty considerations

Propagation of data uncertainty ranges throughout a supply chain cannot be modelled with Excel, and uncertainties and sensitivity analyses are specifically listed as being out of scope in D2 and D3. The project team cannot therefore quantify the impact that uncertainty surrounding a particular parameter (or set of parameters) has on the outputs of the D2 tool, such as LCOE. This explicit treatment of uncertainties, overlapping parameter ranges and sensitivity analysis is the purpose of conducting the detailed process modelling in WP3, and indeed the fundamental step needed to gain the principal insights from the TEABPP project.

Given the above, the project team have so far not taken uncertainties into account quantitatively in the down-selection, other using than the qualitative data quality levels identified in Deliverable 1 to identify technologies where the team are particularly confident, or the data is particularly poor or sparse.

- The project team can be confident in the translation of the data from WP1 into D2, with the various data quality levels and input sources as discussed in the D1 report. These data have been reviewed, and improved via the new parameterised relationships discussed below.
- The Characterisation of Feedstocks project is supplying the feedstock data, and hence they are best placed to answer regarding the quality of their supplied databases. Some feedstocks have more data points than others, with 96 Miscanthus data points, 70 for SRC willow, 96 for SRF conifers, 66 for broadleaf SRF, and 3 for SRC poplar (out of scope). The standard deviations of the datasets are also relatively large. The lack of LRF pellet data in the COF project has led us to source this separately for D2, along with assumptions on the form, size and density of the starting feedstocks.
- The additional data added to D2 on logistics and storage has been sourced from a variety of industry and academic sources, but cross-checked against UK haulage rates and existing databases. Much of this data is for mature technologies, and so has low uncertainties.

This data quality aspect forms one of the secondary selection criteria, which the project team proposed to consider qualitatively in the down-selection. Given that the ETI and its reviewers in the workshop were keen to push for selection of more innovative technologies, where the costing data quality is known to be more uncertain, this necessitated a de-prioritisation of this selection criterion.

Linked to this is the concept of innovation headroom, and what scope there is within the various technologies to improve their performance – either to improve efficiencies and costs, or to better manage and mitigate against the impacts of particular biomass characteristics. This will be considered in detail within Work Package 4 of the TEABPP project, once the full modelling and sensitivity analysis is complete. In line with the project scope, innovation headroom has therefore not been considered in detail within the WP2 analysis.

4 Workshop report

The down-selection workshop was held on 29th October 2015 at Imperial College London, with the TEABPP Work Package 2 members, the ETI and its reviewers in attendance. This Chapter summarises the process leading up to the workshop, the actions arising from the workshop and the subsequent improvements that have been made to the WP2 down-selection analysis. Specific comments on the choice of chains have been incorporated into the reasons for down-selection given in Chapter 5.

4.1 Initial chains selected

The initial chains below were selected based on information from an earlier, simpler version of the D2 tool, using the down-selection criteria agreed prior to the workshop, and following a similar procedure to that described in detail in Section 5. The rationale for these initial choices is not described further in this report, as these have been superseded by the workshop discussions, reviewer feedback on the new conversion relationships, and subsequent revisions to the D2 tool.

It is however worth noting that a variety of end vectors (electricity, heat and CHP) were selected, with conversion technologies split evenly between combustion and gasification, across a wide range of scales. Each conversion technology had an “Off” chain without pre-processing, and none of the selected chains had excessive additional energy inputs above 20% (hence likely to be avoiding the risk of high chain GHG emissions). When choosing the pre-processing technologies to match with the conversion technology, the LCOE of each choice was carefully justified versus the other pre-processing options. The project team had therefore followed a structured process to select these 10 chains based on the original D2 model (with the functionalities it had at the time), and the agreed primary selection criteria.

Table 1: Initial chains selected as input to the workshop

Chain number	Conversion technology, output and scale	Pre-processing option
1	Underfed combustion to heat <1 MW_{th}	No pre-processing
2		Pelleting
3	BFB gasification to CHP at 1-10 MW_e	No pre-processing
4		Drum drying
5	BFB combustion to CHP at 10-100 MW_e	No pre-processing
6		Torrefaction+pelleting
7	Entrained flow gasification to electricity at >100 MW_e	No pre-processing / screening
8		Pelleting
9		Torrefaction+pelleting
10		Pyrolysis

4.2 Overall workshop comments

The workshop participants agreed with several of the initial choices of chains that had been proposed, and better understood the reasons behind those choices after the workshop discussions. In particular, the group ended up with a good agreement about the conversion technologies worth modelling in WP3, and agreed with the justifications given for exclusion of several of the pre-processing technologies.

However, participants thought that the overall balance of chains chosen in Table 1 did not sufficiently match the aims of the study, namely the requirement to compare a variety of pre-processing options. If these initial chains were to be taken forward, the focus on drying and densification would not allow WP3 to identify and quantify some of the key opportunities for pre-processing to add value to bioenergy supply chains through changing the chemical composition of the feedstock. This imbalance in the selection arose because:

- The initial choices made did not cover a wide enough range of pre-processing technologies. Some choices were repeated (pelleting and torrefaction + pelleting), albeit with different conversion technologies, which would reduce the potential breadth of study insights. As a result, fewer repeated choices should be included.
- Some choices included were well known already (drying, pelleting), with insufficient criteria weighting given to more innovative technologies. It was felt that there is already a good understanding of the chain impacts of feedstock moisture and density on conversion technologies and logistics steps, but not enough understanding about chemical composition impacts. As a result, more pre-processing technologies that have effects on the chemical composition of biomass should be included.
- The model used to compare the chains (D2 tool) did not take into account all of the benefits of the pre-processing technologies on the subsequent conversion steps – particularly how chemical composition impacts plant efficiency, availability and opex. As a result, there was concern that the analysis in WP2 was not been robust enough, nor the data and relationships collected in WP1 complete enough, to be able to down-select the technologies for WP3 with sufficient confidence. The ETI want to be sure that the chains selected are realistic, and the benefits of pre-processing are significant, which means that these missing relationships need to be quantified in D2, to the extent that this is possible in Excel. This additional work is to be followed by conducting a "due diligence" on the chains selected, checking the chemical composition lie below conversion technology limits.
- Combinations of pre-processing technologies could be important, and ETI were keen that more were considered, as we had initially only considered water or chemical washing + drum drying chains. The project team had offered to put the selected technologies from the workshop into the gPROMS model, and let the user set their own combinations – i.e. use the modular flexibility of gPROMS. However, after further investigation, only a few combinations of technologies were found to be feasible (washing + pelleting, and washing + drying) – most new combinations are infeasible or unrealistic (e.g. trying to pellet a torrefied pellet). Given it was possible to model the sequential impacts in Excel using a first then second pre-processing step, we therefore agreed to also include these new washing + pelleting options in the D2 tool before re-running the down-selection.

- It is important to note that the ETI's preference was that the selection of the chains should be carried out in D2 and D3 (freezing the choice and order of the steps), and not left to WP3 to model different combinations and then freeze the chains.

Despite the clear conclusion from the workshop that additions to the D2 tool were needed, the participants accepted the project team's explanation of the limitations of an Excel based tool compared with the more powerful process modelling to be done in D4 (and the full consideration of uncertainties and sensitivities in D6). In addition, there were a few areas that were discussed that were out of scope:

- D2 does not consider environmental emissions (GHGs or non-GHGs). These are out of the scope for D2, but the chain net energy balance is used as a valuable proxy for the chain GHG emissions (chains with large amounts of additional energy inputs are unlikely to be compliant with UK GHG emission thresholds). Compliance with non-GHG emission limits are implicitly assumed via the (feedstock dependent) clean-up costs within each technology.
- It is not possible to carry through uncertainty ranges and conduct sensitivity analysis in Excel (given the number of chains being assessed – over 2,000 in total), so representative transport distances and storage times were chosen over which pre-processing chains could potentially provide benefits. This is why the transport distances are fairly large in D2, and total chain costs are relatively high. These distances and storage times will be key sensitivities investigated in detail within WP3.
- Some attendees were calling for a different approach in the project, using the concept of a "nameless" technology where you wish to determine the input set of parameters in order to meet a user-specified LCOE benefit. This relates to the ETI question of what conditions need to be met in order for pre-processing to add value. This is effectively running the WP3 model in reverse (something gPROMS is capable of), by setting the outputs and calculating the necessary inputs. However, this is not something Excel is capable of, as there are hundreds of parameters varying (and a What-If analysis can only consider one parameter at a time), and there are thousands of chain and feedstock choices. This question is therefore only addressable in WP3 and WP4.
- D2 is only the Excel tool, building on the WP1 data collected, hence separate model documentation accompanying the Excel tool is out scope. However, the D2 sheets contain multiple notes and references, together with a starting legend giving user instructions, and this D3 write-up provides greater detail for the process .
- The participants were keen to understand the level of confidence in the data more clearly. The project team explained that this has been partially addressed in the revised D1, and will be modelled explicitly in WP3. Uncertainties cannot be quantified in D2, as Excel is unable to model the flow-through of parameter distributions.
- Blending (either onsite or off-site) is not a consideration in the down-selection, as it will be included as an available option in all the WP3 chains, in order to mix different fractions of Miscanthus, SRC willow, SRF deciduous, SRF conifers and LRF pellet feedstocks.

4.3 Revisions to D2 as a result of workshop feedback

4.3.1 Derivation of new parameter relationships

The WP1 analysis and the original D2 model only considered the impact of feedstock moisture content and conversion plant scale on the conversion efficiency, as well as relationships between higher ash content feedstocks and higher ash disposal costs, higher nitrogen content and higher urea use, and higher sulphur and chlorine contents and higher lime use.

However, there are further effects and different intermediate mechanisms related to biomass composition that were not initially included, that the workshop participants recommended for inclusion in D2. These include:

- Moisture impacts on combustion flame temperature (a secondary impact on plant efficiency). Higher moisture content should therefore reduce plant efficiencies more than by just the latent heat of evaporation of water
- Ash effect on combustion flame temperature (a secondary impact on plant efficiency). Higher ash contents should therefore slightly reduce plant efficiency
- Dew point back-off – ensuring that the combustion plant operates at a high enough back-end temperature to avoid condensation of acid gases. Higher sulphur and chlorine contents should therefore require a higher back-end temperature, lowering plant efficiency
- High temperature corrosion back-off – higher chlorine contents require lower steam temperatures, lowering plant efficiency

The above efficiency recommendations only apply to combustion technologies, and not to gasification systems. However, the following recommendations for availability and operating costs apply to both combustion and gasification technologies:

- Higher ash contents lead to increased slagging, fouling and erosion, hence more downtime (reduced availability), as well as higher opex due to labour for de-scaling and slag removal, and equipment replacement due to fouling and erosion maintenance
- Higher alkali index (presence of potassium and sodium) leads to more fouling, and hence more downtime (reduced availability), as well as higher opex for labour and equipment replacement
- Higher chlorine contents lead to increased corrosion, and hence more downtime (reduced availability), as well as higher opex for labour and equipment replacement
- Increased lime use should have higher residue disposal costs

There is also the assumption, agreed by the workshop participants, that each plant would be operated and maintained to keep the same overall technical lifetime, and not sacrificed for any short-term gains before shutting the plant early.

To address these recommendations, the project team prepared **new equations for how different biomass species impact efficiency, availability, and operating costs**. This was not a straight-forward task, as little data was available in the public domain. Imperial, B&V and Sheffield discussed and derived these new relationships through a combination of academic and grey literature data points (e.g. quoting loss in availabilities for use of specific feedstocks), industry handbook data on combustion temperatures, separate modelling of the likely magnitude of downtime stoppages, and the use of industry threshold data for species limits (i.e. above which the formulae below start to kick in). References have been provided in an Excel workbook of new relationships, already reviewed by the ETI's team of project experts. These formulae are given in Equations (1) – (4) below, with the high-level strategy behind the formulae summarised in Table 2.

Table 2: Summary of new efficiency, availability and opex relationships

Biomass species	**Efficiency impact – Equation (1)** (combustion only)	**Availability impact – Equation (2)**	**Opex impact – Equation (3)**
Moisture	Change in flame temperature	No impact	No impact
Total ash	Change in flame temperature	Increased downtime if ash >1%	Increased labour and parts costs with higher downtime
Alkali index	No impact	Increased downtime if alkali index >0.17	Increased labour and parts costs if alkali index >0.17
(Effective) Chlorine[2] - **Equation (4)**	Raise back-end temperature to avoid acid gas dew point, and lower steam temperature to avoid high temperature corrosion	Increased downtime if effective chlorine >0.1%	Increased labour and parts costs with higher downtime
Sulphur	Raise back-end temperature to avoid acid gas dew point	No impact recommended, as literature is divided	No new impact

$$(\mathbf{1})\quad \frac{Efficiency}{Efficiency_{base}} = \left(1-\left(1-\frac{273+T_{backend}}{273+T_{flame}-760\times(\boldsymbol{moisture}\%-20\%)-260\times(\boldsymbol{ash}\%-1\%)}\right)\middle/\left(1-\frac{273+T_{backend}}{273+T_{flame}}\right)\right)$$
$$\times\left(1-\ 1\%\ \times\frac{8}{20}\times\frac{\boldsymbol{Cl}\%}{0.6\%}-\ 1\%\ \times\frac{10}{20}\times\frac{\boldsymbol{S}\%}{0.1\%}\right)$$
$$\times\left(1-5\%\times MAX\left\{0,\ \frac{\boldsymbol{Cl}\%_{\boldsymbol{eff}}-0.1\%}{1\%-0.1\%}\right\}\right)$$

$$(\mathbf{2})\quad \frac{Availability}{Availability_{base}} = \left(1-\ 10\%\times MAX\left\{0,\ \frac{\boldsymbol{ash}\%-1\%}{10\%-1\%}\right\}\right)$$
$$\times\left(1-\left(\frac{8766}{Availability_{base}}-1\right)\times 15\%\times MAX\left\{0,\ \frac{\boldsymbol{alkali\ index}-0.17}{0.34-0.17}\right\}\right)$$
$$\times\left(1-20\%\times MAX\left\{0,\ \frac{\boldsymbol{Cl}\%_{\boldsymbol{eff}}-0.1\%}{1.6\%-0.1\%}\right\}\right)$$

$$(\mathbf{3})\quad \frac{Opex}{Opex_{base}} = \left(8766-\ Availability_{base}\times\left(1-10\%\times MAX\left\{0,\ \frac{\boldsymbol{ash}\%-1\%}{10\%-1\%}\right\}\right)\right)\middle/(8766-Availability_{base})$$
$$\times\left(1-\left(15\%\times MAX\left\{0,\ \frac{\boldsymbol{alkali\ index}-0.17}{0.34-0.17}\right\}\right)\right)$$
$$\times\left(8766-\ Availability_{base}\times\left(1-20\%\times MAX\left\{0,\ \frac{\boldsymbol{Cl}\%_{\boldsymbol{eff}}-0.1\%}{1.6\%-0.1\%}\right\}\right)\right)\middle/(8766-Availability_{base})$$

$$(\mathbf{4})\quad Cl\%_{eff}\ =\ Cl\%\ \times\left\{\begin{array}{ll} 3, & IF\ \boldsymbol{alkali\ index}>0.34\\ 2, & IF\ 0.17<\ \boldsymbol{alkali\ index}\le 0.34\\ 1, & IF\ \boldsymbol{alkali\ index}\le 0.17\end{array}\right\}$$

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[2] As bromine and fluorine contents are very low in biomass (typically << 0.01%), these have been added to the chlorine contents within D2. Effective chlorine calculation given in formulae (4)

4.3.2 Feedback on new conversion plant relationships

ETI and its reviewers provided a review of the new relationships, leading to refinements within Table 2 and Equations (1) – (4). These review comments focused on:

- The loss of availability for increasing ash content appeared to be based on data from poultry litter ash, which is different chemically from the feedstocks in scope. The project team subsequently examined a couple of different references involving rice straw and hulls, which came to similar conclusions, and hence the relationship was left unchanged.
- Incorrect calculation of the alkali index, which now correctly uses Higher Heating Value (GJ/odt).
- Unlikely low values for combustion technology ash content limits. These have since been revised upwards to allow higher ash feedstocks.
- Chloride related corrosion may be seen at levels lower than 0.2%, and hence our formulae thresholds were adjusted down to 0.1%.
- Lime consumption (with a cost impact) now also leads to a cost impact via lime residue disposal costs – this has been implemented by adding disposal costs into the lime price. Urea consumption is assumed not to lead to further disposal costs. Ash disposal costs are already incorporated into D2.
- There was a question as to whether mitigation for NO_x and acid gases would not be required for very low N, Cl and S feedstocks (below some cut-off), and hence whether the SNCR and acid gas scrubbing capital costs could be avoided. However, the consensus expectation was that plant emissions performance levels will continue to tighten in the future (e.g. via the Medium Combustion Plant Directive), and hence it is likely that SNCR and acid gas abatement equipment cannot be removed from the plant specifications. In other words, it is valid to assume that SNCR will always likely be required for NO_x abatement, and acid gas removal using lime required for Cl and S acid gas abatement. Lower feedstock N, Cl and S contents already lead to lower material consumption of lime and urea.
- Water washing figures for ash removal seem low, although there is a balance to be struck between wash times, temperatures, particle size, species removal rates and wetting of the biomass. Different feedstocks have very different ash removals under water washing. Saddawi et al (2011) gave inherent ash removals of 6% for SRC willow, 62% for Miscanthus, 68% for Eucalyptus. Gudka et al (2015) also have a table summarising dozens of sources that also shows a wide variety of behaviour from ~5 to 60% ash removal. The ranges are therefore very wide, but the team are using specific data points where available, noting that there is very little wood/forestry data available.
- Acidic impacts of N species have not been considered, as these are only second or third order effects.
- The opinion on the use of ash fusion temperatures was that it is acceptable not to consider these explicitly, provided that halide and slagging impacts were quantified. The team has therefore taken this latter approach.

- Not all slagging is alkali-based, with some plants facing Si-Ca slag deposit challenges. The team has modelled the alkali index as one of the key determinants, but has also modelled the impacts of total ash content on availability and opex, which would to a large extent cover this Si-Ca point.
- D2 should consider compounding effects, i.e. how much more corrosive is chlorine content when combined with high slagging or fouling? The resultant acid becomes effectively "locked" behind the slag or fouling and has free reign rather than the transient impacts when being continually "swept" from the surfaces. It was therefore assumed that the effective chlorine content (and hence corrosion impacts on efficiency, availability and opex) doubles if fouling is likely (0.17 kg/GJ < alkali index < 0.34 kg/GJ), or triples if fouling is certain (alkali index > 0.34 kg/GJ). Within the COF dataset, feedstock chlorine contents are all <0.03%, except for Miscanthus at a mean of 0.13% – this multiplicative impact is therefore only significant for Miscanthus chains. Starting COF alkali indices are generally less than 0.26, hence the “fouling certain” zone is unlikely to be entered.
- Higher ash contents could require more capital costs for ash handling kit. However, this incremental capex is very small in comparison to the overall plant capital costs – and removals could be more frequent, rather than having a larger bin. D2 already considers increasing ash disposal costs with increased ash content.
- Torrefied material should have a higher % dry ash content than the source material. The project team have modelled that the dry matter loss (as volatiles) in the torrefaction process translates into an equivalent increase in ash content (% dry basis).
- Further implicit feedback from the ETI and its reviewers at the down-selection was that many of the real-world relationships between biomass species and plant operation are not linear. Efficiency improves with plant scale via a power law, and varies with moisture content via a quadratic relationship. The flame temperature efficiency formulae above rely on inversely proportional relationships, as do the new downtime relationships on overall increases in LCOE. Several of the other relationships rely on a threshold, below which there is no impact assumed, and above which a linear relationship is assumed (as a refined first order approximation). The project team have also taken on board the feedback that impacts may be multiplicative, with the use of an effective chlorine content. The conversion plant modelling is therefore now considerably more sophisticated, and the majority of relationships are now non-linear, compared with the original D2 tool.

4.3.3 Impact of pre-processing on biomass parameters

The project team also received clear guidance in the workshop to quantify more clearly how each of the pre-processing technologies affects the biomass’ chemical characteristics. This data was already within the different WP1 sheets, and has therefore been aggregated into Table 3. Drum drying, belt drying, screening, chipping, briquetting and pelleting have no impact on the biomass chemical characteristics, and have therefore not been included in Table 3, for brevity.

Table 3: Impact of pre-processing on output biomass chemical characteristics

Biomass species	Water washing	Chemical washing	Pyrolysis	Torrefaction	Steam Explosion	AFEX
Moisture content (% wet)	50%	50%	25%	2%	1.4%	10%
LHV (GJ/wet tonne)	= (input LHV dry *(1-50%) – 2.443*50%) / (1-input ash%)*(1-output ash%)	= (input LHV dry *(1-50%) –2.443*50%) / (1-input ash%)*(1-output ash%)	13.4	= 1.09 * input LHV dry * (1-2%) - 2.443*2%	= 1.052 * input LHV dry * (1-2%) - 2.443*2%	= input LHV dry *(1-10%) –2.443*10%
Ash softening temperature (°C)	= Input * 1.21	= Input * 1.3	= Input	= Input + 70	= Input	= Input
Ash content (% dry)	= Input * {0.94 Willow, 0.38 Miscanthus, 0.31 Wood}	0.1%	= Input * 0.05	= Input * 1.2	= Input * 0.8	= Input
Total halides (% dry)	= Input * 0.1	0	= Input * 0.25	= Input * 1.2	= Input * 0.9	= Input
Total alkali metal (% dry)	= Sum of K, Na	0	= Input * 0.003	= Input * 1.2	= Input * 0.6	= Input
Alkali index (kg/GJ)	= Input * {0.54 Willow, 0.38 Miscanthus, 0.55 Wood}	0	= Input * 0.003	= Input * 1.1	= Input * 0.57	= Input
Total volatile content (% dry)	= Input	= Input * 0.945	= Input * 0.8301	= Input * 0.8	= Input	= Input
Fixed carbon (% dry)	= Input	= Input * 1.38	= Input * 1.2856	= Input * 2.0	= Input	= Input
Carbon content (% dry)	= Input	= Input * 1.05	= Input * 1.2856	= Input * 1.09	= Input * 1.05	= Input
Hydrogen content (% dry)	= Input	= Input * 1.03	= Input * 1.0617	= Input * 1.09	= Input	= Input
Nitrogen content (% dry)	= Input	= Input * 1.79	= Input * 0.3617	= Input * 1.2	= Input * 1.1	= Input + 0.4*3%*14/17 / (1-input moisture%)
Silicon content (% dry)	= Input * 0.95	= Input * 0.32	= Input * 0.05	= Input * 1.2	= Input * 0.8	= Input
Chlorine content (% dry)	= Input * 0.1	0	= Input * 0.25	= Input * 1.2	= Input * 0.9	= Input
Bromine content (% dry)	= Input * 0.1	0	= Input * 0.25	= Input * 1.2	= Input * 0.9	= Input
Fluorine content (% dry)	= Input * 0.1	0	= Input * 0.25	= Input * 1.2	= Input * 0.9	= Input
Aluminium content (% dry)	= Input * 0.9	= Input * 0.6	= Input * 0.05	= Input * 1.2	= Input * 0.9	= Input
Potassium content (% dry)	= Input * {0.54 Willow, 0.38 Miscanthus, 0.55 Wood}	0	= Input * 0.0026	= Input * 1.2	= Input * 0.6	= Input
Sodium content (% dry)	= Input * {0.70 Willow, 0.47 Miscanthus, 0.40 Wood}	0	= Input * 0.0083	= Input * 1.2	= Input * 0.6	= Input
Calcium content (% dry)	= Input * {0.97 Willow, 0.81 Miscanthus, 0.96 Wood}	= Input * 0.1	= Input * 0.0018	= Input * 1.2	= Input * 0.8	= Input
Sulphur content (% dry)	= Input * {0.90 Willow, 0.67 Miscanthus, 0.92 Wood}	= Input * 0.28	= Input * 0.2679	= Input * 1.2	= Input * 0.9	= Input
Oxygen content (% dry)	By difference	By difference	= Input * 0.7516	= Input * 0.9	= Input * 0.9	= Input

4.3.4 Inclusion of biomass data into D2

Using the feedstock sampling data provided by the ETI's Characterisation of Feedstocks (COF) project, and revised on 23rd December 2015, average parameter values were derived for all the feedstocks within the study scope. This data is given below in Table 4.

Table 4: Mean values for the TEABPP feedstocks

Name	Miscanthus	SRC willow	SRF conif	SRF decid	LRF pellet
Form	Bales	Chips	Chips	Chips	Pellets
Bulk density (wet tonne/m^3)	0.145	0.359	0.355	0.390	0.675
Size (mm)	2450	38	38	38	20
Moisture content (% wet)	22.0%	53.2%	54.7%	51.2%	6.6%
LHV (GJ/wet tonne)	13.41	7.27	7.46	7.67	17.56
Ash softening temperature (°C)	1,121	1,450	1,409	1,476	1,315
Ash content (% dry)	2.22%	1.60%	1.55%	2.80%	0.93%
Total halides (% dry)	0.14%	0.01%	0.03%	0.02%	0.016%
Total alkali metal (% dry)	0.34%	0.20%	0.20%	0.35%	0.086%
Alkali index (kg/GJ)	0.23	0.13	0.13	0.23	0.055
Total volatile content (% dry)	80.9%	82.6%	78.1%	80.0%	0.8%
Fixed carbon (% dry)	16.7%	15.9%	19.9%	17.0%	0.16%
Carbon content (% dry)	48.5%	49.4%	51.7%	49.5%	50.5%
Hydrogen content (% dry)	5.9%	6.1%	6.2%	6.0%	6.1%
Nitrogen content (% dry)	0.40%	0.45%	0.55%	0.62%	0.29%
Silicon content (% dry)	0.47%	0.02%	0.05%	0.03%	0.12%
Chlorine content (% dry)	0.135%	0.012%	0.026%	0.016%	0.015%
Bromine content (% dry)	0.00056%	0.00020%	0.00027%	0.00025%	no data
Fluorine content (% dry)	0.00020%	0.00020%	0.00021%	0.00021%	0.00063%
Aluminium content (% dry)	0.0037%	0.0045%	0.0090%	0.0050%	0.030%
Potassium content (% dry)	0.33%	0.20%	0.19%	0.34%	0.077%
Sodium content (% dry)	0.0094%	0.0044%	0.0080%	0.0104%	0.0085%
Calcium content (% dry)	0.12%	0.41%	0.28%	0.67%	0.145%
Sulphur content (% dry)	0.011%	0.010%	0.021%	0.032%	0.012%
Oxygen content (% dry)	43.60%	42.80%	40.30%	41.55%	no data

With the new relationships, and aggregation of the impacts of each pre-processing technology into a consistent format, the project team had initially planned on conducting a manual process outside of D2, whereby each feedstock from Table 4 would be fed through the factors in Table 3 to derive pre-processed biomass forms. The impact on conversion plant efficiency, availability and opex could be estimated using the new relationships in Table 2, and then the intention was to manually update D2 with these improved operational parameters to see the impact on overall chain LCOE.

However, the number of parameters and their multiplicative impacts meant that this hard-coding approach outside of D2 was no longer simple, nor feasible. The project team therefore took the decision to take a more sophisticated approach, by including the biomass parameters within the D2 tool, and hence explicitly following these parameters through the different supply chains. This more reliable approach is also in line with previous ETI requests to build out the D2 tool with more functionality, and turn it into a simple process model.

During this process, drying and dry matter losses incurred in storage were included (dependent on the weeks of storage, type of storage and the starting and ending moisture content), in order to quantify the biomass parameters at the conversion plant gate, with and without pre-processing. Each of the conversion technologies in D2 has then been modified to include the new efficiency, availability and opex relationships, in order to be influenced by the different biomass parameters.

The project team note that this new approach was deemed essential to carry out this extra work in order to more accurately quantify the costs and benefits of pre-processing, and hence robustly justify the chain choices in D3.

5 Down-selection

5.1 Introduction

The results of the D2 tool for all chains are shown in Figure 2. This shows that the primary determining factor for the LCOE is the choice of energy end vector produced (hot water, electricity or syngas). It is therefore not advisable to directly compare the LCOE of chains across all these different energy vectors, rather LCOE values should only be compared within sectors that have the same end vector. Further differentiation between the end vectors is shown in Figure 3, with the different chain efficiencies (note that CHP applications add power and heat outputs together).

This led to the decision to choose a set of representative applications and scales, as a way to make sure that the chains chosen covered the range of typical project types that might be used in the UK. As agreed with the workshop participants, the key applications of interest are:

- Power at >100 MW_e
- Power at 1-10 MW_e
- Heating at < 1 MW_{th}

Although one of the primary criteria was variation across technologies and vectors, it was agreed at the workshop not to consider any CHP vector chains. In technical terms, the CHP technologies are same as power only, as they have the same gas engines or steam turbines (but with waste heat captured), and identical boilers or gasifiers with identical feedstock requirements. As a result, the insights gained from power and CHP chains in terms of upstream biomass pre-processing would be similar. As well as helping to narrow down the available options, CHP units are often led by their heat demands, and so their operational regimes are not reflective of true technical availabilities.

One of the choices for power at >100 MW_e is entrained flow gasification + CCGT power (further justified below). As entrained flow gasifiers are also a good choice for syngas production (important for CCS and hydrogen production), and the turbine component requires the same syngas specification as the syngas end vector applications, this removed the need to consider syngas routes separately. It was agreed at the workshop that this approach allows the project to keep more chain options available for investigating pre-processing variations.

The variation in pre-processing was agreed to be far more valuable to the TEABPP study than the variation in end vector, leading to this focus on small heating, mid-scale and large-scale power.

For each of these three applications, the criteria from Section 3 were used to select one or two conversion technologies. Then for each of these selected conversion technologies, the same criteria were then used to select at least two chains with (and without) different pre-processing options for comparison. Note that in some cases, the comparator chain might not be a chain without pre-processing – it might be a chain already including e.g. pelleting. This would be the case for entrained flow gasifiers and dust combustion plants, which cannot take chips.

Despite the desire from the workshop to focus on selecting chains representing a range of different pre-processing technologies, there was also limited interest in several of the technologies as discussion in section 5.5. This means that some technologies are considered in more than one chain.

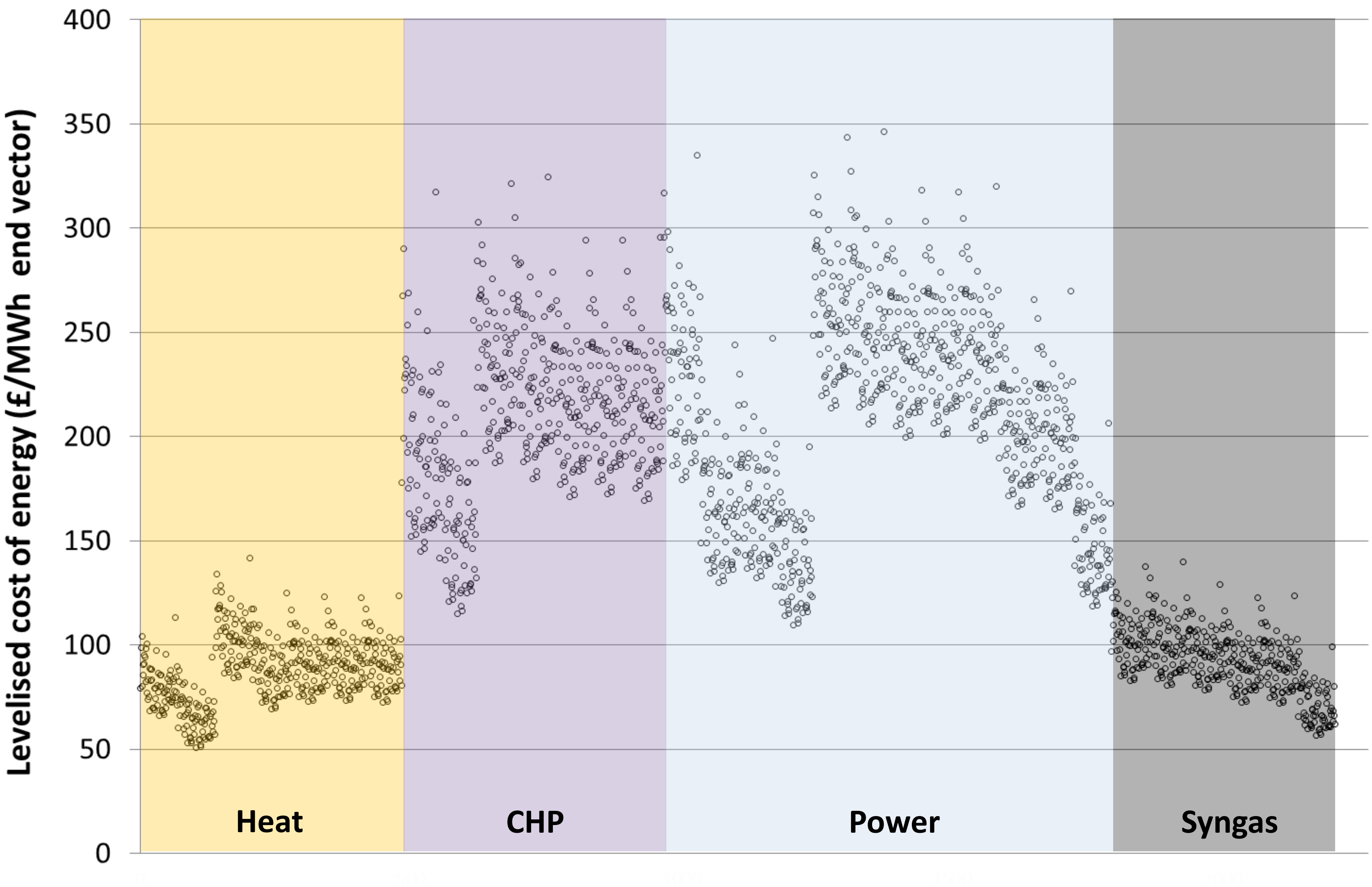

Figure 2: LCOE for all chains in D2

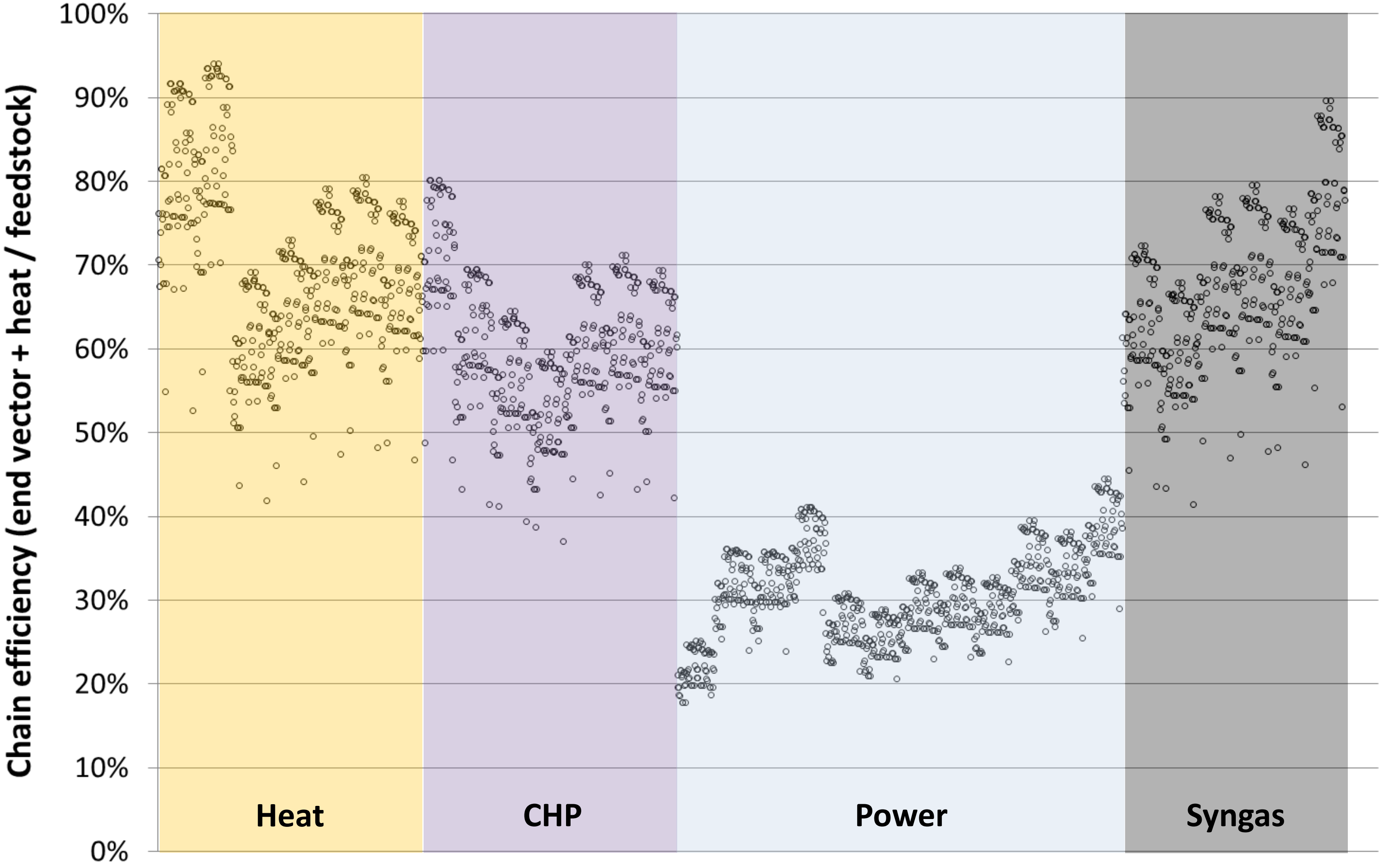

Figure 3: Chain efficiency for all chains in D2

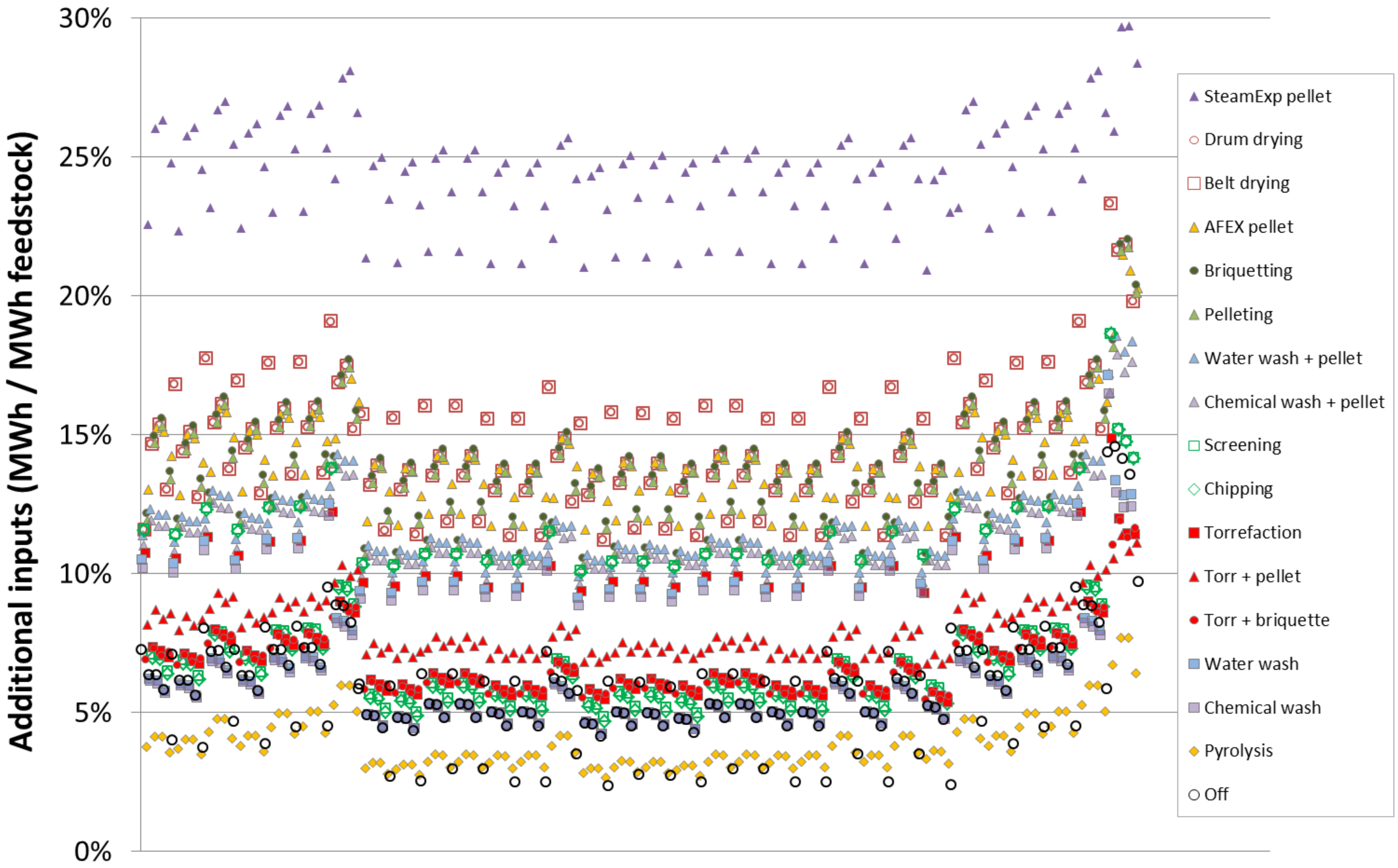

Figure 4: Additional energy inputs for all chains in D2, categorised by pre-processing technology

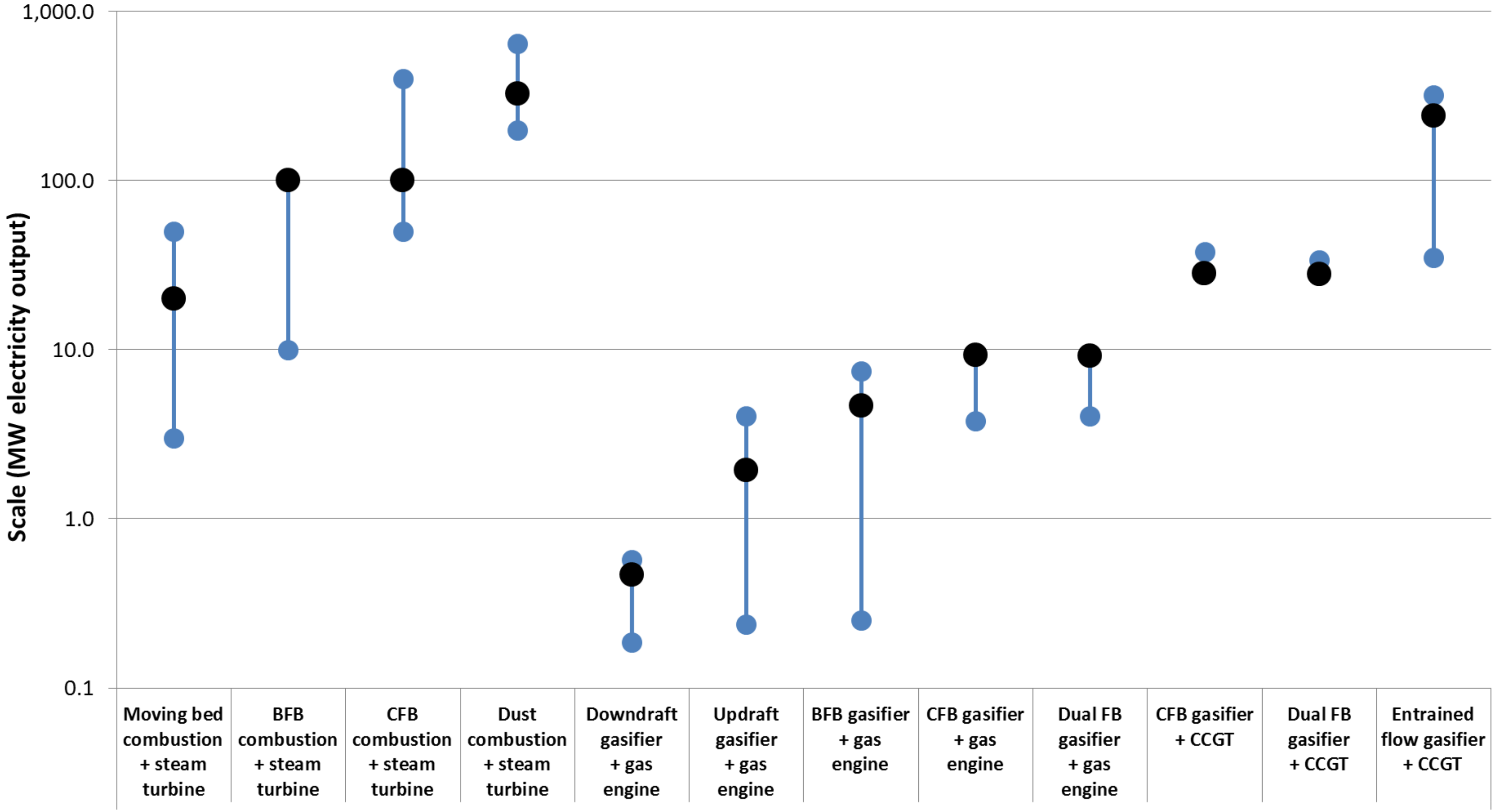

Figure 5: Electricity conversion technology scale ranges (black dot = base case capacity, blue dots = min/max capacity range)

5.2 Power at >100 MW_e

The conversion technologies for large scale power production are shown in Figure 5. This illustrates that although there are several technologies that are applicable in the 50-100 MW_e scale range, there are only three technologies that can be used at over 100 MW_e: CFB combustion + steam turbine, dust combustion + steam turbine, and entrained flow gasification + CCGT. These technologies are compared below in Table 5, at their base case scales, and assuming pellets, as dust combustion and entrained flow gasifier technologies are not designed to handle chipped material. Note that “Net balance” is the chain efficiency minus additional inputs, as defined in Section 2.1.

Table 5: LCOE for large-scale power technologies, for SRC willow pellet chains

Conversion technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)	**Min-base-max scales** (MW output)
CFB combustion + steam turbine	**147**	**35%**	**13%**	**22%**	**50 - 100 - 400**
Dust combustion + steam turbine	123	41%	13%	27%	200 - 320 - 645
Entrained flow gasifier + CCGT	**136**	**43%**	**13%**	**30%**	**35 - 236 - 320**

If comparing these technologies at the same scale, e.g. 270 MW_e, with only one unit of each conversion technology set within each chain (not 3 units, as the CFB base case would have as default), then the CFB chain has a lowered LCOE of £135/MWh_e, the Dust combustion chain remains at £123/MWh_e, and the Entrained flow chain improves slightly to £131/MWh_e. Although CFB combustion has lower capex and opex than dust combustion and EF gasifier options, it also has the lowest conversion efficiency of the three, and therefore there is a higher contribution of feedstock cost to the LCOE. If the CFB chain were to instead only use SRC willow chips, then the LCOE discussed in the text above would fall further to £125/MWh_e, making this chain competitive (certainly within the error bounds) of the Dust and EF gasifier options.

Workshop discussions concluded that it would be useful for the TEABPP project to select:

- **Entrained flow gasification + CCGT** – these large scale entrained flow gasifiers could be a good match with CCS technologies, and would likely be needed for hydrogen or bioSNG production from biomass if used in decarbonising the gas grid (at a town or city scale). The degree of gas clean-up for power generation in the CCGT component would be similar to that required for syngas-using applications, and therefore it was considered worthwhile to select this as a power route rather than a syngas end vector alone (which would already be cleaned up to turbine specifications).
- **CFB combustion + steam turbine** – as this is the technology typically chosen for large dedicated biomass electricity plant today. Workshop participants noted that the choice of the particular combustion to power technology in the project was less important than the pre-processing options considered, i.e. learnings from this CFB case study would still apply to BFB and moving bed combustion systems, due to multiple boiler commonalities.

Despite its low LCOE, Dust combustion + steam turbine systems were not selected for study, due to a lack of developers globally, and limited interest in new build plants using the technology – to date, biomass dust combustion has only been used after retrofitting from coal power stations.

5.2.1 Entrained flow gasification + CCGT

Table 6 and Table 7 compare the available pre-processing options for Entrained flow gasification + CCGT chains using SRC willow and Miscanthus respectively, noting that use of chipped or briquetted material is not allowed, but use of pyrolysis oil is allowed.

The use of pyrolysis oil in the gasifier (zero grinding energy) is assigned an electricity generation efficiency uplift in terms of grinding energy saved, as are torrefied pellets (at only 4.1 kWh_e/tonne grinding energy), and to a lesser extent, steam exploded pellets (at 26 kWh_e/tonne), compared to the grinding power consumption of 102 kWh_e/tonne for white pellets[3].

Table 6: LCOE for Entrained flow gasifier + CCGT chains, using SRC willow (selected chains in red)

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Water washing + Pelleting	161	39%	11%	28%
Chemical washing + Pelleting	173	37%	10%	26%
Pyrolysis	**177**	**37%**	**4%**	**34%**
Pelleting	**136**	**43%**	**13%**	**30%**
Torr + pellet	**144**	**36%**	**7%**	**28%**
SteamExp pellet	141	40%	24%	15%

Table 7: LCOE for Entrained flow gasifier + CCGT chains, using Miscanthus (selected chains in red)

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Water washing + Pelleting	155	35%	10%	25%
Chemical washing + Pelleting	168	33%	10%	23%
Pyrolysis	**181**	**30%**	**3%**	**27%**
Pelleting	**134**	**39%**	**10%**	**28%**
Torr + pellet	**145**	**32%**	**7%**	**25%**
SteamExp pellet	136	36%	21%	15%

The pre-processing technologies selected for entrained flow gasification + CCGT are:

- **Pelleting** – this takes the place of the "Off" chain, as entrained flow gasifiers need to use a homogenous pre-processed feedstock, rather than chips. In all feedstock situations, pelleting is the lowest cost pre-processed option that is suitable for entrained flow gasifiers.
- **Torrefaction + pelleting** – for most conversion technologies, this is a significantly higher cost option than pelleting alone. However, for entrained flow gasification, the costs are much closer to pelleting alone, because the torrefaction process reduces the energy required for grinding. In the workshop, doubt was cast on the reference performance of torrefaction

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[3] Williams, O. (2014) "Bond Index & Hardgrove Grindability: Index Tests for Biomass & Coal" Presentation available at: http://www.coalresearchforum.org/eccria2014/Sessions%204A%20to%207A/5A1%20-%20Williams%20revised.pdf

given in the IEA Bioenergy Task report, in particular the LHV of the product and the ability of the overall process to be self-sufficient in energy terms. For the output product, 22-24 GJ/tonne is possible, but these pellets would be highly fragile. Expert opinion was that a maximum LHV of 19-20 GJ/tonne is achieved in practice today. Many plants are also using natural gas for feedstock drying, as the torrefaction gases are too wet/insufficient quality to use. Natural gas consumption would add to costs, or alternatively, the efficiency of the process would have to drop significantly if taking a proportion of the feedstock for heating. In D2, all torrefaction options are already modelled using a mix of off-gases and feedstock for drying, hence the LHV of the torrefied product was reduced to 20 GJ/tonne, which also had the impact of reducing the overall process efficiency. The output chain LCOE and efficiencies are already known to be sensitive to the choice of torrefied LHV, and the self-sufficiency of the plant, and hence these chains and parameters are worth exploring in greater detail in WP3.

- **Pyrolysis** – this is only suitable for use in entrained flow gasification. The grinding energy benefit is however not enough to offset the high capex and efficiency losses of pyrolysis (impacted by alkali metals), and the conversion technology efficiency loss through using bio-oil at 25% moisture content – but this is the one chain where pyrolysis is the closest in terms of LCOE to a counterfactual (white pellet), and hence worth investigating when this chain might be beneficial in WP3. It is also the chain most closely aligned with the bioliq® concept at the Karlsruhe Institute of Technology. The learnings from this more innovative supply chain was felt by the workshop attendees to be important to include, as this chain also allows pipelines, liquid tankers and storage tanks to be modelled. Using pipelines instead of liquid tankers in the final two transport steps leads to a LCOE benefit of £7/MWh$_e$ compared to the pyrolysis chain values in Table 6 and Table 7.

Steam exploded pellets are not considered, due the additional energy inputs exceeding 20%. Washing + pellets options remain relatively high cost, and provide less of a benefit to entrained flow gasification systems, as the flame and corrosion management efficiency uplifts for combustion (with lower ash, S and Cl) do not apply, and as the slagging gasifier design is able to accept higher ash contents without availability issues.

5.2.2 CFB combustion + steam turbine

Table 8 and Table 9 compare the available pre-processing options for CFB combustion + steam turbine chains using SRC willow and Miscanthus respectively – noting that pyrolysis oil is excluded as a feedstock. Chipping has also not been considered as a pre-processing step for the SRC willow chains, given the feedstock is already starting as chips post-harvest.

Table 8: LCOE for CFB combustion + steam turbine chains, using SRC willow chips

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Off	**137**	**35%**	**5%**	**30%**
Water washing	175	30%	5%	25%
Chemical washing	189	29%	5%	24%
Water washing + Pelleting	177	32%	11%	21%
Chemical washing + Pelleting	**192**	**30%**	**11%**	**20%**
Drum drying	143	36%	13%	23%
Belt drying	144	36%	13%	22%
Screening	140	35%	6%	29%
Torrefaction	165	30%	6%	24%
Torr + briquette	166	30%	6%	24%
Briquetting	155	35%	14%	22%
Pelleting	**147**	**35%**	**13%**	**22%**
Torr + pellet	168	30%	8%	22%
SteamExp pellet	164	33%	25%	9%
AFEX pellet	190	34%	14%	20%

Table 9: LCOE for CFB combustion + steam turbine chains, using Miscanthus bales

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Off	**151**	**30%**	**6%**	**24%**
Water washing	215	28%	9%	18%
Chemical washing	230	26%	9%	17%
Water washing + Pelleting	170	29%	10%	19%
Chemical washing + Pelleting	**185**	**27%**	**10%**	**17%**
Drum drying	186	32%	16%	16%
Belt drying	187	32%	16%	16%
Screening	191	30%	10%	19%
Torrefaction	204	27%	10%	17%
Torr + briquette	163	27%	6%	21%
Briquetting	151	31%	11%	21%
Pelleting	**143**	**31%**	**11%**	**21%**
Torr + pellet	166	27%	7%	20%
SteamExp pellet	157	30%	21%	9%
AFEX pellet	185	30%	12%	18%

Table 8 and Table 9 follow a similar pattern to Table 11 and Table 12, with increased costs for lower density Miscanthus favouring more involved pelleting options, and the higher density SRC willow chains favouring simpler processing steps such as drying and screening. Water and chemical washing of Miscanthus ends up with chain costs that are more than 40% above the Off chain, and hence can be excluded on cost grounds (the equivalent SRC chip chains are 28-38% more expensive than Off).

Based on these results, and the discussions from the workshop and stage gate review, there was interest in several potential pre-processing options for CFB combustion + steam turbine. The pre-processing options selected are:

- **Minimal pre-processing, with screening** – i.e. natural drying of chips or bales, and screening for chip sizes, is the most appropriate chain to set as the “Off” chain
- **Pelleting** offers the several of the cheapest chain LCOEs, particularly for Miscanthus. The use of pelleting alone is likely appropriate for large-scale power applications, where plants >100MW$_e$ are more likely to source a large percentage of their biomass from outside of the local region, and truck, rail or ship pellet supplies in.
- **Chemical washing + pelletising**. Chemical washing + pelleting adds very significant costs for cleaner feedstocks such as SRC willow (almost exceeding the 40% cut-off), but for Miscanthus, there are benefits of reduced ash and alkali metals on the boiler efficiency and opex. The densification also offers transport step savings, to offset some of the added pre-processing technology step costs. Further investigation of the cost, scales and technical bounds and uncertainties for chemical washing will therefore be an important avenue of research within WP3. We note that this is one of the most expensive chains available, but the ETI and steering group participants were keen to include it, in order to improve the variety of technologies selected within the 10 chains, and so that the high costs and innovation potential could be investigated further in WP3-4. The initial discussions and our analysis had previously led to the selection of the cheaper water washing + pelleting option, but this will be considered elsewhere in chain #4 (see below).

Torrefaction + pelleting has already been selected within the Entrained flow gasification + CCGT to power chain, and so is not selected here. Other low LCOE options are excluded for the reasons discussed in section 5.5. Another selection option for more variety would be to replace pelleting (which is considered for EF gasification + CCGT) with briquetting. This has a very low LCOE but there was little interest in this option in the workshop.

5.3 Power at 1-10 MW$_e$

For power generation in the 1-10 MW$_e$ scale range, several combustion or gasification technologies could be used, as shown in Figure 6. These include fixed bed and fluidised bed gasifier + syngas engine systems, as well as moving bed combustion + steam turbine systems. Potentially only the very smallest BFB combustion + steam turbine systems could meet the 10MW$_e$ threshold, as most systems will be significantly larger. These conversion technology options are compared in Table 10 below, at their base case scales. Note that “Net balance” is the chain efficiency minus additional inputs, as defined in Section 2.1.

Note that downdraft gasifier + syngas engine systems are too small, whilst CFB and dust combustion + steam turbine systems, and all of the gasifier + CCGT systems are too large. BFB combustion + steam turbine systems only start at 10 MW_e (right on the upper bound of the power application range considered), and so are likely to be too big to consider.

Table 10: LCOE for small-scale power technologies, for SRC willow chip chains without pre-processing

Conversion technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)	**Min-base-max scale** (MW output)
Moving bed combustion + steam turbine	186	25%	5%	20%	3.0 - 20 - 50
BFB combustion + steam turbine	135	35%	5%	30%	10 - 100 - 100
Updraft gasifier + gas engine	214	28%	5%	23%	0.24 - 1.9 - 4.1
BFB gasifier + gas engine	**205**	**33%**	**5%**	**28%**	**0.25 - 4.7 - 7.5**
CFB gasifier + gas engine	206	33%	5%	28%	3.8 - 9.3 - 9.3
Dual FB gasifier + gas engine	205	32%	6%	26%	4.1 - 9.2 - 9.2

There is little to distinguish the chains in terms of additional energy inputs, but the overall chain efficiency varies significantly with scale, and the type of system:

- The fluidised bed (BFB, CFB and Dual FB) gasifiers have significantly higher chain efficiencies to electricity (well above 30%) compared than combustion technologies at a similar scale – for example, a larger moving bed + steam turbine chain only achieves 25% efficiency overall.
- Updraft gasifier chains are more expensive and less efficient (mainly to high tar production which requires extensive cleaning), and updraft systems only typically operate at smaller scales, as shown in Figure 5 – examples towards the top end of the updraft gasifier scale range are rare.
- CFB and Dual FB gasifiers have similar costs and energy efficiency if they are compared at the same scale (e.g. £217-220/MWh_e at 4.6 MWe), although BFB is marginally cheaper at £205/MWh_e at the same scale.

BFB gasification + syngas engine was chosen as it has a lower minimum scale (0.5MW_e), and slightly lower costs. BFB is also a good fit with the gasifier technologies that have been considered and undergone FEED in the ETI's Waste Gasification project. There was good agreement in the workshop about the choice of this conversion technology.

5.3.1 BFB gasification + syngas engine

Table 11 and Table 12 compare the available pre-processing options for BFB gasification + syngas engine chains using SRC willow and Miscanthus respectively – noting that briquetting, torrefied briquettes and pyrolysis oil are excluded, as they are unsuitable feedstock forms. Chipping has also not been considered as a pre-processing step for the SRC willow chains, given the feedstock is already starting as chips post-harvest.

Table 11: LCOE for BFB gasifier + syngas engine chains, using SRC willow chips

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Off	**205**	**33%**	**5%**	**28%**
Water washing	246	28%	5%	23%
Chemical washing	260	27%	5%	22%
Water washing + Pelleting	**252**	**29%**	**11%**	**18%**
Chemical washing + Pelleting	267	28%	10%	17%
Drum drying	214	32%	13%	19%
Belt drying	215	32%	13%	19%
Screening	209	32%	6%	27%
Torrefaction	241	27%	6%	21%
Pelleting	218	32%	13%	19%
Torr + pellet	245	27%	7%	19%
SteamExp pellet	238	30%	24%	5%
AFEX pellet	266	31%	14%	17%

Unlike in the heat sector, none of the chains in Table 11 are able to match the "Off" chain LCOE and efficiency (which has natural drying down to ~20% moisture in a shed). For the SRC willow chains, forced drying is relatively cheap, and helps improve the end conversion efficiency, and reduces losses in storage, although does have elevated additional energy inputs. Standalone drying technologies have not been selected for BFB gasifier chains, despite having some of the lowest LCOE (nearest to the "Off" chain). This is because the workshop participants considered that drying technologies are not particularly innovative, and so effort would be better spent on modelling the potential of more novel technologies, given the limit of 10 chains for selection. All the chains involving pelleting also include drying equipment, with the dryer opex dependent on the input biomass moisture content, and hence drying will already be a component within the selected chains, and not worth modelling separately. It is also worth noting that because all chains include natural drying, the impact of feedstock moisture content on the chains can also be assessed by varying storage times (accepting that long-term storage of biomass in the UK might reach an equilibrium of ~30% moisture content if stored uncovered outside, or ~20% if indoors).

Pelleting LCOE is similar to drying chains as the added costs of pelleting are mostly offset by the savings in transport (for the base case transport distances assumed), with the drier material having similar benefits to the forced drying chains (and similar inputs required). Screening is a very simple addition to the "Off" chain, with the added costs and benefits both small. No other chains have particularly low LCOEs.

Table 12: LCOE for BFB gasifier + syngas engine chains, using Miscanthus bales

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Off	**228**	**28%**	**6%**	**22%**
Water washing	287	26%	9%	16%
Chemical washing	303	25%	9%	15%
Water washing + Pelleting	**243**	**26%**	**10%**	**16%**
Chemical washing + Pelleting	260	25%	10%	15%
Drum drying	267	29%	16%	14%
Belt drying	268	29%	16%	14%
Screening	270	28%	10%	17%
Chipping	267	28%	10%	18%
Torrefaction	290	24%	9%	15%
Pelleting	220	29%	10%	18%
Torr + pellet	248	24%	7%	17%
SteamExp pellet	232	27%	21%	6%
AFEX pellet	266	28%	12%	16%

Similar to the heat sector, the “Off” chain for Miscanthus shown in Table 12 has a higher LCOE in comparison to the SRC willow chain, due to the expense of transporting low density bales, and the impact of alkali metals and chlorine on the gasifier availability and opex. Shredding the bales (as required by washing, screening, chipping, torrefaction and the forced drying technologies considered), only makes the density of the material worse. However, those Miscanthus chains that use pelleting see very significant savings in transport costs, with Pelleting having a lower LCOE than the “Off” chain.

Despite Miscanthus being a drier starting feedstock, steam explosion still has the highest additional energy input, and hence lowest overall net balance of the Miscanthus chains, at only a 6% return on the initial feedstock energy. Therefore, although it is one of the cheaper Miscanthus chains, it can be excluded because the additional energy inputs exceed 20%. Torrefaction + pelleting and water washing + pelleting also have a relatively similar costs and net balances, despite the washing chains having an intermediate natural drying step.

Based on these results, and the discussions from the workshop, there was interest in two pre-processing options for BFB gasification + syngas engine. These pre-processing options are:

- **Minimal pre-processing, with screening** – i.e. natural drying of chips or bales, and screening for chip sizes is the most appropriate chain to set as the “Off” chain
- **Water washing + pelletising**. Water washing + pelleting adds significant costs for cleaner feedstocks such as SRC willow, but for Miscanthus, the benefits of reduced ash and alkali metals have a significant beneficial impact due to the high share of operating costs for BFB gasification. The densification also offers transport step savings, to offset much of the added pre-processing technology step costs. Further investigation of the cost and technical bounds

and uncertainties for water washing will therefore be an important avenue of research within WP3.

Although pelleting is again currently the cheapest pre-processing option, it is not selected here due to the need to ensure variety in the 10 chains, and because it is already being selected for both larger power conversion chains (Entrained flow gasification + CCGT, and CFB combustion + steam turbine).

Torrefaction + pelleting has also already been selected within the Entrained flow gasification + CCGT to power chain, and hence is not selected here.

5.4 Heating at < 1 MW_{th}

A range of technologies have been considered for hot water production, at the range of scales shown in Figure 6. Black dots indicate the base case scale assumed in the WP1 benchmarking analysis, and the blue dots indicate the range of scales over which the WP1 techno-economic data and re-scalings are applicable for each technology.

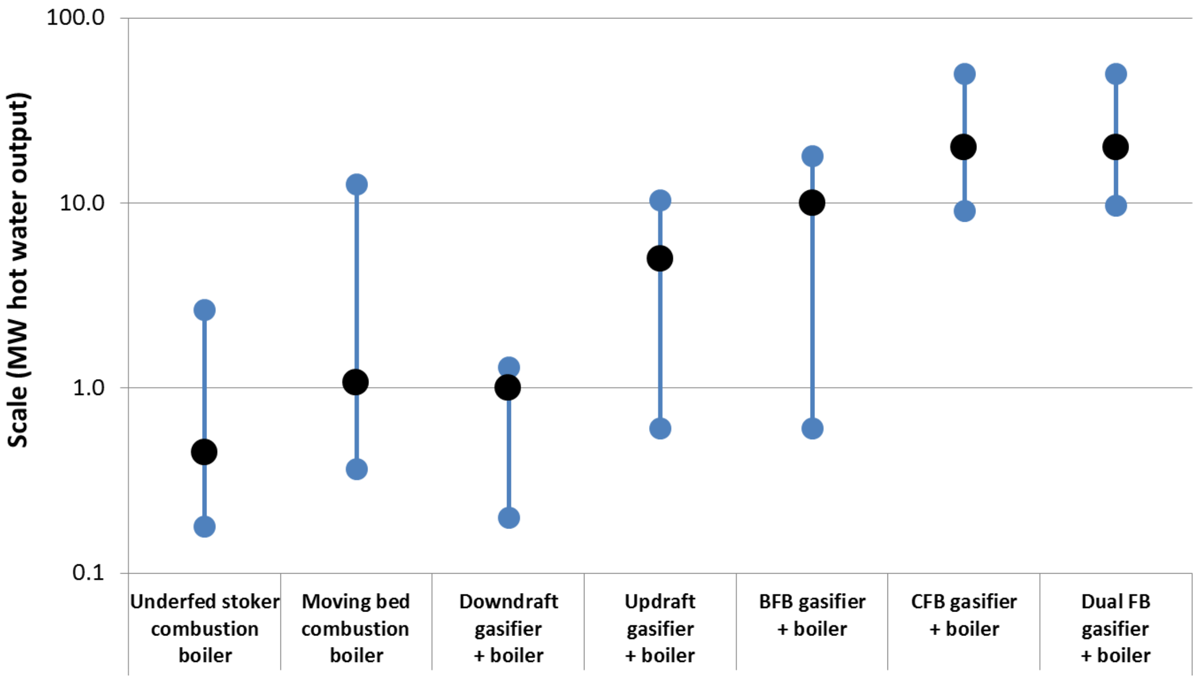

Figure 6: Hot water conversion technology scale ranges (black dot = base case capacity, blue dots = min/max capacity range)

Table 13 compares the LCOE and efficiencies of these heating technologies, at their base case scales. “Net balance” is the chain efficiency minus additional inputs, as defined in Section 2.1. Table 13 shows that biomass combustion heating technologies have higher efficiencies and are cheaper than gasification technologies, even when comparing against gasification systems at larger scales. This comparison is carried out for the “off” chains without pre-processing, and for a chipped woody feedstock such as SRC willow (the LCOE results are higher for Miscanthus, due to the low density bale transport and chlorine content, despite the lower Miscanthus production cost). This focus on combustion agrees with the consensus view at the workshop.

Although it is recognised that district heating and potential futures for the UK energy system could rely more heavily on large-scale heating technologies, the current generation of combustion boilers are focused on the 0.2 – 10 MW$_{th}$ range, as shown in Figure 6.

Table 13: LCOE for hot water technologies, for SRC willow chip chains without pre-processing

Conversion technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)	**Min-base-max scale** (MW output)
Underfed stoker combustion boiler	**68**	**89%**	**6%**	**83%**	**0.18 - 0.45 - 2.7**
Moving bed combustion boiler	53	92%	6%	86%	0.4 - 1.1 - 13
Downdraft gasifier + boiler	87	68%	7%	61%	0.2 - 1.0 - 1.3
Updraft gasifier + boiler	73	72%	6%	65%	0.6 - 5.0 - 10
BFB gasifier + boiler	75	78%	7%	70%	0.6 - 10 - 18
CFB gasifier + boiler	76	79%	7%	72%	9.0 - 20 - 50
Dual FB gasifier + boiler	75	76%	9%	67%	9.7 - 20 - 50

The combustion technologies available for providing hot water in TEABPP are underfed stoker and moving bed combustion boilers. These have similar chain LCOE when at the same scale (e.g. £55/MWh$_{th}$ when at 1 MW$_{th}$). Both have similar additional energy inputs and overall chain efficiencies, as shown in Table 13. Underfed can be used at smaller scales (minimum 170 kW$_{th}$ vs 350 kW$_{th}$ for moving bed), and so could be more applicable for small commercial/large domestic applications (where the Renewable Heat Incentive has seen most uptake). The tighter feedstock requirement for underfed systems (<35% moisture, and pellets or small chips preferred) means that pre-processing options could also add more value to this supply chain than for moving bed, which has more flexibility on feedstock form and moisture content.

There was therefore consensus surrounding the selection of **underfed combustion** boilers as the conversion technology for the hot water routes.

5.4.1 Underfed stoker combustion boiler

Table 14 and Table 15 compare the available pre-processing options for underfed combustion chains using SRC willow and Miscanthus respectively – noting that briquetting, torrefied briquettes and pyrolysis oil are excluded, as they are unsuitable feedstock forms. Chipping has also not been considered as a pre-processing step for the SRC willow chains, given the feedstock is already starting as chips post-harvest.

Table 14: LCOE for underfed combustion boiler chains, using SRC willow chips

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Off	**68**	**89%**	**6%**	**83%**
Water washing	**83**	**78%**	**6%**	**71%**
Chemical washing	88	75%	6%	68%
Water washing + Pelleting	83	82%	12%	70%
Chemical washing + Pelleting	88	78%	12%	66%
Drum drying	69	92%	15%	77%
Belt drying	70	92%	15%	77%
Screening	70	88%	7%	81%
Torrefaction	79	76%	7%	69%
Pelleting	71	91%	15%	76%
Torr + pellet	80	76%	9%	67%
SteamExp pellet	77	85%	26%	59%
AFEX pellet	86	84%	15%	69%

Table 15: LCOE for underfed combustion boiler chains, using Miscanthus bales

Pre-processing technology	**LCOE** (£/MWh vector)	**Chain efficiency** (MWh vector /MWh feed)	**Additional inputs** (MWh/MWh feed)	**Net balance** (MWh/MWh feed)
Off	79	76%	7%	69%
Water washing	**98**	**71%**	**11%**	**60%**
Chemical washing	104	67%	10%	57%
Water washing + Pelleting	80	74%	11%	63%
Chemical washing + Pelleting	86	70%	11%	59%
Drum drying	95	75%	12%	64%
Belt drying	95	75%	12%	64%
Screening	95	75%	12%	64%
Chipping	94	76%	12%	65%
Torrefaction	98	68%	11%	57%
Pelleting	73	81%	12%	69%
Torr + pellet	83	68%	8%	60%
SteamExp pellet	75	76%	23%	54%
AFEX pellet	88	75%	13%	62%

Several of the chains with pre-processing have similar or better LCOEs, and similar or better overall net energy balances to the "Off" chain (which has natural drying down to ~20% moisture in a shed). For the SRC willow chains, forced drying is cheap - the dried chips help improve the end conversion thermal efficiency (from 79% to 85%), the drying step itself results in a rise in LHV (of ~3%) and reduces losses in subsequent storage steps (by ~1%). The net effect is to raise the overall chain efficiency by ~10%, but this does incur some additional energy inputs (an extra input of ~9% due to natural gas use), hence the net energy balance remains almost unchanged, and the chain is lacking in innovation opportunities.

Pelleting LCOE is similar to the "Off" chain as the added costs of pelleting as mostly offset by the savings in transport, with the drier material having similar benefits to the forced drying chains (and similar fossil inputs required in drying biomass down to 10% moisture). Screening is a very simple addition to the "Off" chain, with the added costs and benefits both small.

The "Off" chain for Miscanthus has a high LCOE in comparison to the SRC willow chain, due to the expense of transporting low density bales, and the impact of alkali metals and chlorine on the boiler technology. Shredding the bales (as required by washing, screening, chipping, torrefaction and the forced drying technologies considered), only makes the density of the material worse. However, those Miscanthus chains that use pelleting see very significant savings in transport costs, offsetting even the additional cost of water washing + pelleting (at the base case transport distances and technology scales assumed in D2). Note that the washing + pelleting chain includes a natural drying stage (with losses) after the washing in order to reduce the moisture content from 50% to 20% before pelleting. If this is not done, the natural gas use in the pelletising stage is considerably higher. It is worth the (low) cost of this additional natural drying stage to reduce the cost and energy impacts of pelletisation, rather than pelleting the wet washed material immediately.

Steam explosion pellets have the highest additional energy input, and hence lowest overall net balance of the underfed chains. Therefore, although it is one of the cheaper Miscanthus chains, it can be excluded due to the additional energy inputs exceeding 20%. Torrefaction + pelleting also has a relatively poor net energy balance, and is more expensive.

Based on these results, and the discussions from the workshop, there was interest in several potential pre-processing options for underfed combustion. The pre-processing options selected are:

- **Minimal pre-processing, with screening** – i.e. natural drying of chips or bales, and screening for chip sizes is the most appropriate chain to set as the "Off" chain
- **Water washing only** (without pelletising). Water washing is more expensive than pelleting by £25/MWh$_{th}$, as the additional cost of the washing step and transport is not sufficiently mitigated by the benefits of reduced ash and alkali metals. However, there is the potential for cost reduction in washing, through use of cheaper methods, and so it is worth including this chain in order to allow the WP3 model to explore this possibility.
    - One cheaper method could be rudimentary water washing that could happen in-field, using a hose. This would avoid most of the capex, and waste water and solids treatment costs, but it is not known with certainty how effective it would be in terms of removal of chemical species, compared with washing sized feedstock in a controlled environment. As an indication, removing the capex and waste treatment opex of the washing step would reduce the water washed Miscanthus chain costs to £68/MWh$_{th}$ if transporting chips only 50km, compared to £65/MWh$_{th}$ for an "Off" chain with Miscanthus bales travelling the same distance (much shorter than the generic D2 tool set-up).

- Washing would be of most value for deciduous SRF and Miscanthus, as of the COF feedstocks, these have the highest ash contents and alkali metal contents (with Miscanthus having high chlorine content). It would also be possible to adapt the water washing module to consider the added costs and improved removal efficiencies (effectively modelling chemical washing) as a variant in WP4.
- Although water washing does not reduce N content, and does not result in a very large reduction in Silica, the reduction in (inherent) ash content will be an important consideration for cleaning up feedstocks in order to meet stricter NO_x and particulate matter (PM) limits being introduced from 2017, where it is already known that ash content will be particularly problematic for underfed boilers. The alternative of designing for future boiler improvements will be considered in the WP4 innovation headroom analysis.

Although pelleting is currently the most likely feedstock type to be used in small-scale biomass heating applications in the UK, and is one of the lowest LCOE options given the transport assumptions in the D2 tool, this pre-processing option was not selected, as it is well understood by industry, and pelleting forms two of the chains for Entrained flow gasification + CCGT, and CFB combustion + steam turbine. Ensuring a high level of variety of pre-processing options across the portfolio therefore means it is recommended that pelleting is not selected. Chips are a suitable feedstock for underfed systems, and used in many commercial systems, and are more likely to be utilised if biomass supplies are local, i.e. transport distances are short. Linked to this low cost supply chain concept would be the potential use of low cost pre-processing, as discussed above for rudimentary water washing.

Similarly, water washing + pelleting is also not selected as a pre-processing technology for these heat chains, as this technology is already recommended for selection in the power applications discussion.

5.5 Pre-processing technologies not considered in any chains

The following pre-processing technologies given in Table 16 have not been considered in any of the 10 selected chains. The rationale behind these decisions is explained, and the project team note that the workshop attendees agreed with these exclusion justifications.

Table 16: Excluded pre-processing options

Technology	Reasons
Drum drying **Belt drying**	Well known technologies with lower opportunity for innovation compared with the other pre-processing technologies considered here. Forced mechanical drying, consuming natural gas, is already a fully costed component within all the pelleting chains.
Chipping	SRC willow and SRF feedstocks considered from the COF project are most likely to already be chipped in an industrial setting, and imported LRF arrive as pellets. Only Miscanthus bales could be chopped, but only at the conversion plant (not upstream in the supply chain) – as an upstream pre-processing option, bale shredding adds a lot of costs through reduced material density, and hence higher transport costs. Chipping is therefore not worth modelling as a standalone pre-processing choice.
Briquetting **Torrefaction + briquetting**	Some advantages of briquetting are that it has a slightly lower capex and lower opex than pelleting, and can deal with some lignin melting point issues facing pelleting. However, using a pellet binder overcomes these issues, and the binder costs are already included in the pelletising costs given[4]. Briquettes are too big to be used in some technologies, such as underfed stoker boilers, and are slightly more expensive to transport than pellets. Briquettes are less dusty than pellets, but dust issues are controllable and well understood by industry. Overall, the view at the workshop was that briquettes are a niche option, and of relatively low interest to the UK. Torrefaction + briquetting was excluded for similar reasons.
Torrefied chips	This torrefaction only option is typically the same chain cost, or more expensive, than torrefaction + pelleting, because of higher transport costs.
Steam exploded pellets	High natural gas use leads to a poor energy balance compared to the rest of the pre-processing options (and additional energy inputs >20% as shown in Figure 4), and so steam exploded pellets are likely to give a poor GHG emissions factor for the generated bioenergy, potentially at risk of exceeding future legislated thresholds. The steam energy used is significantly higher than torrefaction + pelleting, so even if biomass-fired heat or waste heat were used to generate the steam in both technologies, torrefaction+pelleting would be a more attractive option from a GHG perspective. In addition, workshop participants discussed other problems with this technology currently, such as steam exploded pellets going mouldy, and being prone to very variable batches.
AFEX pellets	This technology is only potentially applicable to one feedstock in scope (Miscanthus), as it can only process soft, fibrous material that is low in lignin. The AFEX techno-economic data has larger uncertainties than some of the other datasets, plus the addition of ammonia leads to significant increases in biomass N content. AFEX chains are also consistently one of the more expensive chains (with several chains >40% above the Off chain LCOE), and seen by the workshop attendees as of more relevance for biofuels and biochemicals applications, rather than lower value bio-heat and bio-power.

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[4] This applies to all raw feedstocks within the TEABPP scope, plus washed and torrefied materials, as pellet manufacturers have stated that in the majority of mills, binder is required, not only to stick the material together, but also to reduce abrasiveness of the material to the equipment. Developers state that binder is not required for steam exploded or AFEX pellets, due to lignin re-arrangement.

5.6 Summary of case study choices

The 10 chains arising from the heat and electricity applications, the choice of conversion technologies and comparison of pre-processing options are summarised below in Table 17. These 10 chains are the TEABPP project team’s recommendations for incorporation into the WP3 process modelling. The ordering is based on the order of discussion and justification above, and not based on a particular priority order. A breakdown of the component costs is given in the following pages.

Table 17: Selection of final 10 chains

End vector	Conversion	Pre-processing	Rationale	Chain
Heat	Underfed combustion	Natural drying + screening	“Off” chain for comparison, including screening	1
Heat		Water washing	Local sourcing and ability to investigate cheaper rudimentary washing	2
Power	BFB gasifier	Natural drying + screening	“Off” chain for comparison, including screening	3
Power		Water wash + pelleting	Alkali metal and ash reduction to benefit opex, densify for trucking	4
Power	CFB combustion	Natural drying + screening	“Off” chain for comparison, including screening	5
Power		Pelleting	Cheapest large-scale supply option	6
Power		Chemical wash + pelleting	Alkali metal and ash removal to benefit opex, densify for trucking	7
Power	EF gasifier + CCGT	Pelleting	No “Off” chain, nor chips allowed, hence pelleting is best comparison	8
Power		Torrefaction + pelleting	Slightly higher cost, but avoided grinding energy	9
Power		Pyrolysis	High cost, but novel and avoided grinding energy	10

5.6.1 Chain 1 (D2 tool = #18)

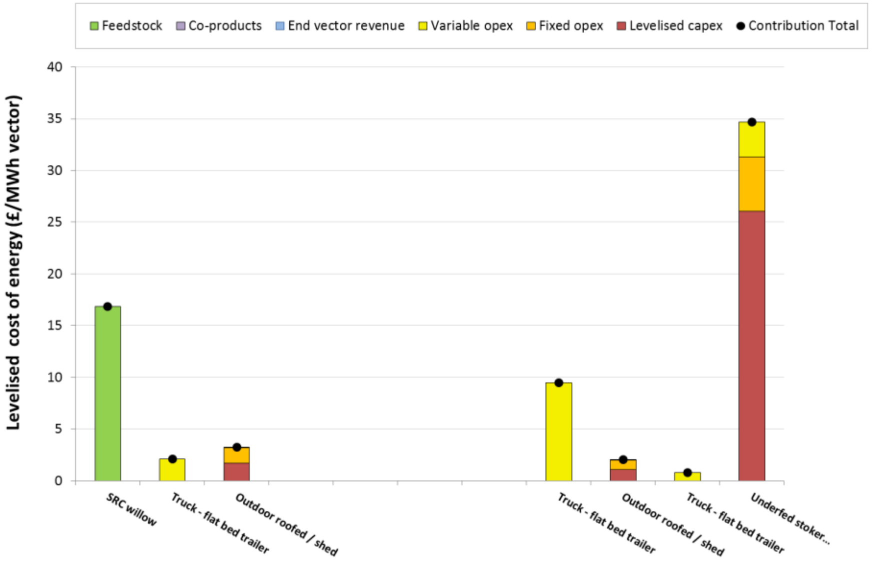
SRC willow chips to underfed stoker combustion boiler (hot water)

1,064 boilers installed

Total chain investment of £444m, and annual opex of £81m/yr

LCOE = £69/MWh$_{th}$

Chain efficiency = 87%, less 6% additional inputs



5.6.2 Chain 2 (D2 tool = #19)

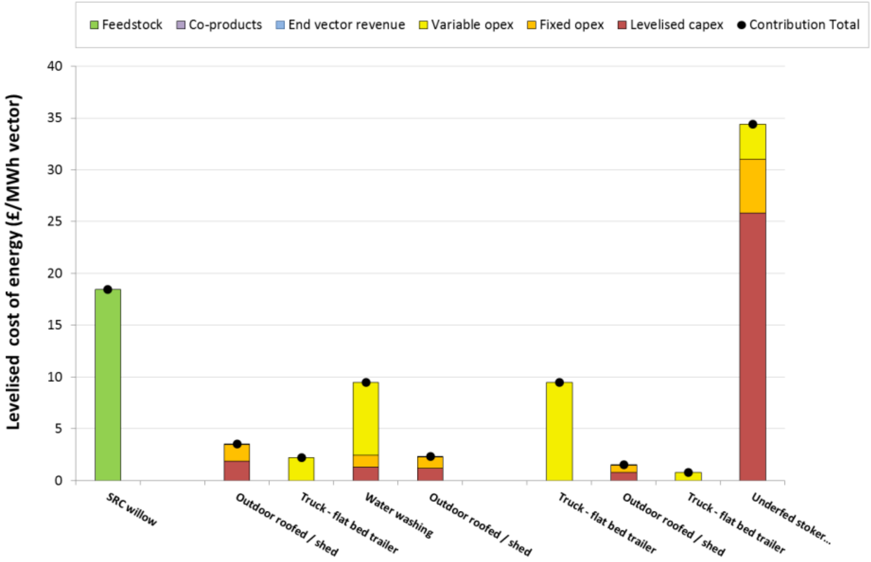
Water washed SRC willow chips to underfed stoker combustion boiler, producing hot water

1,056 boilers installed

Total chain investment of £481m, and annual opex of £103m/yr

LCOE = £82/MWh$_{th}$

Chain efficiency = 79%, less 6% additional inputs



5.6.3 Chain 3 (D2 tool = #1398)

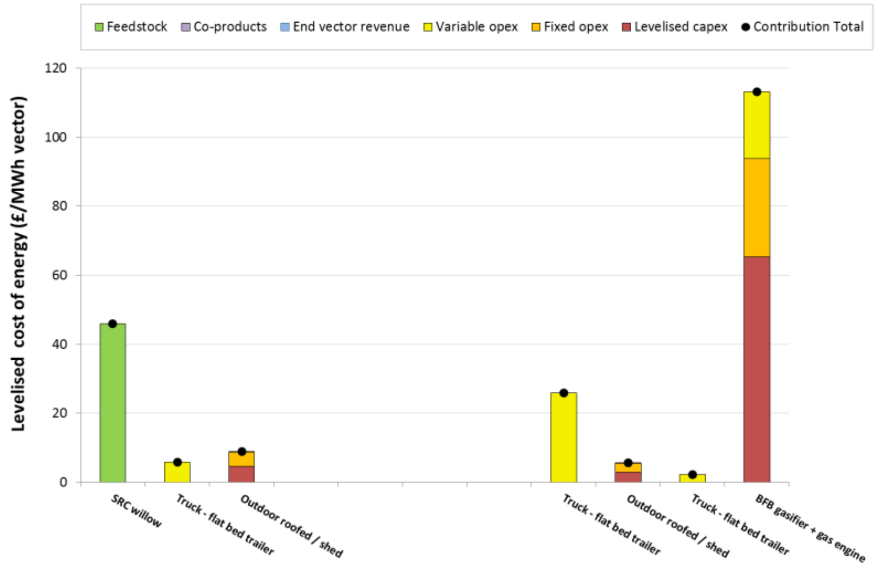
SRC willow chips to BFB gasifier + syngas engine, to power

58 gasifiers installed

Total chain investment of £1,314m, and annual opex of £269m/yr

LCOE = £208/MWh$_e$

Chain efficiency = 32%, less 5% additional inputs



5.6.4 Chain 4 (D2 tool = #1401)

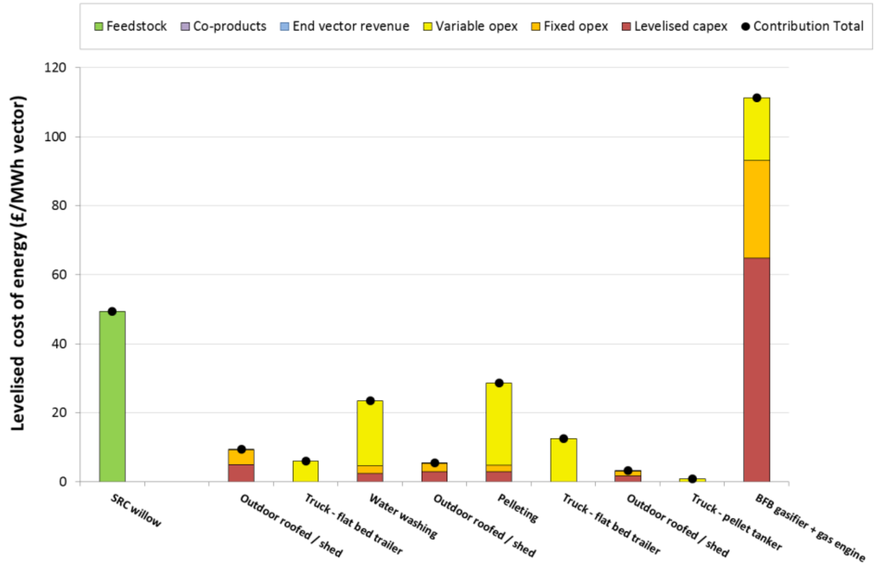
Water washed SRC willow pellets to BFB gasifier + syngas engine, to power

58 gasifiers installed

Total chain investment of £1,431m, and annual opex of £340m/yr

LCOE = £250/MWh$_e$

Chain efficiency = 30%, less 11% additional inputs



5.6.5 Chain 5 (D2 tool = #1122)

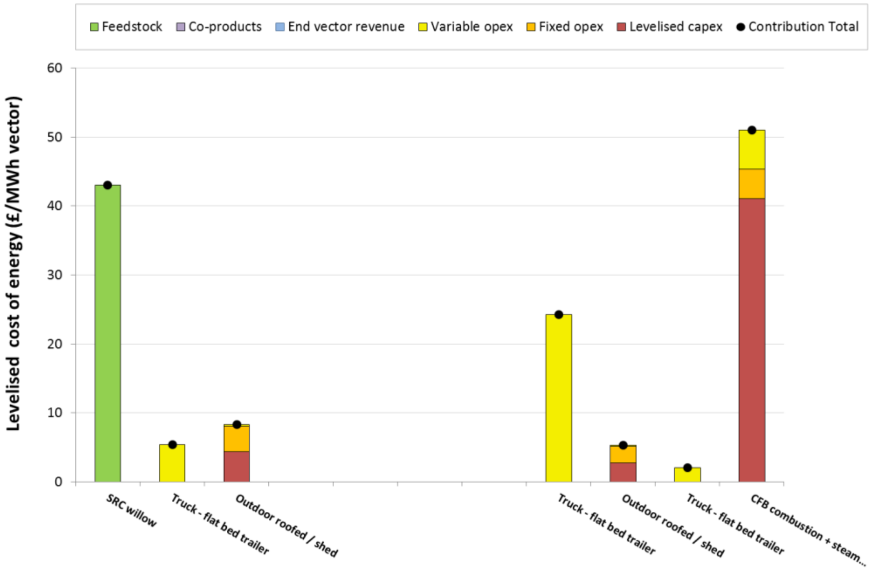
SRC willow chips to CFB combustion + steam turbine, to power

3 boilers installed

Total chain investment of £821m, and annual opex of £182m/yr

LCOE = £139/MWh$_e$

Chain efficiency = 34%, less 5% additional inputs



5.6.6 Chain 6 (D2 tool = #1135)

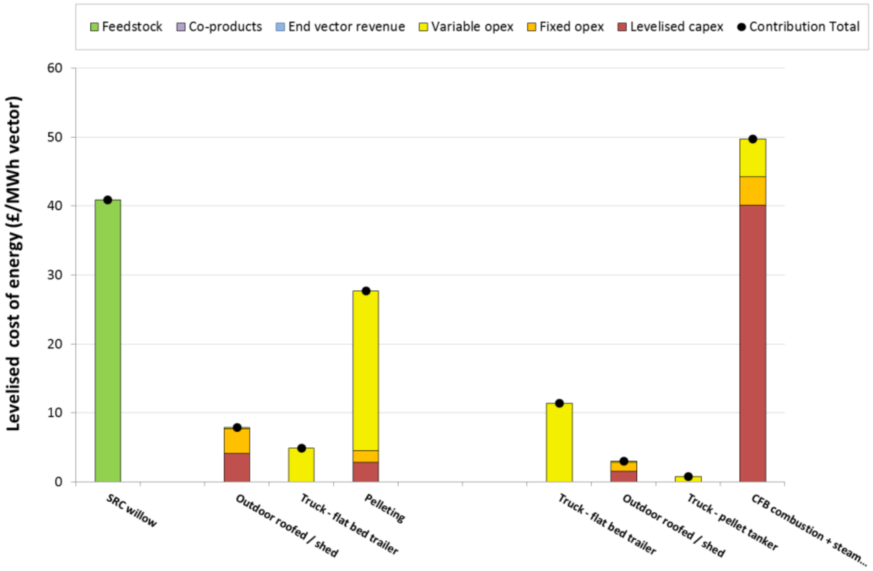
SRC willow pellets to CFB combustion + steam turbine, to power

3 boilers installed

Total chain investment of £827m, and annual opex of £195m/yr

LCOE = £146/MWh$_e$

Chain efficiency = 36%, less 13% additional inputs



5.6.7 Chain 7 (D2 tool = #1126)

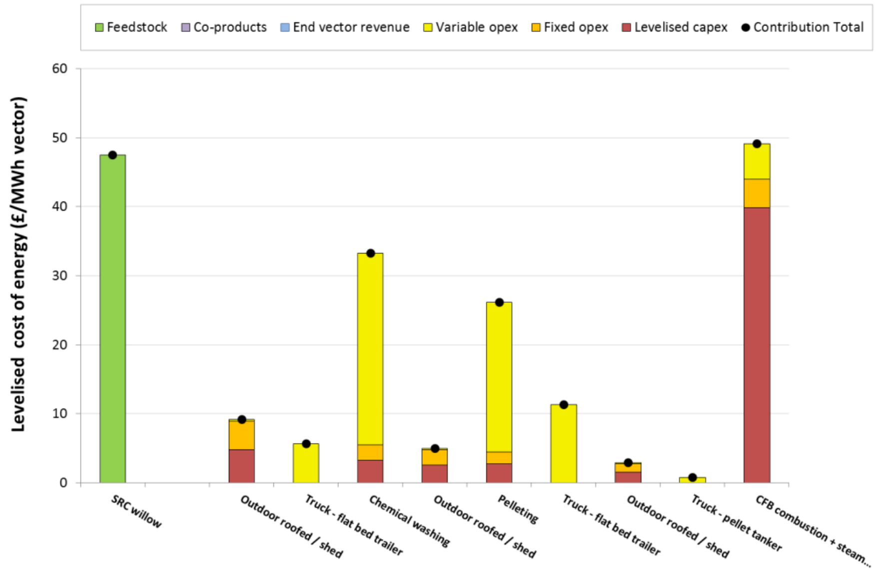
Chemical washed SRC willow pellets to CFB combustion + steam turbine, to power

3 boilers installed

Total chain investment of £932m, and annual opex of £272m/yr

LCOE = £191/MWh$_e$

Chain efficiency = 31%, less 11% additional inputs



5.6.8 Chain 8 (D2 tool = #1756)

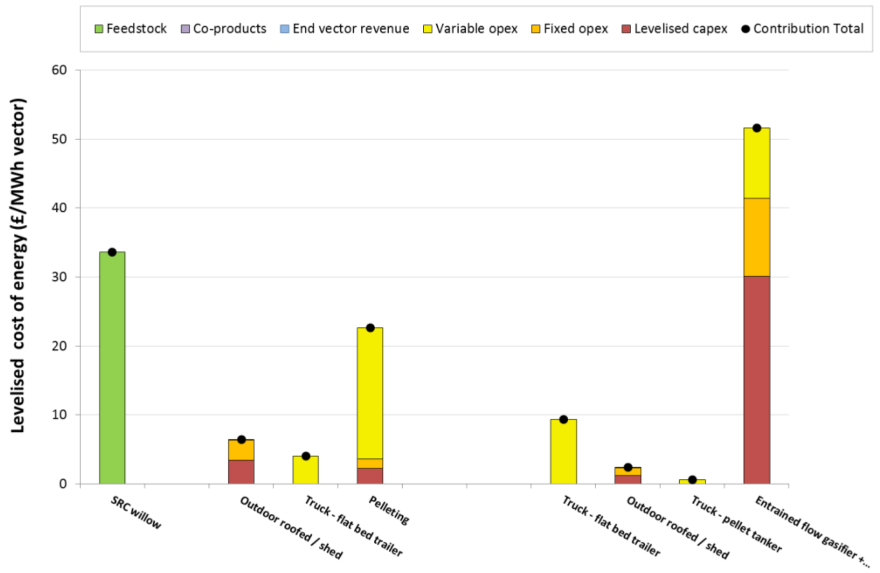
SRC willow pellets EF gasifier + CCGT, to power

1 gasifier installed

Total chain investment of £664m, and annual opex of £187m/yr

LCOE = £131/MWh$_e$

Chain efficiency = 44%, less 13% additional inputs



5.6.9 Chain 9 (D2 tool = #1757)

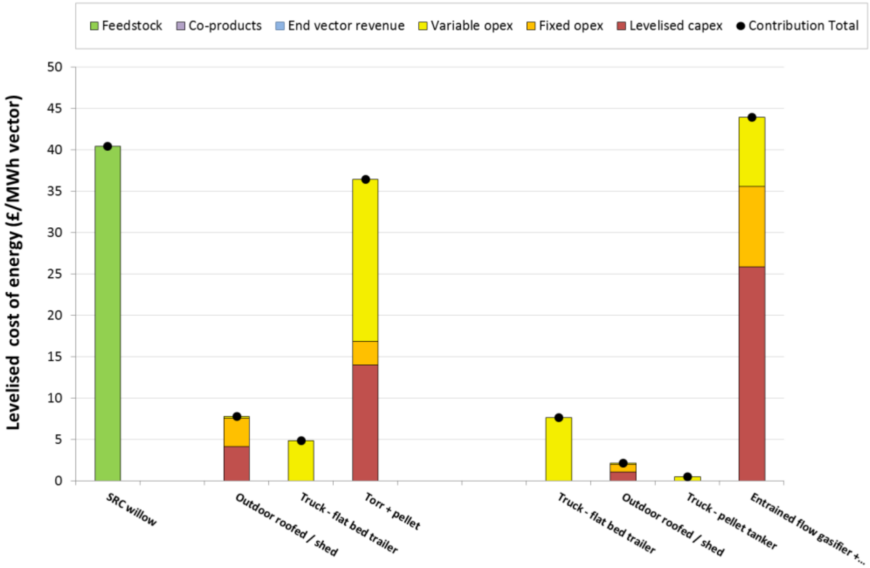
Torrefied SRC willow pellets EF gasifier + CCGT, to power

1 gasifier installed

Total chain investment of £813m, and annual opex of £1979m/yr

LCOE = £144/MWh$_e$

Chain efficiency = 36%, less 7% additional inputs



5.6.10 Chain 10 (D2 tool = #1755)

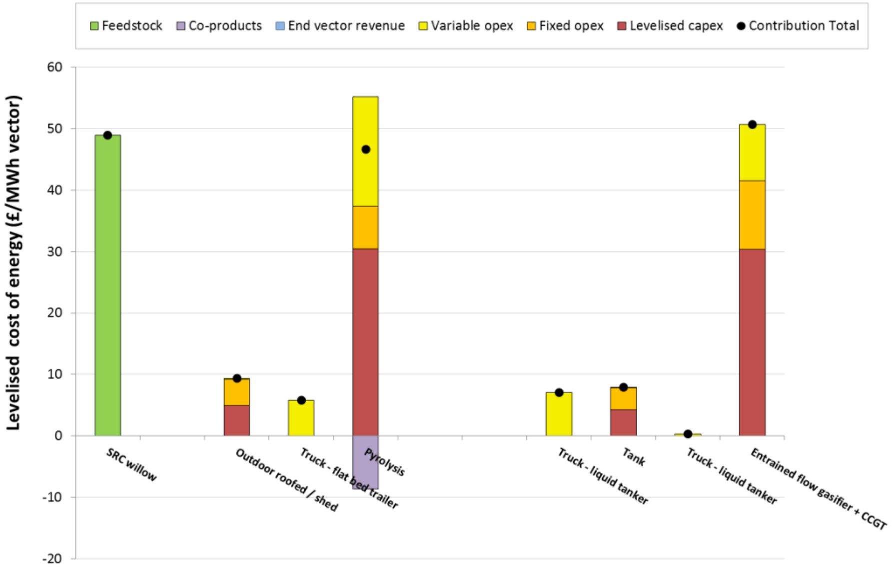
Pyrolysis oil from SRC willow, into EF gasifier + CCGT, to power

1 gasifier installed

Total chain investment of £1,226m, and annual opex of £213m/yr

LCOE = £177/MWh$_e$

Chain efficiency = 38%, less 4% additional inputs



6 Next steps

The next steps for the TEABPP project team are the finalisation of these 10 chains with the ETI, in order to allow the parameterisation of the different technologies within gPROMS. With the new conversion relationships, updated COF data and pre-processing flows, the project team are confident of being able to provide the insights for which the TEABPP project was commissioned.