Techno-economic assessment of power production from the Wellman and BTG fast pyrolysis processes

G.V.C. Peacocke

Conversion And Resource Evaluation Ltd. 9 Myrtle House, 5 Cassowary Road, Birmingham, B20 1NE, UK (corresponding author)

A.V. Bridgwater and J.G. Brammer

Bio Energy Research Group, Chemical Engineering and Applied Chemistry, Aston University, Birmingham, B4 7ET, UK

ABSTRACT The objective of this paper is to present a design evaluation and techno-economic assessment of two technologies being developed within an EU supported contract by Wellman Process Engineering Ltd. and the Biomass Technology Group b.v.. The work produced capital cost estimates and production cost estimates for liquids from both processes and electricity production costs, at a range of scales from 0.25 t/h dry wood input to 10 t/h dry wood input [to the pyrolysis reactor]. The overall system covered from received chipped at site wood to product liquids, or electricity, as generated by a dual fuel diesel engine.

Capital and operating costs have been derived for the production of pyrolysis liquids using standard cost estimation techniques to provide a consistent methodology and avoid concerns over release of confidential information.

Pyrolysis liquid production costs ranged from 9.5 €/GJ at 2 dry t/h feed rate for the Wellman process and 8.0 €/GJ at 2 dry t/h feed rate for the BTG process at 2 t/h federate at zero feedstock cost. Electricity production costs for the pyrolysis processes are relatively high – ranging from 12 €cents/kWh at 10 t/h [net electrical output 13.3 MWe to over 40 €cents/kWh at 0.25 t/h [~0.33 MWe output]. The mean EU price to industrial users for electricity is 4 €cents/kWh. The potential markets for pyrolysis liquids may initially be in selected European countries as a domestic heating fuel, with electricity production as a longer-term aim.

1. INTRODUCTION

Within the tasks of the EU funded JOR3-CT97-0197 contract, Biomass Technology Group [BTG] and Wellman Process Engineering Ltd. [WPEL] were tasked to operate 200 kg/h and a 250 kg/h fast pyrolysis units respectively for the production of pyrolysis liquids. The product liquids were then to be combusted by Ormrod Diesels

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater,* A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

for power generation. The BTG fast pyrolysis plant was already in existence and the Wellman plant was constructed within the framework of the contract, however, due to excessive authorisation costs under IPPC, the WPEL plant never operated beyond initial hot commissioning.

In order to assess the production costs of the liquids and the cost of electricity produced from the liquids, this contract offered a unique opportunity to assess and compare two different fast pyrolysis technologies, with similar wood throughputs, on a consistent basis and with the same starting and end points. It was therefore the task of Conversion And Resource Evaluation Ltd. to determine the production costs of the liquid and electricity, using standard costing methods and then, if possible, compare these costs with the actual costs obtained from WPEL and BTG. The costs calculated are only the breakeven cost and no account of profitability or return on investment is made, due to the R&D nature of the processes. The costs were calculated for a range of input biomass to the pyrolysis reactor from 0.25-10 dry t/h.

The techno-economic assessment of the two processes was made on a consistent basis to minimise errors in the process assessment. The starting point was delivered wood chips [whole tree chipped material, wet], which were then subjected to biomass pre-treatment and preparation followed by fast pyrolysis to a stored liquid product. The liquid products would then be subsequently combusted in a dual fuel diesel engine for the production of electricity, based on a 10% energy input from the diesel. A base plant size of 2 t/h dry feed input was used which can be scaled up or down to give credible capital cost estimates from 0.25 to 10 dry t/h feed rate. The overall system consists of three modules:

Module I Biomass preparation [reception, drying, comminution, storage, feeding],
Module II Fast pyrolysis to a recovered liquid product [based on flowsheets from Wellman Process Engineering Ltd. and BTG bv],
Module III Power generation in a dual fuel diesel engine [based on data from Ormrod Diesels].

A capital and production cost was derived for each module: the capital and production cost of the feedstock for pyrolysis, the capital and production cost of the pyrolysis liquids from the prepared feedstock, and then the capital and production cost of the electricity from the process. This way, the respective costs could be modelled independently and then linked by forwarding the production costs to give an overall electricity production cost. The exact methodology for the calculation of the costs for each stage in the process have been detailed in a report, however, only the main conclusions of the costs determined are presented here (1). The biomass specifications for delivery to site were LHV of 19.5 MJ/kg [dry] and 50wt% water.

2. PROCESS MASS BALANCES AND FLOWSHEETS

The feedstock preparation system consists of wood reception, screening and chipping of feedstock as required, drying of chipped material and then grinding to the required particle size. The ground material is then sent to buffer store prior to use in the pyrolysis reactor. For the Wellman plant the particle size range was 0.5-4 mm and for BTG 0.05-3 mm [minimum and maximum dimensions].

Process flowsheets and mass balances for the fast pyrolysis module were supplied by Wellman (2) and BTG (3), although the basic BTG flowsheet had to be modified to account for additional utilities and process flows to provide a consistent comparison. The flowsheets were adapted to a common basis as agreed with the respective companies, and are shown in Figures 1 and 2 respectively. A key to the process units is given in Table 1. At scales of 2.0 dt/h and above, all pumps and fans have a second identical unit included for redundancy. All flows are assumed to scale linearly with biomass feed rate over the range 0.25-10.0 dry t/h. The yield of pyrolysis liquids from each process is assumed to be constant with scale and are given in Table 4. The mass balances provided and agreed with the companies are in Table 2 and Table 3.

Table 1. Process unit definitions.

No.	Description	W	B	No.	Description	W	B
C01	Wood Loading Conveyor	✓	✓	R03	Char Combustor	✓	✓
C02	Wood Metering Conveyor	✓	✓	R04	Excess Gas Combustor	✓	✓
C03	Wood Feed Conveyor	✓	✓	S01	Char Cyclone 1	✓	
C04	Char Metering Conveyor	✓		S02	Char Cyclone 2	✓	
C05	Char Feed Conveyor	✓		S03	Quench Condenser	✓	✓
C06	Char Return Conveyor	✓		S04	Electrostatic Precipitator 1	✓	✓
E01	Cooling Tower	✓	✓	S05	Ash Cyclone 1	✓	✓
F01	Air Fan 1	✓	✓	S06	Ash Cyclone 2	✓	✓
F02	Air Fan 2		✓	S07	Electrostatic Precipitator 2	✓	
F03	Recycle Gas Fan	✓	✓	V01	Wood Hopper	✓	✓
H01	Air Preheater	✓		V02	Wood Metering Hopper	✓	✓
H02	Quench Liquid Cooler	✓	✓	V03	Char Feed Hopper	✓	
H03	Gas Preheater	✓	✓	V04	Char Receiver	✓	
P01	Quench Liquid Pump	✓	✓	V05	Char Receiver	✓	
P02	Bio-oil Pump	✓	✓	V06	Ash Receiver	✓	✓
P03	Cooling Water Pump	✓	✓	V07	Ash Receiver	✓	✓
R01	Pyrolysis Reactor	✓	✓	V08	Liquid Storage Tank	✓	✓
R02	Process Gas combustor	✓		V09	Recycle Gas Buffer	✓	

For the Wellman system, a detailed plant model allowed variations in heat losses within the process to be taken into account, highlighting whether more or less process gas or char was required with in the process. The flows could then be changed accordingly to ensure that the mass and energy balance variations with increasing plant capacity were accurate. Unfortunately, a similar level of detail was not available for the BTG process. However it is important to note that data for the Wellman plant is based on estimates from published data, data obtained from Aston University using the same feedstock on their laboratory reactors and models while data for BTG was from operational experience, although not all of the liquids are recovered in their current collections system, therefore some losses are apparent.

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater,* A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

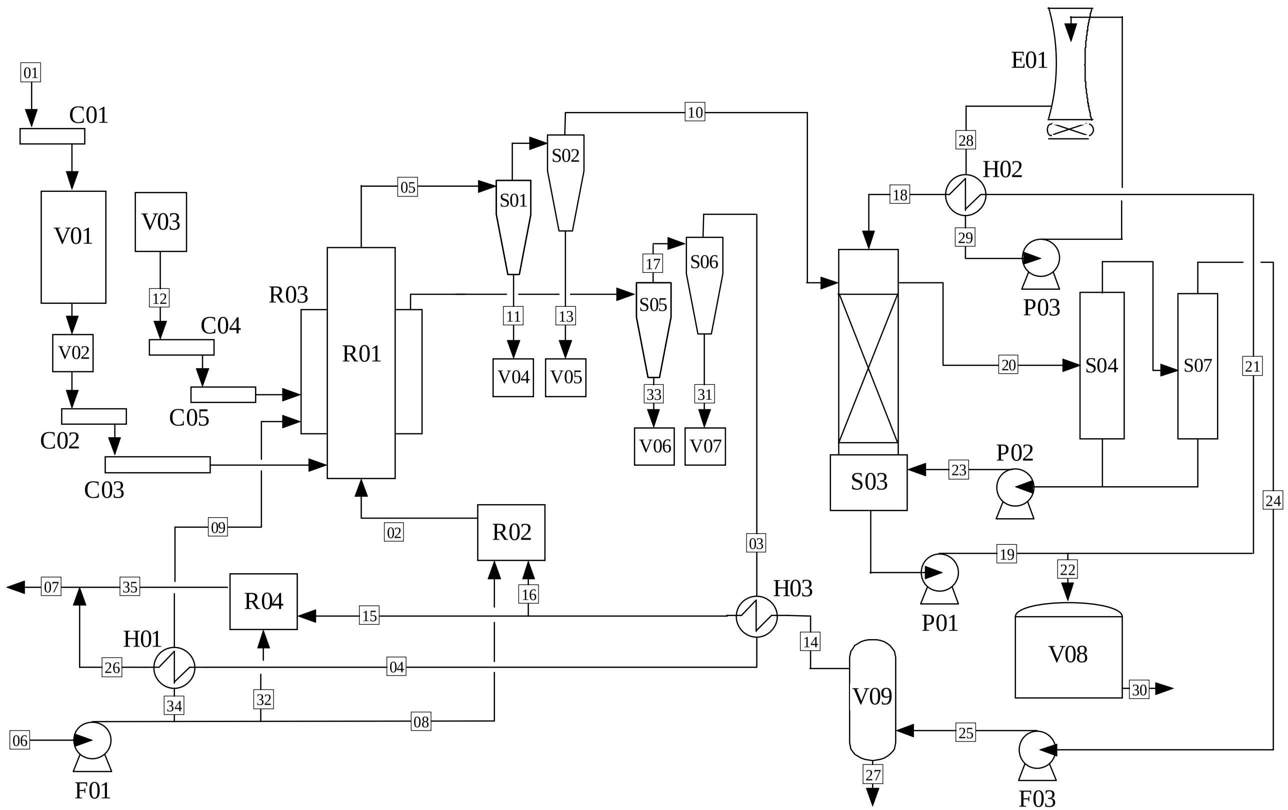

Fig. 1. Wellman Process Engineering Ltd. Fast pyrolysis flowsheet [see Table 1 for unit operations].

Published in *Science in Thermal and Chemical Biomass Conversion*, *Bridgwater*, A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

Table 2. Mass balance for Wellman Process Engineering system, 2.0 dt/h wood (2).

Stream No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Description	Wood	Fluidising Gas	Hot Gas	Hot Gas	Pyrolysis Gas	Cold Air	Flue Gas	Comb Air	Comb Air	Gas	Char	Char	Char	Recycle Gas	Excess Gas	Hot Gas	Heating Gas	Quenching Liq.
Hydrogen					2.0					2.0				2.0	0.6	1.4		
Methane					7.1					7.1				7.1	2.2	5.0		
Water	241.1	70.7	419.8	419.8	535.0	65.8	470.6	8.1	33.6	535.0				44.7	13.4	31.3	419.8	44978
Carbon Monoxide					137.8					137.8				137.8	41.4	96.5		
Nitrogen		1267	1574	1574	1267	3079	3079	380.0	1574	1267				1267	380.0	886.7	1574	
Oxygen			70.3	70.3		825.2	328.2	101.8	421.8								70.3	
Carbon Dioxide		780.3	472.4	472.4	860.7	1.8	807.4	0.2	1.0	860.7				860.7	258.2	602.5	472.4	
C2+					6.0					6.0				6.0	1.8	4.2		
Organics					1289					1289					0.0			118224
Dry Wood	2000																	
Char					255.0					2.2	249.5	187.1	3.4					195.6
Ash	9.6		0.2	0.2	9.6		7.0			0.1	9.4	7.0	0.2					7.4
Total	2251	2118	2537	2537	4369	3972	4692	490.2	2030	4106	258.9	194.2	3.5	2325	697.7	1628	2537	163405
Temp (^oC)	20	800	585	460	452	25	375	75	200	452	452	452	25	77	215	215	585	26
Pressure (bar a)	1.01	1.23	1.04	1.03	1.1	1.01	1.02	1.26	1.16	1.06	1.12	1.01	1.1	1.26	1.03	1.26	1.05	2.5

Stream No	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Description	Pyrolysis Liq.	Gas	Recycle Liquid	Product	Precip Liquid	Recycle Gas	Compr. Gas	Cooled Gas	Water	Cooling Water	Cooling Water	Product Liquid	Ash	Air	Unburnt Char	Cold	Inert Gas
Hydrogen		2.0				2.0	2.0										
Methane		7.1				7.1	7.1										
Water	45584	160.5	44978	490.2	115.8	44.7	44.7	419.8	trace	352000	352000	490.2		24.0		33.6	50.8
Carbon Monoxide		137.8				137.8	137.8										
Nitrogen		1267				1267	1267	1574						1125		1574	1505
Oxygen								70.3						301.5		421.8	258.6
Carbon Dioxide		860.7				860.7	860.7	472.4						0.6		1.0	335.0
C2+		6.0				6.0	6.0										
Organics	119938	425.3	118224	1289	425.3	trace						1289					
Dry Wood																	
Char	197.7		195.6	2.2								2.2					
Ash	7.4		7.4					0.2				0.1	0.5		6.3		
Total	165727	2866	163405	1781	541.0	2325	2325	2537	trace	352000	352000	1781	0.5	1451	6.3	2030	268.7
Temp (^oC)	43	50	43	43	50	50	77	360	30	21	26	42	60	75	60	75	401
Pressure (bar a)	3.5	1.04	3.5	3.5	1.03	1.03	1.27	1.02	1.3	1.01	3	1.01	1.05	1.04	1.07	1.17	1.02

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater*, A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

Table 3. Mass balance for Biomass Technology Group system, 2 dt/h wood.

Stream No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Description	Feed	Cut	Reactor Exit	Riser Air	Riser	Air	Ash	Flue Gas	Gas and Oil	Pyro-gas	Bio-oil	Bio-oil	Cooling Water	Air	Cooling Water	Bio-oil	Bio-oil
Wood (d.a.f.)	2000																
Water	200						20	1955					1955		72000		
Ash	20		20		20												
Bio-oil									1600		1600	72000				46.6	73600
Pyro-gas									200	200							
Char			400		400												
Air				1000	1000	4000								4684			
Flue gas								5400									
Sand		72000	72000		72000												
Total	2220	72000	72420	1000	73420	4000	20	7355	1800	200	1600	72000	1955	4684	72000	46.6	73600
Temp (^oC)	18	570	530	18	521	18	570	570	530	29	41	29	18	18	35	29	29
Pressure (bar a)	1.06	1.06	1.06	1	1.2	1	1	1	1.06	1	1	3	1.2	1	3	1.03	3

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater*, A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

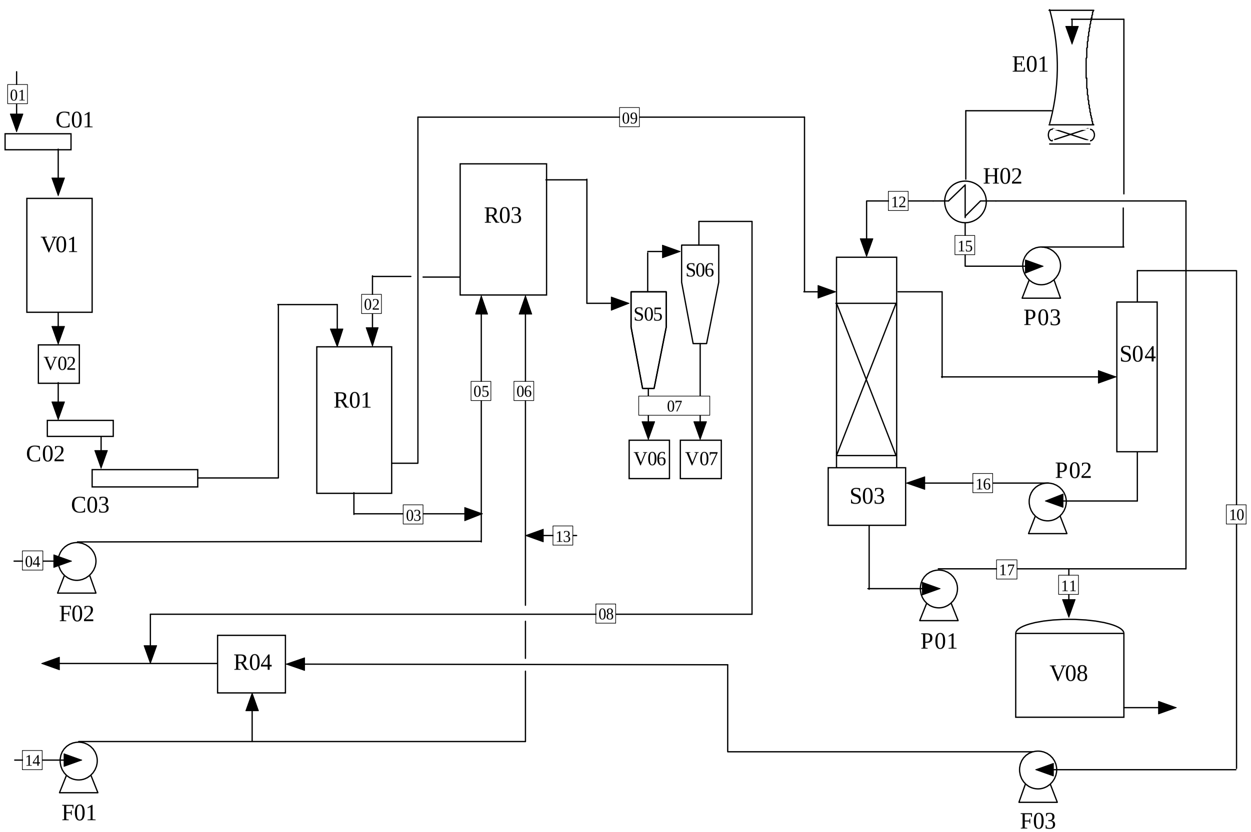

Fig. 2. BTG Fast pyrolysis process flowsheet. [see Table 1 for unit operations].

Published in *Science in Thermal and Chemical Biomass Conversion*, *Bridgwater*, A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

Table 4. Pyrolysis liquids yield from each process (2, 3).

Process	Wellman	BTG
Yield, litres of oil per tonne of dry ash free wood	755	678
Yield, tonnes oil per dry ash free delivered tonne wood	0.89	0.80
Yield, tonnes oil per tonne wood fed to reactor	0.79	0.72

The basic mass and energy balances would therefore form the basis for the costing of the two technologies, but should be viewed as indicative. Yields will also vary for other feedstocks such as grasses, which was not considered here. For power generation in a modified diesel engine, Ormrod Diesels provided data.

3. COST METHODOLOGY

3.1 MODULE APPROACH

The process was separated into three modules, each one independent of the other, but allowing the costs for each module to be added together to give the overall liquids capital and production cost and the electricity capital and production cost.

For all three modules, costs associated with the production of the biomass feedstock [Module I] the pyrolysis liquids [Module II] and the electricity [Module III] comprises an annual cost of servicing the capital as a combined interest and capital repayment (assuming all of the capital is loaned), to which are added the annual operating costs of the plant. The operating costs comprise feedstock, labour, utilities, maintenance and overheads. The cost of pyrolysis liquids is obtained by summing the annual production cost elements, and dividing by the total annual production of pyrolysis liquids; and a similar methodology is used for power costs. The methodology for calculating each of the production cost elements in the modules is described below.

3.2 CAPITAL COST

Capital cost is calculated as a total plant cost, which includes both direct costs [installed equipment] and indirect costs [engineering, design, supervision, management, commissioning, contractor's fees, interest during construction, contingency].

The validity of any model can only be confirmed by comparison with actual cost data for installed plants. Unfortunately, there are few operational fast pyrolysis plants in the EU, or even in the world which can be used as reference plants for model validation. The inclusion of two technologies in one contract provided a unique opportunity to compare the model predictions with the costs derived from the detailed engineering work of Wellman and BTG. After the model for Module II was constructed based on the agreed flowsheets, the costs were then derived for each process. Ideally, the results should be validated against data from the two companies, but this was not possible, although it is understood that the results are within an acceptable level of uncertainty.

The supplementary information included engineering, design, management and estimate of commissioning costs, with detailed engineering drawings for the entire plant and a basis for the labour costs and man hours involved in the project from conception to completion. Wellman provided extensive detailed information on equipment specifications and performance, which provided a high degree of accuracy for the cost estimates, although an actual mass balance was not available. However the data was supplied from analogous experimental fluid bed work, taking conservative yields and accounting for the process conditions expected in their plant during operation.

The data provided by BTG and KARA unfortunately did not provide as much detail, with limited data on main process equipment and no confirmed basis for the costs. Power consumption in the 200 kg/h process appeared, in our view, to be optimistically low and the lack of process integration meant that key aspects of the mass balance were scant. In addition, the figures of BTG were apparently not confirmed by actual experimental data from the unit. The lack of a reliable mass balance for an operational plant was of some concern although it is recognised that char measurement in the BTG process is difficult as the char is internally recycled and burnt. Where data was not available, costs and performance were estimated from publicly available sources.

3.3 TOTAL PLANT COST

Total plant cost (*TPC*) is built up from the equipment costs, using factors to allow for both direct and indirect costs as described below. The delivered cost of each process unit shown in Fig. 1 and Fig. 2 (referred to as the equipment cost, *EC*) is obtained mostly from cost estimation charts for process equipment published by Garrett in 1989 and updated to 2000 using a cost index (4). The use of published cost estimations from a single source is believed to provide the fairest basis for process cost comparison. Garrett also gives factors for material of construction, applied as appropriate based on data supplied by WPEL (2).

The cost estimation charts give equipment cost as a function either of a flow parameter or a dimension parameter, depending on the unit type. Values for flow parameters are obtained directly from the mass balances, scaled appropriately for biomass feed rate. Values for dimension parameters are obtained from unit design data supplied by Wellman (2) and BTG (3), scaled appropriately for biomass feed rate.

For the Wellman pyrolysis reactor and char combustor [units R01 and R03], which are both fluid beds, the cost estimation chart for a fluid bed dryer is used, with nickel alloy and stainless steel material factors respectively. This is the closest match in the absence of any cost estimation charts for high-temperature fluid bed reactors. For the BTG rotating cone reactor (unit R01), none of Garrett's charts provides a credible means of cost estimation. Instead, the equipment cost of the rotating cone reactor is set as a multiple of the fluid bed pyrolysis reactor cost F_R. F_R is nominally set to 1.0, but variations were considered in a sensitivity study (1) showing that feedstock costs, plant availability and liquid yield are the most important parameters. The rotating cone was considered similar to a fluid bed reactor, the main difference being the movement of the walls, rather than the sand.

Various items related to installation are then added to the equipment cost *EC* to give the direct cost for each process unit. This is done using direct cost factors published by the UK Institution of Chemical Engineers (5). The factors were calculated from Equation {1}:

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater*, A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

$$F = c(aEC^b) \quad \{1\}$$

where a and b are constants for a given factor, and c is a multiplier to be included if unusual or atypical conditions pertain. Factors are applied for piping, instrumentation, lagging, electrical, civils, structures and buildings. The direct cost DC is then given in Equation {2}:

$$DC = EC(1+\sum F) \quad \{2\}$$

The direct costs are added to give the direct plant cost *DPC*. Indirect costs are then added to give *TPC*. This is done using factors published by Bridgwater (6). All costs were brought to a 2000 basis using the Chemical Engineering Plant Cost Index as published by Chemical Engineering magazine (5).

The installed capital cost of the BTG process is significantly lower than that of the Wellman process, by around 30% at all scales. This is mainly due to the larger size of the liquids recovery system in the Wellman process, resulting from the higher gas volume flow rate and particularly the requirement for two electrostatic precipitators. The need for two electrostatic precipitators results from the relatively large flow rate of condensables leaving the quencher with the gas, which must be controlled to strict limits under IPPC regulations. Additional factors are the need for two gas combustors in the Wellman process, as well as the need for a gas pre-heater due to the very low calorific value of the gas [calculated at 0.9MJ/kg of recycled gas]. The equivalent condensables flow rate in the BTG process is much lower. A comparison of the capital costs is given in *Fig. 3* below from wood reception to liquids storage.

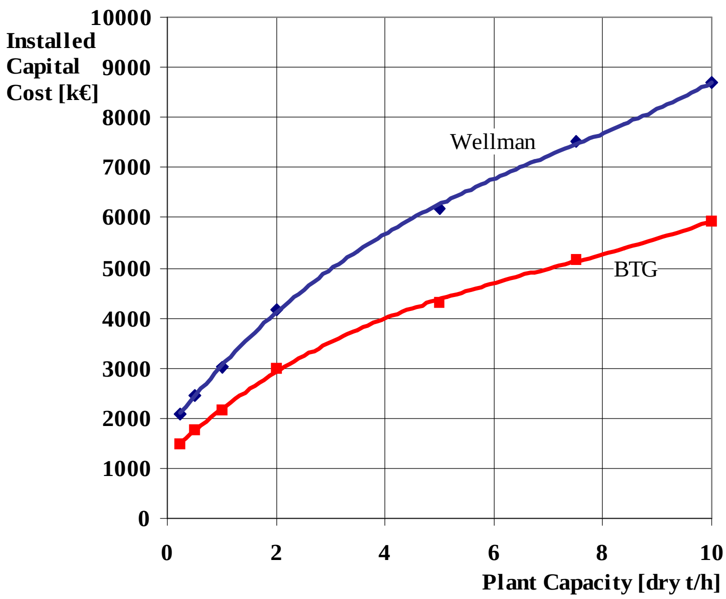

Fig. 3. Installed capital costs for the processes [Modules I and II]

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater*, A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.

3.4 ANNUAL COST OF SERVICING CAPITAL

For calculating an annual production cost, the capital is assumed to be loaned over the project lifetime *l* at a rate *d*, the nominal discount rate for borrowing investment capital. A real annual cost of capital *AC* is determined by first calculating the nominal annual fixed charge. The fixed charges over the project lifetime are then discounted to present values using an inflation rate *i*. The discount rate was set to 12% in line with a recent UK government review of renewable energy technologies (7). Inflation is set at 3%, and project lifetime at 20 years.

3.5 LABOUR

Wellman have supplied personnel estimates for their process, as shown in Table 5 (2), which were compared with those estimated from the model and were in general agreement with our assumptions. These are taken to apply to a full plant including feed pre-processing and power generation. For a fully developed, commercially operating plant, the staff levels would be about 50% of those quoted in Table 5.

Table 5. Personnel requirements (Wellman) per shift, for a demonstration plant.

Scale, dt/h	0.5	1.0	2.0	5.0	10.0
Wood handling, conveying	1	2	2	2	2
Fast pyrolysis	2	2	2	3	3
Control	1	1	1	1	1
Total	4	5	5	6	6

3.6 ELECTRICITY

In a complete electricity production plant, the electrical power necessary to operate the plant would be taken from the gross output from the generator terminals prior to the point of connection to the customer. The parasitic electricity consumption is not accounted for in calculating the cost of pyrolysis liquids. It was taken that power for equipment on site would be purchased at €0.057/kWh for the purposes of this assessment. The parasitic consumption of various process units are presented for a 2.0 dry t/h plant in Table 6, based on data from various sources. The power consumption of fans and pumps is calculated from the known flow rates and pressures assuming typical efficiencies of 40% and 65% respectively. The power consumption of conveyors, and of a site compressor, was calculated from data supplied by Wellman for units in a 0.25 dt/h plant, scaled by feed rate (2). For a commercially operating plant at large scale, internally generated power would be used. No data were available on the power requirement of the drive motor for the rotating cone pyrolysis reactor; this has therefore been ignored, although the power consumption could be significant [estimated at 10-20 kWe at 2 t/h throughput by the authors].

Table 6. Total Plant Process electricity requirements, 2.0 dry t/h wood (2, 3).

Unit	No.	Wellman [kW]	BTG [kW]
Wood loading conveyor	C01	2.4	2.4
Wood metering conveyor	C02	2.4	2.4
Wood feed conveyor	C03	14.0	14.0
Char metering conveyor	C04	2.4	
Char feed conveyor	C05	14.0	
Char return conveyor	C06	14.0	
Cooling tower fan	E01	40.0	8.2
Air fan	F01	57.1	66.3
Air fan	F02		14.2
Gas fan	F03	30.1	3.3
Quench liquid pump	P01	6.0	2.6
Cooling water pump	P03	30.1	6.2
Site air compressor		24	24
Cone drive motor [estimate]			*10-20**
TOTAL		236.6	153.5-163.5

Note: these are the installed electrical requirements and should be viewed as maximum values and operating values may be less than this

3.7 WATER

Water requirements are for make-up water for the quencher cooling circuit (both processes) and for char combustor temperature control (BTG process only). The requirements are calculated from data supplied by Wellman and BTG and scaled linearly by feed rate. A water price of €1.27/m^3 (taken from the tariff of a UK water utility in 1999) was used for make-up water for the cooling towers.

3.8 MAINTENANCE AND OVERHEADS

Maintenance and overheads are both included as a fixed percentage of *TPC* per annum. A typical value of 4% is set for each.

4. BIOMASS PREPARATION COSTS

One of the important requirements for thermal conversion systems is the specification of the feedstock for the pyrolysis reactor. Most fluid bed reactors have tight particle size requirements; due to heat transfer limitations in large particles. It assumed that the feedstock will be delivered as purchased wood chips from a conventional forestry operation, or an energy crop such as short rotation coppice willow or poplar, or other chipped forestry material. It is expected that the feedstock will contain a significant proportion of bark since the removal of bark would make the feed too expensive for the energy market.

Feed moisture content and feed costs before delivery are variables in the biomass preparation module, allowing cost impacts to be evaluated. Based on data received from commercial wood harvesting operations in the UK, the typical cost of delivered woodchips in the UK is ~€47/wet t, (end 2000 basis) for 200 wet t/d (8, 9). The cost of feedstock has an important influence on systems with different efficiencies and a variation of feed costs is explored in the systems evaluations below.

Wood chip production costs are summarised in Table 7, demonstrating the difference in production cost if internal power is used, i.e. parasitic load on the diesel engine, or whether the power is imported. Two cases are presented: one assuming that power is generated onsite from the use of liquids burned in an engine and the other is buying imported electricity at a contracted price [€0.057/kWh].

This is a significant cost penalty for systems less than around 2 dry t/h, as the output electricity is virtually all consumed in the generation of electricity for on-site use, as indicated in Table 7. It can be seen that the installation of a complete wood preparation system for small plants less than 2 t/h is simply not viable, due to the large electrical requirements to operate the equipment. In most cases, purchase of a feedstock to the required specifications is cheaper. Final moisture content in the dried chip was 15et% for Wellman and 10wt% water for BTG.

Table 7. Wood chip production cost [€/t dry material] from delivered wet wood [€47/wet t].

t/h dry wood	0.25	0.5	0.75	1	2	5	7.5	10
Use own power	275	168	131	113	84	71	66	62
Imported power	339	200	153	129	92	76	69	65
Parasitic load [MWe]	0.29	0.29	0.30	0.30	0.32	0.48	0.52	0.74
Output power	0.33	0.67	1.0	1.33	2.67	6.67	10.0	13.3
% parasitics	88	43	30	23	12	7	5	6

5. BIOMASS FAST PYROLYSIS LIQUIDS PRODUCTION COSTS

5.1 INTRODUCTION

Module II allows the calculation of the production cost of pyrolysis liquids from fast pyrolysis of wood via the two processes. This module links into Module I in that the wood chip production cost at various scale of operation from Module I is used in the calculation of the liquids production cost in Module II.

The upstream boundary of the model is the withdrawing of the prepared wood feedstock from a storage vessel at the end of the wood chip preparation stage [Module I]. The downstream boundary of the model is the withdrawal of pyrolysis liquids from a storage vessel at the end of the pyrolysis liquids production stage, for supply to the electricity production stage [an IC engine generating set – Module III]. The model was used to calculate cost of pyrolysis liquids at a range of plant scales from 0.25-10.0 t/h dry ash free wood feed [odt/h], as shown in Table 8.

Data are presented for 3 different purchased feedstock costs: 0, 50 and 100 €/t delivered. The BTG costs increase above Wellman at 100 €/t feedstock cost, due to a lower yield of liquids of liquids, which was offset at lower capacities by savings in utility and maintenance costs.

Table 8. Cost of pyrolysis liquids [€/t] vs wood feed rate and feedstock cost.

Feed cost [€/t]	Plant capacity [dry t/h]						
	0.25	0.5	1	2	5	7.5	10
Wellman							
0	555	321	203	134	84	70	63
50	625	392	274	205	155	141	134
100	696	462	344	276	226	212	204
BTG							
0	514	294	184	120	73	60	53
50	592	372	262	198	151	138	132
100	670	450	340	276	229	217	210

A cost comparison of the liquids is also given below in Table 9 on mass, volume and energy basis for a 2 t/h plant, 7000 hours/y operation.

Table 9. Pyrolysis liquids production cost – different units [2t/h capacity]

Feedstock Cost [€/t delivered]	€/t		€/m^3		€/GJ	
	Wellman	BTG	Wellman	BTG	Wellman	BTG
0	134	120	111	99	9.5	8.0
50	205	198	170	164	14.6	13.2
100	276	276	228	228	19.6	18.4

5.2 COST VALIDATION –MODEL AND INDUSTRY COSTS

An assessment of the accuracy of the predictive costs of the techno-economic model was made for the Wellman process at a specified plant throughput. The degree of inaccuracy for the total installed plant cost, including engineering, design, management, etc. was within 5% of the estimated project cost of Wellman for the 2 dry t/h plant.

The data provided by KARA on the BTG process was not detailed enough to allow a similar comparison to be made. The basic BTG flowsheet had to be significantly modified to include additional unit operations for the plant to operate to an industrial standard and BTG did not have actual installed costs for such equipment. The lack of detailed mass and energy balances for both processes means that there will be some errors in the calculation of equipment sizes and hence the installed capital costs, but such errors are minor [less than 10% variation on the costs of some items] compared to the most significant variable of the feedstock cost as discussed later for 7000 h/y operation.

Time between overhauls for an engine operating on pyrolysis liquids will be reduced by approximately 50% compared with the same engine on diesel oil in respect of fuel injection equipment and cylinder head maintenance. The maintenance frequency for major overhauls should not be affected. Engine tests carried out so far with a normally aspirated medium speed engine show a reduction of 2% in thermal efficiency when operating on pyrolysis liquids compared with operation at the same load and speed on diesel oil.

Table 10. Engine Operational Parameters.

Lubricating oil costs	0.0014 €/kWh
Labour Costs(Operator and Maintenance)	0.034 €/kWh
Spare Parts Costs	0.011 € /kWh
Availability	80%
Load factor	85%
Diesel cost [UK, year 2000]	0.57€/kg
Engine cost [2.5 MWe on pyrolysis liquids]*	2.9 M€
Catalyst for exhaust emissions [if required]	0.035M€

* includes bulk storage tanks, the fuel handling and heating equipment and all auxiliaries

A budget cost for converting a 2.5MWe medium speed engine is estimated to be €136,000 as provided by Ormrod Diesels (10). This represents the fully overheaded cost for installation, supervision, commissioning and engineering. There has been no indication of any necessity for an engine de-rating when operating on pyrolysis liquids. An engine package with air-cooled radiator has been assumed with no heat recovery.

5.3 CALCULATION OF ELECTRICITY PRODUCTION COSTS

The production of pyrolysis liquids is tied to that of the engine, i.e. the pyrolysis plant and engine are perfectly coupled in that the engine uses all liquids produced. There are too many possible scenarios to cover for the real advantage of producing a liquid fuel that can be stored or transported. The cost model is constructed slightly differently for the engine in that the electrical output of the engine is calculated based on the LHV of the input pyrolysis liquids, which differ for the processes due to differing moisture contents of the product liquids [14.1 MJ/kg for the Wellman plant and 15 MJ/kg for the BTG plant, whole oil basis].

5.4 ELECTRICITY PRODUCTION COSTS

The electricity production cost is based on the overall plant and takes into account all of the wood preparation, pyrolysis and subsequent utilisation in a dual fuel diesel engine. The costs are presented for both processes in Table 11 and Table 12. The cost of electricity is relatively high for both processes, well in excess of the domestic and industrial rates in most of the EU countries, as indicated in Fig. 4. Different options for power generation were recently assessed by van de Broek for Ireland (11). Three promising routes for electricity production from biomass in the short term in Ireland are: co-firing of biomass in the Europeat peat fired power plant, small scale CHP generation with fixed bed gasification, and co-firing of biomass in the a coal fired power plant. Costs of co-firing biomass were estimated to range between €0.033 and €0.053/kWh, dependent on fuel prices. For peat this costs is €0.041/kWh. Small scale gasification CHP generation costs range between €0.10 and €0.13/kWh. Co-firing in a pulverized coal power plant was estimated to range between €0.033 and €0.065 /kWh as compared to €0.030/kWh for coal based electricity. Compared to conventional power production by steam cycle from biomass combustion, the costs for electricity for pyrolysis liquids are still high compared to other options.

Table 11. Electricity production cost for Wellman process + engine – different pyrolysis plant capacities [delivered feedstock cost €50/t].

	Pyrolysis Plant capacity [t/h feed]					
	0.25	0.5	1	2	5	10
Electrical output [MWe]	0.33	0.67	1.33	2.67	6.67	13.33
Pyrolysis liquids cost	935	1171	1636	2454	4634	7983
Engine capital amortisation	96	145	220	334	578	877
Labour cost	16	22	31	43	67	93
Utilities	60	121	241	483	1207	2414
Overheads	19	28	43	65	113	171
Maintenance	23	35	54	81	141	214
TOTAL	1149	1523	2225	3460	6741	11752
Electricity Production Cost [€cents/kWh]	49.2	32.6	23.8	18.5	14.4	12.6

Table 12. Electricity production cost for BTG process + engine – different pyrolysis plant capacities [delivered feedstock cost €50/t].

	Pyrolysis Plant capacity [t/h feed]					
	0.25	0.5	1	2	5	10
Electrical output [MWe]	0.339	0.678	1.357	2.714	6.785	13.56
Pyrolysis liquids cost	829	1043	1471	2219	4239.8	7373
Engine capital amortisation	97	147	223	337.4	584.6	886
Labour cost	16	22	31	43.4	67.0	93
Utilities	65	131	261	522.3	1305.7	2611
Overheads	19	29	43	65.8	114.0	173
Maintenance	24	36	54	82.2	142.5	216
TOTAL	1050	1407	2083	3270	6454	11353
Electricity Production Cost [€cents/kWh]	44.2	29.6	21.9	17.2	13.6	11.9

From the data presented in Table 11 and Table 12 and in Fig. 4, it can be seen that the cost of "bio-electricity" is very high, especially at scales less than 2 dry t/h. Only those processes where the net electrical output is over 10MWe appear to be viable in the longer term. This will also depend on whether any incentives are offered for the "green" electricity and whether taxation on fossil fuels, i.e. environmental credits, can be applied to the technology. If the end user is using the electricity for on-site use, in a domestic capacity, then there is an opportunity for pyrolysis liquids to meet demand, as domestic prices are much higher than industrial prices.

Further work on the long-term operation of commercial plants producing electricity is required to validate the electricity production costs calculated here. The lack of such data is influencing the rate of deployment of the technology and, with replication; production costs should drop to some degree [5-15%].

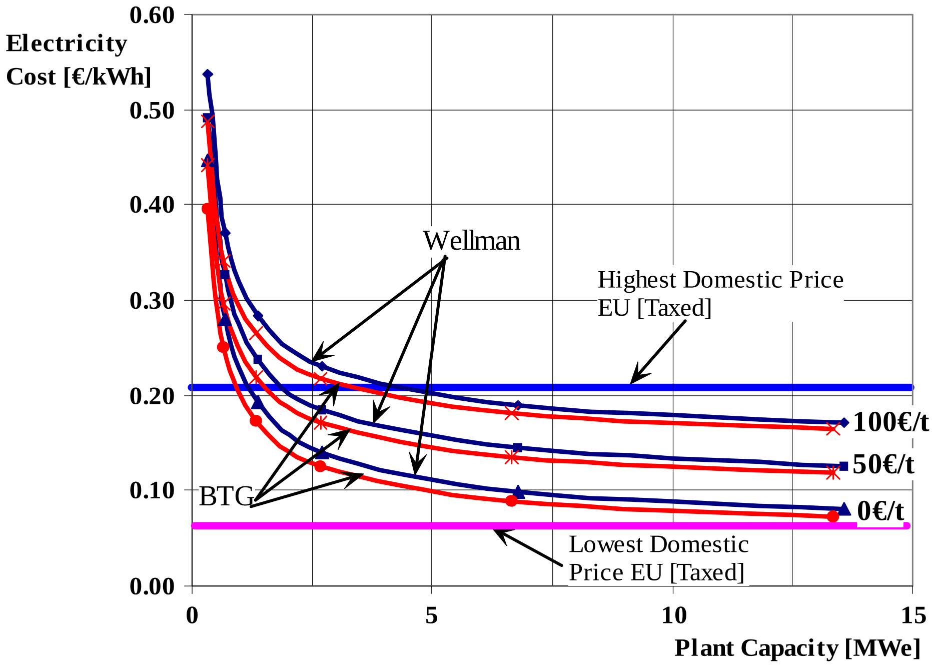

Fig. 4. Electricity Production Costs vs Net Electrical Output [MWe] and feedstock cost [€/dry t] for both processes

There is the opportunity of direct replacement for domestic consumers in niche locations, where there is not a suitable grid connection and there is a supply of suitable biomass in countries such as Denmark, the Netherlands, Italy and Austria.

6. CONCLUSIONS

6.1 COST OF PYROLYSIS LIQUID

The production cost of the pyrolysis liquids is very high, on an energy basis with a cost of 14.6 €/GJ and 13.2 €/GJ for Wellman and BTG respectively for a feedstock cost of 50€/dry t and a plant capacity of 10 dry t/h. The relative differences between Wellman and BTG are small, but the higher proposed yield for Wellman [79wt% relative to 72wt% for BTG] offsets the higher installed capital cost. The cost for domestic heating oil averages 9.9 €/GJ across a range of EU member states. The opportunity for pyrolysis liquids for use purely as a heating fuel oil are in a select few countries where taxation levels are high such as in Denmark, Italy and the Netherlands for example. Given that the costs do jot include any incentives for green fuels, CO_2 mitigation or waste avoidance charges, then the costs are fairly competitive with conventional fuels at large plant capacities.

6.2 COST OF ELECTRICITY GENERATION

For both processes, the electricity breakeven cost is very high [see Table 11 and Table 12], at 12.6 €cents/kWh and 11.9 €cents/kWh for Wellman and BTG respectively at 10 dry t/h wood input and a dry feedstock cost of €50/t. These prices cannot compete with base electrical production costs for industry, but may offer some limited scope for domestic consumers in a few countries such as Denmark, Italy and the Netherlands.

6.3 CAPITAL COST FOR THE BTG ROTATING CONE REACTOR

The equipment cost of the rotating cone pyrolysis reactor has only a relatively small effect on the cost of pyrolysis liquids - doubling the rotating cone reactor equipment cost gives only a 4% rise in pyrolysis liquids cost at 2.0 dt/h. This is a unit for which engineering costs are required from a contractor who has built such units. There is a significant difference in the overall capital costs for the processes as shown in Fig. 3 overleaf. The Wellman process has higher costs due to the use of two electrostatic precipitators and more detailed process integration with heat exchangers and catalytic oxidisers.

6.4 SCALE LIMITATIONS FOR THE PROCESS EQUIPMENT

During the cost estimation, it was assumed that all unit operations are not limited in their scalability. In the wood preparation systems, checks were made on all unit operations and there were no scale limitations for plants processing less than 10 t/h of material. Within the pyrolysis module, the only items for which there is not enough data is the scalability of the pyrolysis reactors. Limitations are likely due to be heat transfer based on reactor geometry as scaling is a volumetric phenomenon and heat transfer is surface area limited; and the use of by-product gas and char in the generation of process heat. The other unit operations in the fast pyrolysis module are not otherwise considered scale limited up to processes with a wood throughput of 10 t/h. Similarly for the power generation module, engines come in various power ranges and do not have significant turndown ratio, therefore with changes in pyrolysis liquid output, there would be a change in engine size with increasing power output, but there is little economy of scale for engines.. In some cases, it may be more economical to use several small engines rather than one large engine [e.g. 4 x 2.5MWe compared to 1 x 10 MWe engine] for reasons of load, availability and reliability, but this analysis was not considered here.

7. ACKNOWLEDGEMENTS

The authors would like to thank the European Commission DG XII [Contract No. JOR3-CT97-0197] and Aston University for providing the funding which made this work possible. We would also like to thank the partners in the contract, namely Wellman Process Engineering Ltd. and BTG for supplying the information required for the cost models.

8. REFERENCES

1. "Development of Advanced Pyrolysis Processes for Power and Heat", JORS-CT97-0197, Final report submitted to the European Commission, 2002, Aston University.
2. Patel, K. B. (2000). Private communication, Wellman Process Engineering Ltd. UK
3. Wagenaar, B. M. (2000). Private communication, Biomass Technology Group, the Netherlands.
4. Garrett, D. E. (1989). *Chemical Engineering Economics*. Van Nostrand Reinhold.
5. Ed. Gerrard, A. M. (2000). *A Guide to Capital Cost Estimating, 4th Edition*. UK Institution of Chemical Engineers.
6. Bridgwater, A. V. (1994) *Capital Cost Estimation Procedures*. Aston University, UK.
7. UK Department of Trade and Industry (1999). *New and Renewable Energy: Prospects for the 21st Century*.
8. Kielder Forest Products Ltd., UK, private communication, January 2000.
9. Forestry Commission, UK, private communication, February 2000.
10. Ormrod Diesels, private communication, 2000.
11. van den Broek R., Teeuwisse S., Healion K., Kent T., van Wijk A., Faaij A., Turkenburg W. (2001) Potentials for electricity production from wood in Ireland. *Energy,* **26**, 991–1013.

Published in *Science in Thermal and Chemical Biomass Conversion, Bridgwater,* A.V. and Boocock, D.G.B., (eds.), CPL Press, 2006, vol. 2, p. 1785-1902.