COST AND OPERATIONAL ACCEPTABILITY IMPROVEMENTS TO GASIFIERS

ETSU B/U1/00677/REP

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The work described in this report was carried out under contract as part of the DTI New and Renewable Energy Programme, which is managed by Future Energy Solutions. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of the DTI or Future Energy Solutions.

First Published 2003

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EXECUTIVE SUMMARY

Biomass Engineering Ltd. have operated two gasifiers on their site for 5 years, one of which is now operating as a commercial unit [75kWe gross, 55-65 net output] in Northern Ireland in the Ballymena ECOS Millennium Centre, where a variety of sawmill wastes and other woods have been used. Based on the tar and particulate sampling performed under contract by CRE, very low tar levels were measured in the raw gas of 11 mg/Nm^3, particulates of < 50 mg/Nm^3 after the first cyclone. The very high tar destruction level also meant that the gas CV was more acceptable – 5.2 MJ/Nm^3 [LHV basis]. Biomass Engineering Ltd. decided to utilise this information in the operation of their remaining installation at their works - by drastically simplifying the gas conditioning system by using a back-pulsable ceramic filtration system to remove the particulates and trace organics from the gas. This would then be followed by gas cooling to remove water and final filtration before the gas engine. The benefits of using a ceramic filtration system are continuous operation, simplified system and lower installed and operational costs.

A small filter system was purchased from CFI Ltd., who has had prior experience in biomass gasification filtration systems, in the UK and in other European countries. There were some considerable delays in obtaining the unit and the ceramic filter elements. The gasifier has also been rebuilt and relocated, and a new gas engine has also being installed. Unfortunately, the gas was not tested in the newly installed gas engine. Mass and energy balances for the overall gasification have been presented, highlighting a gasifier efficiency of typically 80% [LHV basis] and overall system efficiency to electricity of 25% or more.

Locally available pallet wood and wood wastes from spruce were used as feedstock. Gas samples were taken for analysis and operation of the filtration unit carried out. No testing of tars and particulate levels have been done at this time.

A techno-economic assessment of the original wet scrubbing system and the new dry filtration system has shown that significant cost savings up to 12% can be made, with net electricity production costs of 2.4 p/kWh for a 293 kWe output system. Use of the dry filtration system in the CHP scenario can reduce costs by 16-25%, depending on the feedstock cost and the power output required.

Further work is required to optimise the operational parameters of the filters, which will be carried out later this year.

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1. INTRODUCTION

Biomass gasification processes generate organic contaminants in the exit gases that are generally referred to as tar. Before use of the gases in a boiler, engine or turbine, particulate matter and the organic tar must be removed, or reduced to a level that is acceptable to end user requirements. The specifications vary from manufacturer to manufacturer and careful matching of the technology and the end user is required. In addition, the actual determination of the level of "tars" is still under development (1, 2).

The subsequent removal of gasification tars from the process gas has led to the development and selection of a wide range of gas cleaning and solids removal technologies. Small-scale users generally do not appreciate what is happening in the gasification field at large and quite often, there is a lag phase where new small-scale technologies are slowly developed. At present, there are several gasification technologies under development in the UK for the production of low – medium heating value gas for subsequent use in an engine or turbine. However, their deployment has been hampered by negative press, high costs, poor reliability and a lack of skills on the behalf of the technology provider to offer a comprehensive service contract and equipment guarantees. Usually, wet scrubbing has been employed at small scale to remove residual tars and particulates after initial solids removal in a cyclone.

One of the most significant hurdles leading to the development and subsequent scale up of biomass gasification is gas cleaning for particulate and organic contaminants removal prior to use in power generation applications. Many of the emerging technologies in the UK are small scale and therefore the end user requirements in terms of gas quality will be strict. Typically, the tar levels are significant from small-scale gasifiers, due to poor design, feedstock specification and poor design. Biomass Engineering Ltd. has however overcome the apparent "tar" problem by careful control of the gasifier reduction zone and smooth continuous gasifier operation resulting in tar levels of 11 mg/Nm^3 in the raw gas [measured by CRE]. By achieving such low tar levels, the gas conditioning system can be greatly simplified and significant cost savings made. To this end, a small back-pulsable ceramic filtration system was planned to remove particulates and trace organics, leaving a tar and particulate free gas.

Limited attempts have been made in the UK to use ceramics at small-scale, the only known example was Power Gasifiers International (3). 1000 hours operational experience were gained. There are no other small-scale activities in biomass gasification below 1MWe using ceramic filtration to remove the particulates and trace tars. The use of ceramic filtration offers the advantages of a continuous process, which is self-cleaning and therefore lowers maintenance costs. The most notable experience of high temperature hot gas filtration has been the 18MW_{th} Varnämo plant in Sweden, for which some operational data is available. In the Varnämo plant, ceramic elements were used for 1200 hours, but due to three filter failures, these have been replaced with sintered metal elements (4).

2 EXPERIMENTAL WORK

2.1 Biomass Feedstock

The gasifiers of Biomass Engineering Ltd. have processed a range of materials successfully, including spruce, poplar, pine, mahogany, willow and wood wastes from pallets and sawmill operations.

The gasifier installed at Biomass Engineering Ltd. premises is a refractory lined downdraft gasifier. By having a refractory lined unit, the heat loss from the pyrolysis and reduction zones is reduced, improving tar destruction and thereby increasing the gasifier efficiency. The gasifier nominal throughput is 55-60 kg/h of wood, as the throat diameter has been significantly increased.

2.2 Gasification System

The gasifier is a throated downdraft gasifier, which was originally designed in 1996/1997 by Marick International, however this design did not operate correctly and was modified in 1999 to ensure that it operates as a very low tar downdraft gasifier. The gasifier is refractory cast and has tuyeres equidistant above the reduction zone. The maximum operational capacity of the gasifier is ~75 kg/h of wood. Biomass is fed in batchwise to allow for runs of 1-2 hours, although a continuous feed system will be installed shortly. Char and ash are removed by riddling of the reduction zone and this is removed from the base of the unit at the end of a run. The gasifier is double skinned to allow the exiting hot gases to preheat the incoming air, thereby improving the thermal efficiency of the gasifier.

2.3 Filtration Unit

The filtration test unit, supplied by CFI Ltd. is designed to handle all of the flow of gas from the gasifier at its outlet temperature of 200-400ºC. The schematic of the filtration unit is shown in Figure 1. Unfortunately, during the course of the work, CFI Ltd. was found to be in various financial and directorial difficulties and no significant technical input by the company was made. The ceramic filtration unit is designed to operate at the parameters given in Table 1. 9 elements are held in the housing, with 6 elements online with three being periodically back-pulsed to remove accumulated particulates consisting of char and ash. Differential pressure measurement is made over the filter elements and the readings are continuously monitored. When the pressure drop reaches a setpoint, three of the filters are backpulsed with clean producer gas. The dislodged char and ash drops down into the collection drum. The 6 filters are capable of handling the increased gas flow for the brief backpulse time. The 3 groups of 3 filters are back-pulsed in sequence, controlled by independent valves. Madison Filters supplied the elements, as recommended by USF Schumacher [now Pall Schumacher].

2.4 Conventional Gas conditioning system

The remainder of the producer gas is passed through a water scrubber to cool the gas and remove residual particulates after the cyclone. The moist gas is then cooled further to remove condensate, passed through a gas buffer tank prior to use in the engine. This is depicted in Figure 2.

2.5 Layout of filtration unit and Gasification system

The present gasifier is situated outside the works of Biomass Engineering Ltd., and the other components of the gas conditioning system and the test engines are located inside. Two test engines are available- a Series 1000 Perkins and an Iveco-Aifo gas engine. The Series 1000 engine is a modified diesel engine operating solely on producer gas.

The ceramic filtration unit is located outside with the gasifier, as shown in Photograph 1. This photograph shows the filtration unit before completion of the installation.

3. GASIFIER EFFICIENCY, MASS AND ENERGY BALANCES

Process measurements are made at various points in the system for the determination of temperatures, pressures, flowrates etc., which allow the mass and energy balance for the gasifier to be calculated. Operational data also allows the efficiency of the gasifier to be calculated.

3.1 Gasifier Efficiency

The gasifier operates at a typical efficiency of 80%. The overall efficiency of the gasification process, η, can be defined as the energy content of the producer gas in relation to the energy content of the solid feedstock.

$$\eta = \frac{H_G V}{H_S m}$$

where:

η	gasification efficiency [typically expressed as a %]
H_G	lower heating value of the producer gas [kJ/Nm^3]
V	volume flow of the producer gas [Nm^3/s]
H_S	lower heating value of the biomass feedstock [kJ/kg]
m	mass flow of the biomass feedstock [kg/s]

The energy content of the by-products, char and tars, must therefore be considered as losses. Efficiency losses in most gasifiers are in the range 2-30%, related to incomplete conversion that leads to the production of char in the ash or liquid condensate by-products, i.e. tars. Additional heat losses from the reactor [4-10%] and the sensible heat of the producer gas [4-10%] lead to overall losses of 10-50%, which corresponds to an overall conversion efficiency of 90-50%. By improving various features of the gasifier, some of these losses can be reduced, i.e. improved insulation, increased tar destruction and lower char production. Removing char from the gasifier will also lead to a reduction of the gasification efficiency, but the char may be used elsewhere in the process. The Biomass Engineering Ltd. gasifier incorporates features which lead to low heat losses [5%], extremely low loss of energy in the very low quantity of tars [<0.01%], and the remaining energy is retained in the char [15%].

3.2 Mass and Energy balance

Based on data obtained from the unit, by measuring the input mass of wood, recording the duration of the run until total consumption of the wood, measurement of the producer gas flow and composition and other basic pressure and temperature measurements, the overall mass and energy balance for the unit have been calculated. Representations for a 100 kg/h throughput are given in Figure 3 and Figure 4 for the mass and energy balances respectively, using data and measurements from the Biomass Engineering Ltd. gasifiers.

Each feedstock will give slightly different values and therefore the data presented should not be viewed as absolute for all possible feedstocks. The, "typical", mass balance summary used for the purposes of the cost calculations are given in Table 2. For the dry system there is no wet scrubbing stream [stream 12].

4. COSTS OF BIOMASS GASIFICATION SYSTEMS

There has been little work done on the costing of small-scale biomass gasification systems, as most installations are very specific to the local conditions and costs are therefore highly variable (see for example). For the purpose of this work, a standard cost estimation approach was used to determine indicative costs of the existing Biomass Engineering Ltd. wet gas cleaning system, as installed in their Ballymena ECOS Centre project, and the costs of a new modified system using a back-pulsable filtration system, thus avoiding a wet gas cleaning system. The advantages in moving to a dry gas conditioning system are:

- Avoidance of use of wet scrubbing, generating a significant quantity of dilute waste requiring treatment
- Gasifiers, which have very low tar production, are more suited to a dry gas conditioning system as the main contaminant to be removed is char and ash particles.
- System can be automated for continuous cleaning of the filter elements, reducing labour requirements and solids handling problems.
- System can operate in more extreme climates of low temperatures as no waster required.

4.1 Methodology

Costs associated with the production of electricity produced by biomass gasification comprise an annual cost of capital (assuming all of the capital is loaned), to which are added the annual operating costs of the plant. The operating costs comprise feedstock cost, labour, utilities, maintenance and overheads. The cost of electricity is obtained by summing the production cost elements, and dividing by the total annual production of electricity and also the variant of combined heat and power, taking into account revenues from the sale of heat. The methodology for calculating each of the production cost elements is described in the following parts.

4.2 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 small-scale biomass gasifiers in the UK, which are not specifically built for the application and the comparison of costs on a consistent basis is always very difficult. 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. The mass balance used as the basis for the cost estimation is given in Table 2 and the energy balance from Figure 4.

4.3 Total Plant Cost

Total plant cost (*TPC*) is built up in the following manner:

- The delivered cost of each process unit shown in Figure 5 and Figure 6 (referred to as the equipment cost, *EC*) is obtained from cost estimation charts for process equipment published by Garrett in 1989 (5) and from Biomass Engineering Ltd. own cost data for the costs of the installations on site and in Ballymena. The use of published cost estimations from a single source is believed to provide the fairest basis for process cost comparison where other data is not available. Garrett also gives factors for material of construction, which are applied as appropriate.
- 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 the design data for the Ballymena plant and the existing filtration system at Biomass Engineering Ltd.'s site again scaled appropriately for biomass feed rate.
- 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 (6). The factors take the form given in Equation 1:

$$F = c(aEC^{b}) \qquad [1]$$

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.

- Values for *a* and *b* and guidelines for the setting of *c* are given in Table 3. Actual values used for both systems are given in Table 5 and Table 6. The direct cost *DC* is then given by Equation [2]:

$$DC = EC(1 + \sum F) \qquad [2]$$

- 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 (7) and given in Table 4. All costs are brought to a mid-2002 basis using the Chemical Engineering Plant Cost Index as published by Chemical Engineering magazine (6). This allows a consistent approach to be used to derive the relevant cost data for both systems, incorporating in-house and external data as appropriate.

4.4 Operating Cost Calculations

For the operation of the system, it was assumed that 2 staff would be employed to maintain the system during the day and ensure adequate supplies of wood were available after drying and for continuous feeding to the gasifier. The components of the operating cost are: annual cost of capital, labour, utilities [electricity and water], maintenance and overheads.

4.4.1 Capital Amortisation

Capital is amortised using the standard relationship given below. This is a simplification since the equipment used is likely to have different working lives and some items may need replacing during the life of the project. Capital amortisation is the money required to pay back the loan on capital required to set up the plant. It is calculated by the using Equation [3].

$$\text{Fixed charge,} \quad \text{k/y} = TPC \times i \times \frac{(1+i)^l}{(1+i)^l - 1} \qquad [3]$$

where	TPC:	Total plant cost, k£
	i:	annual nominal interest rate, %
	l:	length of project, years (assumed to be the same as the loan period)

This fixed charge is constant in nominal terms and must therefore be adjusted to real terms for consistency with all other production costs. The cost in real terms of capital amortisation can be calculated for each year of the project by applying Equation 4. An average of the annual charges is used to give the approximate cost of capital amortisation in real terms.

$$\text{Annual charge,} \quad \text{k/y} = \frac{1}{(1+f)^n} \qquad [4]$$

where	n_x	project year
	f:	annual rate of inflation, %

Other factors assumed in the work are given below in Table 7.

4.4.2 Utilities

Only utility requirements for continuous operation are taken into account; any start-up requirements are ignored. The two utilities considered are electricity and water.

4.4.3 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 power consumption of fans and pumps is calculated from the known flow rates and pressures using in-house data. The power consumption of the conveyors and motors is taken from manufacturers data and scaled appropriately. The difference in gross and net power outputs are given in Figure 8.

4.4.4 Water

Water requirements are for make-up water for the cooling tower. A water price of £0.85/m^3 was taken for replacement of cooling water losses from the cooling tower. For the original system the make-up water for the scrubbing system is also required.

4.4.5 Maintenance and overheads

Maintenance and overheads are both included as a fixed percentage of *TPC* per annum. A typical value of 4% was used.

4.5 Results – Techno-economic assessment

Based on the data given and the methodology presented, the results of the techno-economic assessment are given in Figure 7 and Figure 8, Table 8,Table 10 and Table 11. The assessment will discuss the following:

- Total plant cost [wet v's dry] and electrical output [gross and net],
- Electricity production cost [wet v's dry, variation with biomass throughput and cost]
- Combined heat and power production cost [for dry system].

4.5.1 Total Plant Cost [TPC] and electrical output

The TPCs for a range of biomass throughputs are given in Table 8. It can be seen that the TPC for the dry filter system is significantly lower than that for the wet scrubbing system, with the dry system being 18% lower in cost relative to the wet scrubbing system at 200 kWe for example. This difference reduces to 11% at 300 kg/h biomass input to the gasifier.

The total plant cost is comprised of all the plant components. The breakdown for a 250 kWe system, excluding the engine is given in Table 9 for the wet and dry systems.

It can be seen that the most significant cost contributors are the gasifier and the respective gas cleaning unit operations. The gas compressor cost is also significant for the dry system. For a system with a typical gasifier efficiency of 80%, and an engine efficiency of 30%, the gross power from the system can be calculated. Using the installed power consumptions of the motors, fans, compressors, etc., the net electricity output for sale to the grid is shown in Figure 10. In all the presented costs given below, it is based on the net electrical output, assuming that all relate equipment will use internal power to reduce costs.

4.5.2 Electricity production cost

Based on the data presented and the cost factor approach described, then using the net electricity generated, and the annual operating cost of the plant, including the amortised capital and all other costs, then the net electricity cost can be calculated. As required, based on the ability to recover twice as much heat from the system as electricity [gas cooling, engine cooling system and engine exhaust], then as appropriate, the effects of income from the sale of heat from the system can be assessed, as discussed later. The calculated net electricity production costs are given in Table 10 and Table 11 for a range of options.

From the tables, the electricity production cost ranges from 5.2 p/kWh for the wet system ar 91 kWe output to 2.5 p/kWh for a 293 kWe system. The dry system costs are lower at 4.6 p/kWh and 2.4 p/kWh respectively. There appear to be more significant cost savings for the smaller systems using a dry filtration system, but these costs would appear to be acceptable, based on a zero cost feedstock. One of the key factors is the feedstock cost, and previous work has shown that the feedstock costs has one of the largest influences on the electricity production cost and data for a range of costs are given in Table 11. Data for comparison the two systems is depicted in Figure 8, showing that there is a significant cost difference for the two systems.

4.5.3 Combined heat and power production costs

Using a gasifier allows it to be operated purely as a "power" gasifier, generating electricity with heat being used to dry the feedstock, or supply space heating for onsite use. The other option, which may become of more interest, is the combined heat and power system, where recovered heat is exported for commercial benefit and sold to a local user. Some cost for the dry system were carried out, assuming an income of 1 p/kWth. The results are given in Table 12 for the dry system and depicted in Figure 9 for the system only. The sale of heat can reduce the net electricity production cost by 25% by 293 kWe output and a zero cost feedstock, which is a significant improvement and this reduces to a 16% reduction for a £50/t feedstock cost.

CHP therefore has the strong potential to make a significant cost impact and more opportunities for such systems need to be identified. Based on the data presented, the Biomass Engineering Ltd. can be built economically and used in the CHP mode to provide a reliable system for a range of biomass types.

The costing of biomass gasification systems is difficult, as there are usually site specific costs which cannot always be allowed for in the determination of generic costs for small scale biomass gasification systems.

5. RESULTS – OPERATION OF THE FILTER UNIT

The test rig using the 9 ceramic filter elements has been subject to a long testing period, with the key aim being the optimisation of the pulsing of the filter elements. One problem, which was quickly identified, was that pulsing three elements of the 9 tended to cause the gasifier to become unstable, as the nitrogen used to back-pulse the filters caused the gasifier to go out. Air is drawn into the gasifier by the action of the gas fan, therefore it is under a slight negative pressure and the intake of air was interrupted each time the filters were pulsed.

The problem can be overcome by pressurising the gasifier, however, this was not done within the timescale of the project, but by reducing the back pulse time and the amount of gas used, the filter could be operated continuously. The back-pulse of three of the filter elements can be done in manual or on the pressure drop measurement.

Further work on the longer term operating and monitoring of the elements is planned and the gasifier is to be modified to have a semi-continuous feed system, allowing longer run times. It is expected that the original filter system will be shortly replaced with a unit containing more elements and an improved back-pulse system.

Samples of particles recovered from the filter were characterised to give their particle size distribution. The results showed that the 60% of particles are less than 82 µm, of the size fraction less than 1 mm.

6. CONCLUSIONS

- The CFI filter system has been used satisfactorily to produce a clean gas, which has been used in an Iveco-Aifo engine.
- Modifications have been made to the back-pulse sequence and duration of the back-pulse to prevent nitrogen being blown back into the gasifier.
- Further test work will modify the gasifier to allow for semi-continuous running and also replace the current filter system.
- A techno-economic assessment of the original wet system and the new dry filtration system has demonstrated that there are significant cost savings to be made.
- The net electricity production cost the dry filtration system to produce 293 kWe is 2.4 p/kWh. For a CHP system, this cost drops to 1.8 p/kWh, for a zero cost feedstock.
- The dry filtration system has distinct advantages and allows continuous running with automatic solids removal and recovery.

7. RECOMMENDATIONS

The following recommendations are made:

- Modify filter system and carry out full monitoring programme on contaminants before and after filter system. Characterise the particle recovered and assess filter performance.
- Modify gasifier to allow semi-continuous feeding and therefore increase run times
- Remove gas fan and install air fan to pressurise the gasifier and therefore improve smooth operation of the gasifier and filter system.
- Carry out long term engine testing on the clean gas from the filter system

8. ACKNOWLEDGEMENT

Biomass Engineering Ltd. would like to acknowledge the financial support that has enabled this work to be carried out, as managed on behalf of the DTI by Future Energy Solutions.

TABLES

Table 1. Operational parameters for the ceramic filters

No. of elements	9
Length	1 m
Diameter	0.15 m
Space velocity	0.02 m/s
Operational temperature	300-700ºC
Operational Pressure	Up to 2 bar g

Table 2. Mass balance summary based on wet scrubbing system

Stream No	1	2	3	8	9	12	14	15	16-17
Description	Wood	Air in	Hot Prods	Hot Gas	Char/ Ash	Water	Condensate	Cold gas	Cooling water
Hydrogen			4.4	4.4				4.4	
Methane			2.1	2.1				2.1	
Water	16.0	2.3	14.9	14.9		13779.1	14.9	0.0	2551.7
Carbon Monoxide		0.0	49.4	49.4				49.4	
Nitrogen		161.0	151.0	151.0				151.0	
Oxygen		37.8							
Carbon Dioxide		0.9	68.9	68.9				68.9	
C2+		0.0							
Organics									
Wood (d.a.f.)	83.0								
Char			10.0		10.0				
Ash	1.0		1.0		1.0				
Total	100.0	202.0	301.7	290.7	11.0	13779.1	14.9	275.8	2551.7
Volume, Am^3/h	0.0		676	676		13.8		275.8	2.6
Temp In (^{o}C)	25.0	25.0	400.0	400.0	600.0	25.0			18.0
Temp Out (ºC)	0.0					50.0	25.0	25.0	45.0
Pressure Kpa Abs	1.0	1.0	1.0	1.0	1.0	2.0	1.0	1.0	2.0

Table 3. Direct cost factors

Factor, *f*	***a***	***b***	***c***	
Erection	1.924	-0.261	0.56 1.32 4.26	low, e.g. erection included high, e.g. some site fabrication very high, e.g. much site fabrication
Piping, ducting	31.953	-0.358	0.3 0.71 1.42	very low, e.g. ducting only low, e.g. small diameter piping high, e.g. large diameter piping, complex
Instrumentation	13.942	-0.33	0.46 0.8 1.28	very low, e.g. locate only low high
Electrical	4.2112	-0.231	0.23 0.83 1.46	very low, e.g. lighting only low, e.g. for ancillary drives only high, e.g. transformers and switchgear
Civil	1.997	-0.231	2.25 2.9	high very high
Structures, buildings	4.99	-0.244	0.35 0.83 1.18 1.89	very low, e.g. negligible low, e.g. open air or ground level high, e.g. covered building very high, e.g. elaborate under cover
Lagging	10.338	-0.419	0.61 1.16 1.84	low, e.g. service only high very high, e.g. cold lagging

Table 4. Indirect cost factors

Item	Range	Factor Used
Direct plant cost (*DPC*)		1.0
Engineering, design and supervision	0.10-0.20	0.15 *DPC*
Management overheads	0.05-0.20	0.10 *DPC*
Installed plant cost (*IPC*)		1.25 *DPC*
Commissioning	0.01-0.10	0.05 *IPC*
Contingency	0.00-0.50	0.20 *IPC*
Contractor’s fee	0.05-0.15	0.10 *IPC*
Interest during construction	0.07-0.15	0.10 *IPC*
Total plant cost (*TPC*)		1.45 *IPC*
		1.81 *DPC*

Table 5. Nomenclature and Direct Cost factors for original [wet] gasification system

			DIRECT COST FACTOR , F							
Eqpt. No.	Equipment	Equipment Type	Erection	Piping (gas)	Piping (liquid)	Instrumentation	Electrical	Civils	Structures	Lagging
C01	Wood Feed Conveyor	Belt conveyor	0.124			0.519	0.557	0.297	0.551	
C02	Char/Ash Conveyor	Conveyor, Screw	0.149			0.637	0.660	0.348	0.653	
V01	Gasifier	Refractory lined, furnace	0.244	0.775		0.365	0.417	0.226	0.413	0.198
F01	Start up fan	Axial Small, 1 atm, 0.5 atm vac	0.153	1.573		1.143	0.677	0.356	0.282	0.277
F02	Operational Gas Fan	Blower, Turbo 3psi	0.147	1.488		0.627	0.652	0.344	0.272	
H01	Producer Gas Cooler	Heat Exchanger, Shell and Tube	0.252	1.983		1.042	0.521	0.332	0.621	0.463
S01	Char Cyclone	Dust Collector, Cyclone	0.254	2.005		0.000	0.145	0.334	0.754	0.404
S02	Char Cyclone	Dust Collector, Cyclone	0.254	2.005		0.000	0.145	0.334	0.754	0.404
S03	Quench Condenser	Cooler/Quencher, Quencher	0.131	0.203	0.692	0.620	0.340	0.186	0.406	0.140
S04	Gas Buffer	Small Tank, Flanged & Dished Heads	0.142	1.800		0.602	0.145	0.333	0.623	0.245
P01	Quench recirculation	Centrifugal Pump, Conventional	0.151		1.400	0.647	0.668	0.352	0.661	0.271
P02	Cooling tower recirculation	Centrifugal Pump, Conventional	0.158		1.490	0.679	0.695	0.366	0.688	0.290
E01	Cooling Tower	Cooling Tower	0.463		2.884	0.870	0.708	0.443	0.000	0.783
V02	Char/Ash Storage Bin	Small Tank, Flat Top and Bottom	0.162					0.373	0.297	
V03	Char/Ash Storage Bin	Small Tank, Flat Top and Bottom	0.162					0.373	0.297	

Table 6. Nomenclature and Direct Cost factors for back-pulsable filter [dry] gasification system

			DIRECT COST FACTOR , F							
Eqpt. No.	Equipment	Equipment Type	Erection	Piping (gas)	Piping (liquid)	Instrumentation	Electrical	Civils	Structures	Lagging
C01	Wood Feed Conveyor	Belt conveyor	0.124			0.519	0.557	0.297	0.551	
C02	Char/Ash Conveyor	Conveyor, Screw	0.149			0.637	0.660	0.348	0.653	
V01	Gasifier	Refractory lined, furnace	0.244	0.775		0.365	0.417	0.226	0.413	0.198
F01	Air booster fan	Axial Small, 1 atm, 0.5 atm vac	0.157	1.627		1.175	0.693	0.364	0.289	0.288
F02	Gas compressor	Air, 125 psi discharge	0.146	1.465		1.077	0.645	0.340	0.154	0.418
H01	Producer Gas Cooler	Heat Exchanger, Shell and Tube	0.252	1.983		0.599	0.521	0.332	0.621	0.463
S01	Filter + demister	Baghouse filter [ceramic eleemnts]	0.150	0.976		0.217	0.386	0.210	0.383	0.320
S02	Gas Buffer	Small Tank, Flanged & Dished Heads	0.142	1.800		0.602	0.145	0.333	0.623	0.245
P02	Cooling tower recirculation	Centrifugal Pump, Conventional	0.158		1.490	2.154	0.695	0.366	0.688	0.290
E01	Cooling Tower	Cooling Tower	0.463		2.048	0.000	0.708	0.443	0.000	0.783
V02	Char/Ash Storage Bin	Small Tank, Flat Top and Bottom	0.162					0.373	0.297	
V03	Char/Ash Storage Bin	Small Tank, Flat Top and Bottom	0.162					0.373	0.297	

Table 7. Calculation factors used in the techno-economic assessment

No of plant replications	1
Life of project [years]	20
Interest rate [%]	8%
Inflation rate [%]	3%
Labour rate [£/y]	20000 per person
No. of shifts	1
Overheads [%CC/y]	4%
Maintenance [%CC/y]	4%
Availability	90%

Table 8. Total Plant Cost for the two systems- variations with biomass throughput

Biomass throughput [kg/h]	100	150	200	250	300
Electrical output [kWe]	91	140	191	242	293
Electrical output [MWh, annual]	2574	3986	5418	6823	8316
Wet system [£ x 1000]	359	397	432	464	494
Dry system [£ x 1000]	258	309	356	399	441
Electrical output [Gross, kWe]	110	165	221	276	331

Note: does not include engine cost

Table 9. Breakdown of TPC: contribution of plant components to overall cost

Wet system		**%**		**Dry system**		**%**
C01	Wood Feed Conveyor	4		C01	Wood Feed Conveyor	4
C02	Char/Ash Conveyor	2		C02	Char/Ash Conveyor	2
V01	Gasifier	26		V01	Gasifier	30
F01	Start up fan	4		F01	Air booster fan	4
F02	Operational Gas Fan	4		F02	Gas compressor	11
H01	Producer Gas Cooler	7		H01	Producer Gas Cooler	7
S01	Char Cyclone	4		S01	Filter + demister	28
S02	Char Cyclone	4		S02	Gas Buffer	5
S03	Quench Condenser	32		P02	Cooling tower pump	4
S04	Gas Buffer	5		E01	Cooling Tower	2
P01	Quench recirculation	3		V02	Char/Ash Storage Bin	1
P02	Cooling tower pump	2		V03	Char/Ash Storage Bin	1
E01	Cooling Tower	2				
V02	Char/Ash Storage Bin	1				
V03	Char/Ash Storage Bin	1				

Table 10. Summary of Net Electricity Production Costs [p/kWh] for the two systems – variation with biomass input [kg/h]. Zero cost feedstock. % relative cost saving.

Biomass throughput [kg/h]	100	150	200	250	300
Net electrical output [kWe]	91	140	191	242	293
Annual Operating cost [wet]	91000	97000	106000	122000	131000
Annual Operating cost [dry]	75000	83000	94000	112000	122000
Wet system [p/kWh]	5.2	3.6	2.9	2.9	2.5
Dry system [p/kWh]	4.6	3.2	2.7	2.7	2.4
% cost saving [dry system compared to wet]	12	9	7	5	4

Table 11. Summary of Net Electricity Production Cost [p/kWh] for the two systems – variation with feedstock cost and electrical output

Net electrical output [kWe]	91	140	191	242	293
Wet system [£0/t]	5.2	3.6	2.9	2.9	2.5
Wet system [£25/t]	5.9	4.3	3.6	3.6	3.3
Wet system [£50/t]	6.7	5.0	4.4	4.3	4.0
Dry system [£0/t]	4.6	3.2	2.7	2.7	2.4
Dry system [£25/t]	5.3	4.0	3.4	3.4	3.2
Dry system [£50/t]	6.1	4.7	4.2	4.1	3.9

Table 12. Net electricity production cost v's electrical output and CHP option. Income 1 p/kWh for CHP option. Variation with feedstock cost for dry system only

Electrical output [kWe]	91	140	191	242	293
Heat output [kWth]	182	280	382	484	586
Power only[£0/t]	4.56	3.21	2.69	2.70	2.44
Power only[£25/t]	5.33	3.96	3.42	3.42	3.15
Power only [£50/t]	6.09	4.70	4.15	4.14	3.86
CHP [£0/t]	3.96	2.61	2.09	2.10	1.84
CHP [£25/t]	4.73	3.36	2.82	2.82	2.55
CHP [£50/t]	5.49	4.10	3.55	3.54	3.26

FIGURES

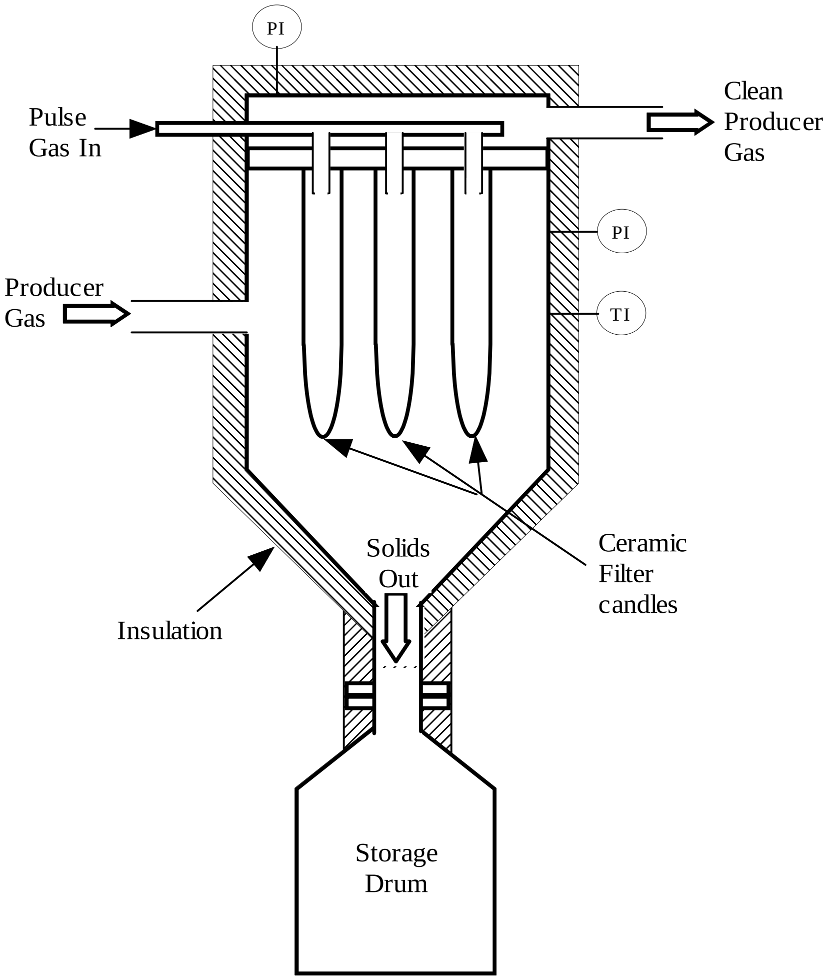


Figure 1. Schematic of test filtration unit

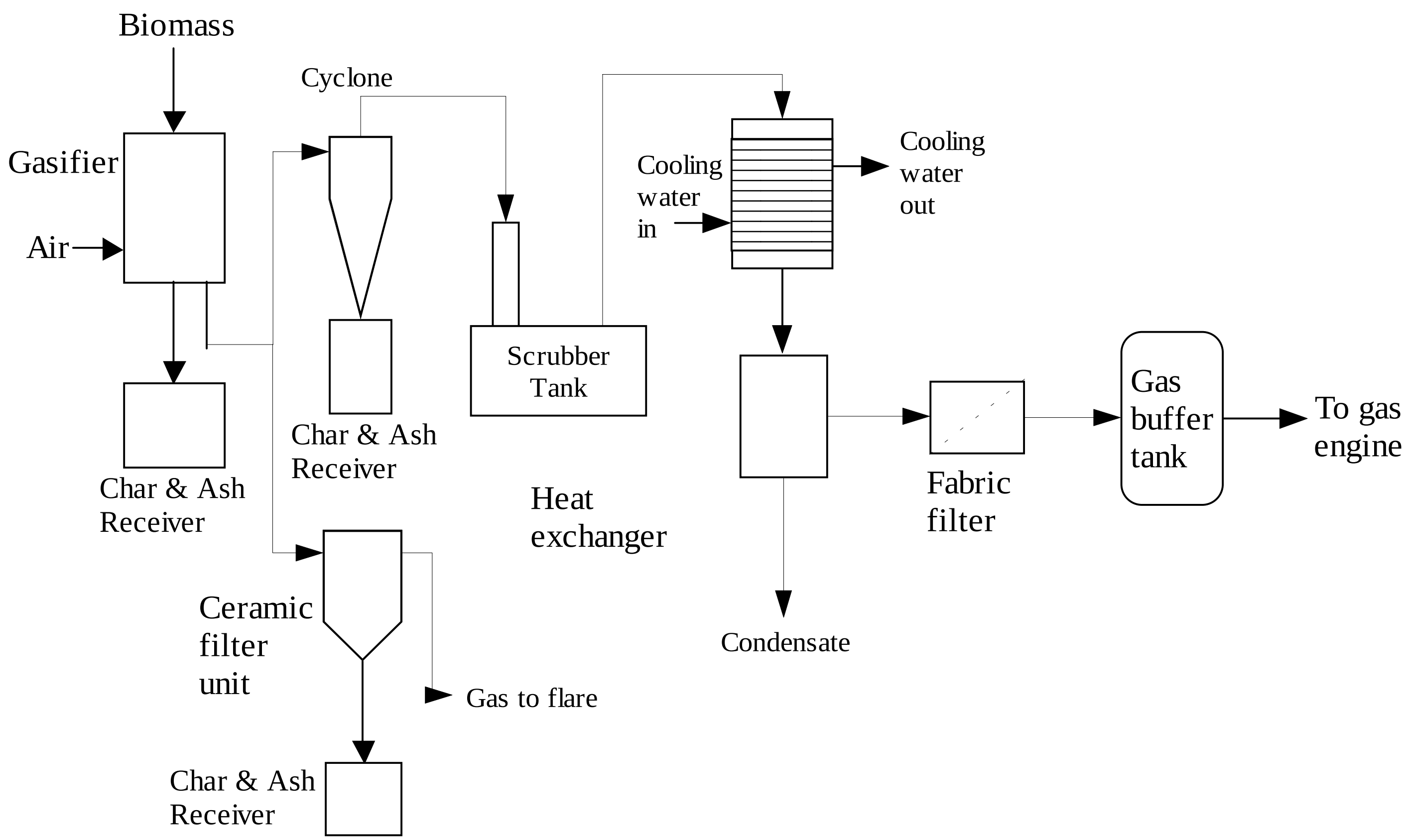


Figure 2. Basic layout of existing gasification system and test rig

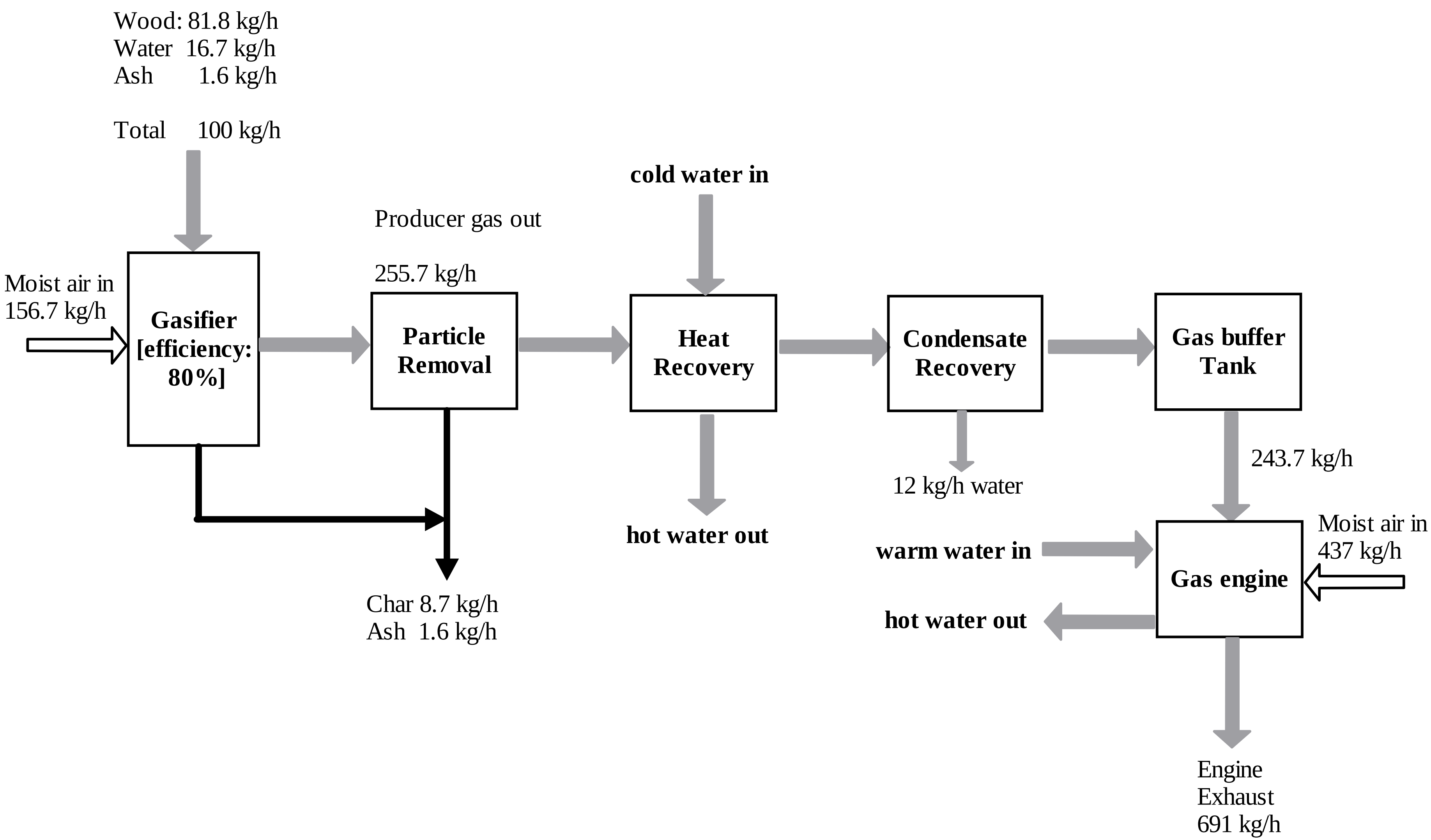


Figure 3. Gasification System Mass Balance

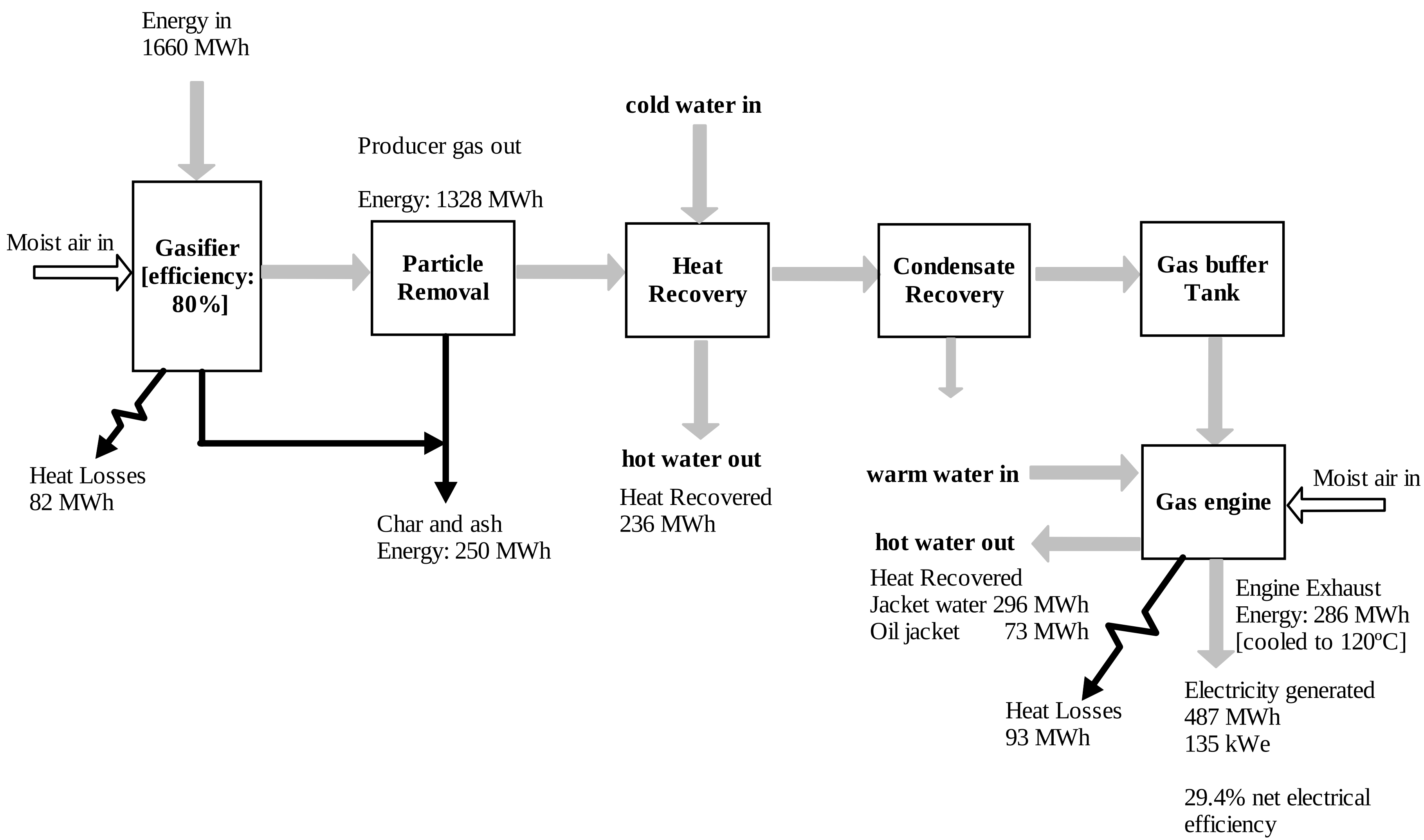


Figure 4. Gasification system Energy Balance

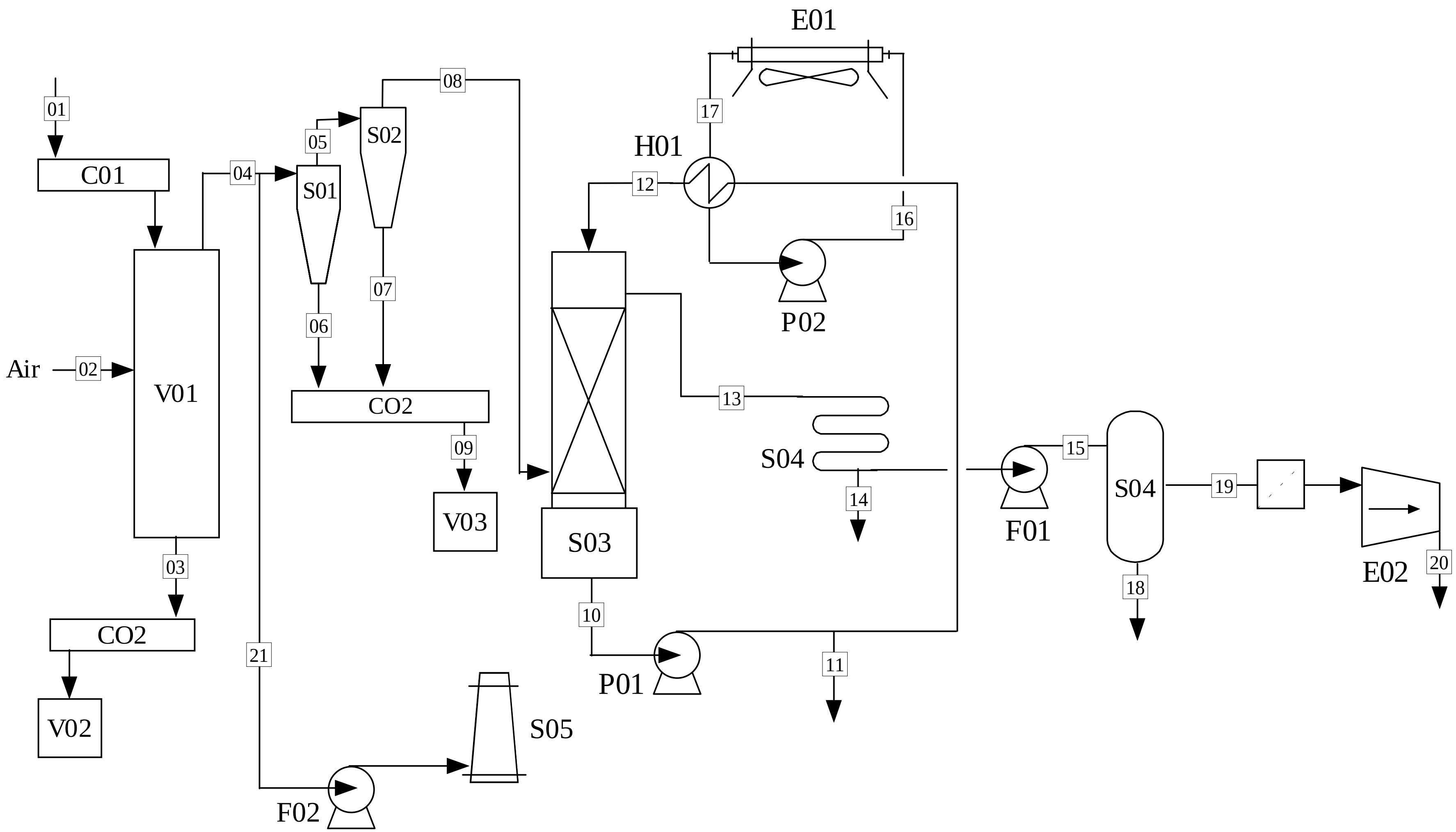


Figure 5. Flowsheet for techno-economic assessment - original system [see Table 5 for equipment codes]

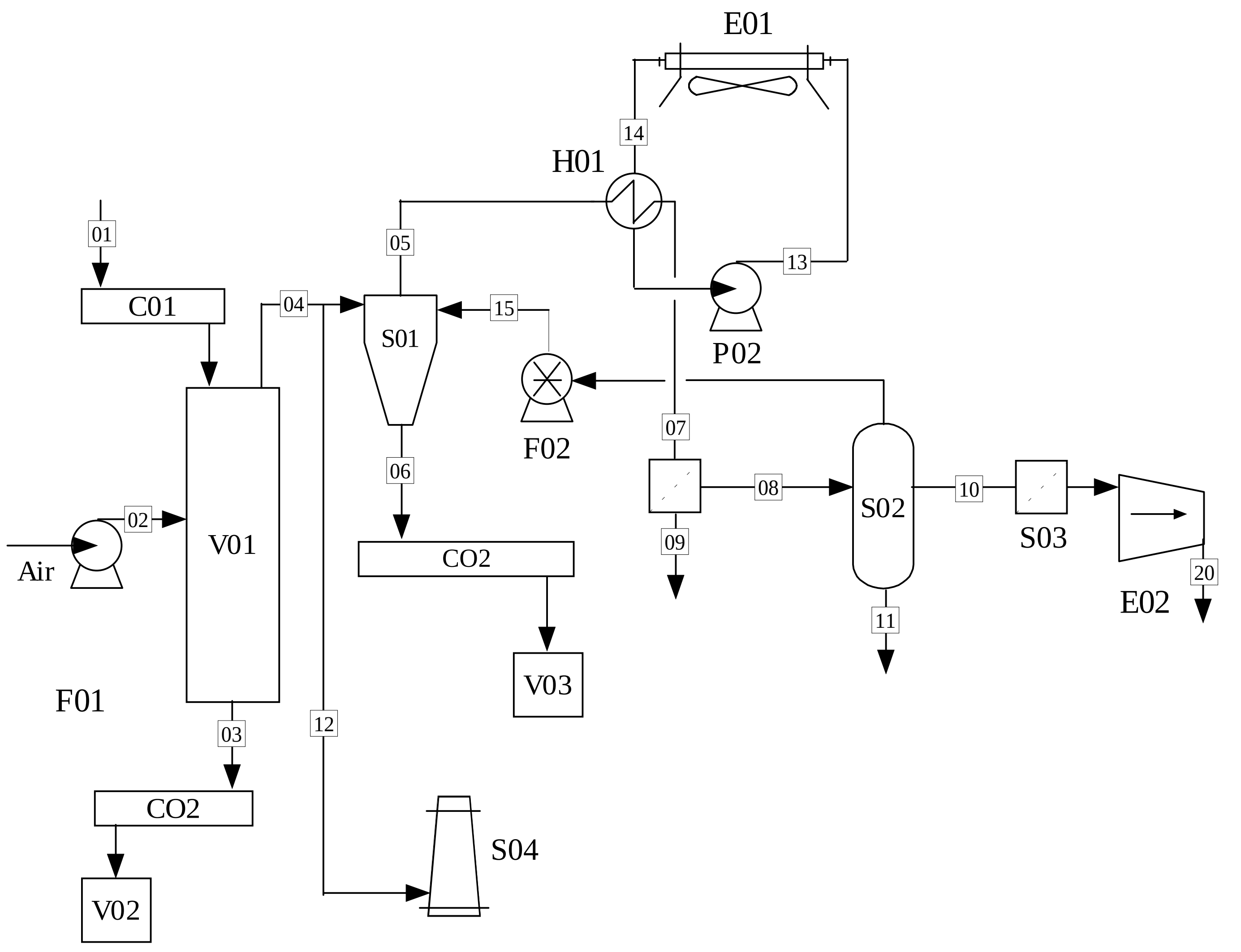


Figure 6. Flowsheet for techno-economic assessment - modified system [back-pulsable filter system] [see Table 6 for equipment codes]

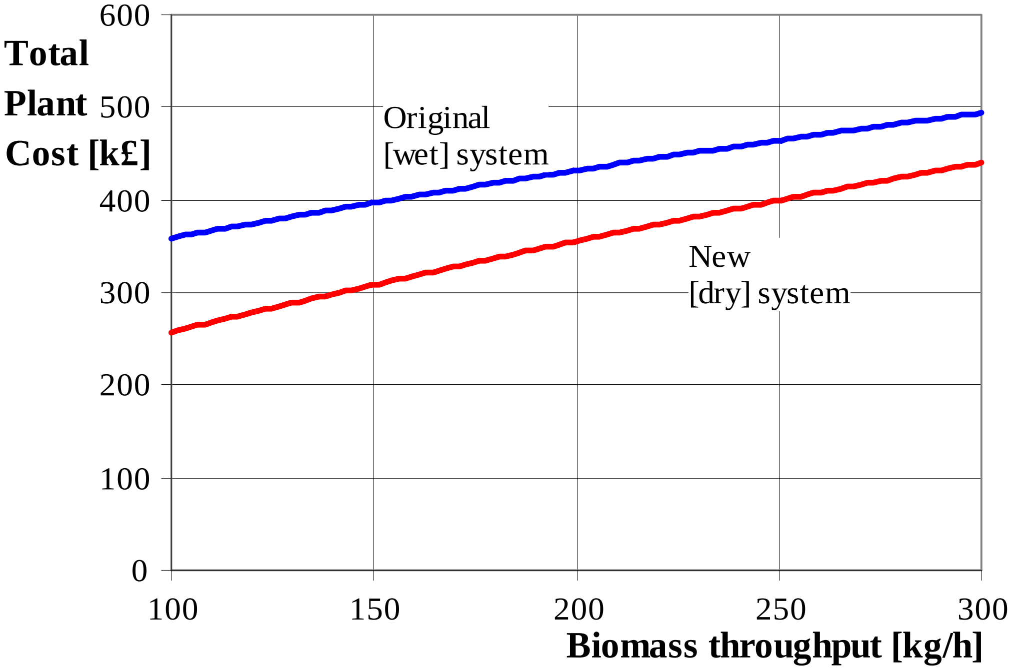


Figure 7. **Total Plant cost [gasification system excluding engine] v's biomass input to the gasifier**

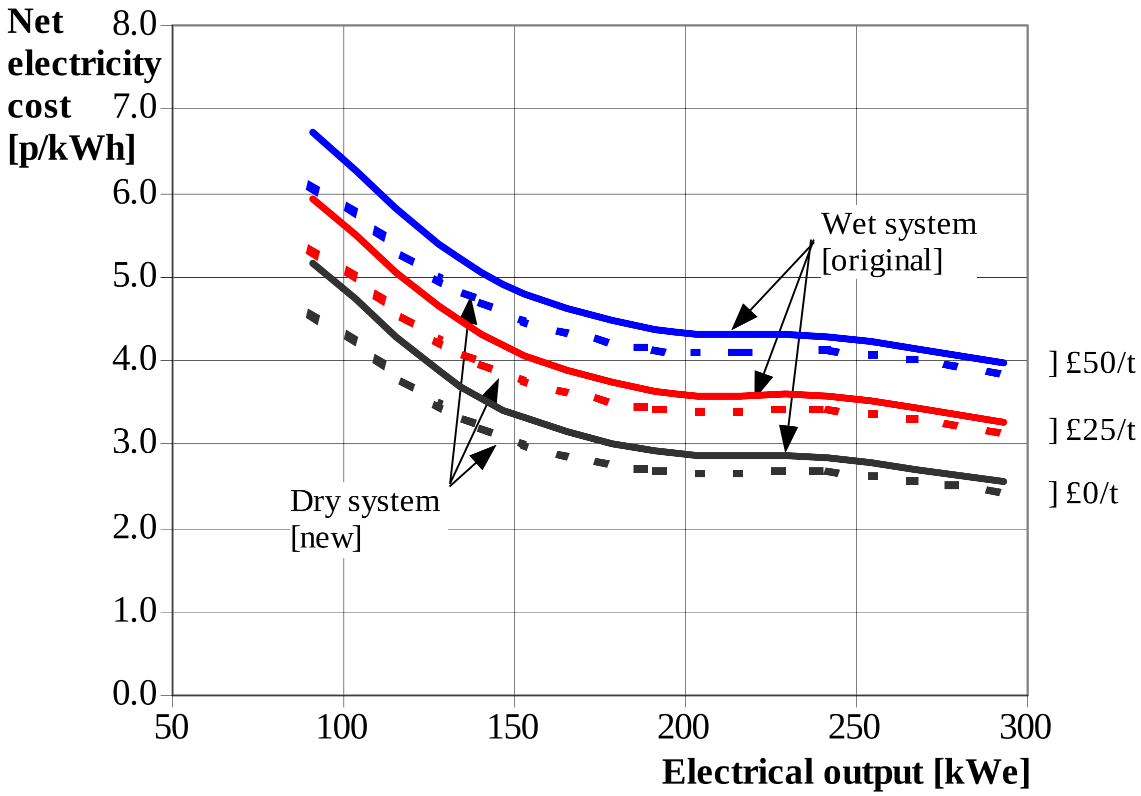


Figure 8. **Net Electricity Production cost v's electrical output: variation with prepared feedstock cost**

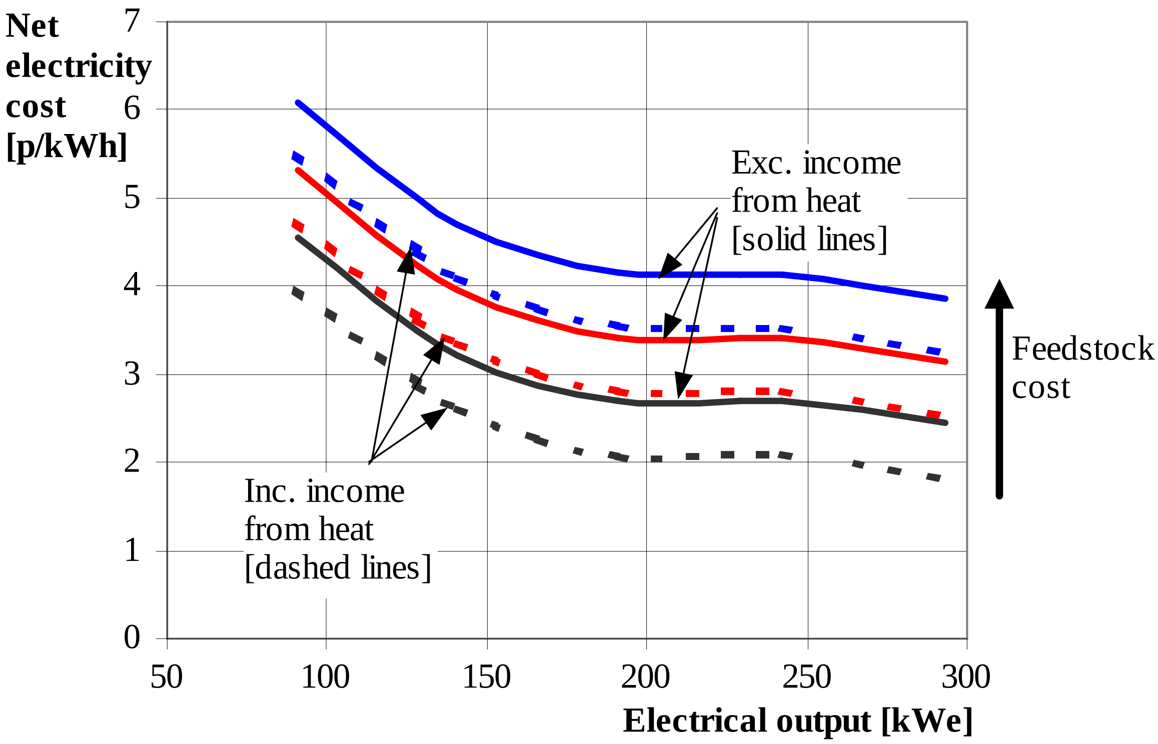


Figure 9. **Comparison of net electricity production cost with CHP option – income from heat [1 p/kWh]. Variation with feedstock cost [£0/t, £25/t and £50/t]**

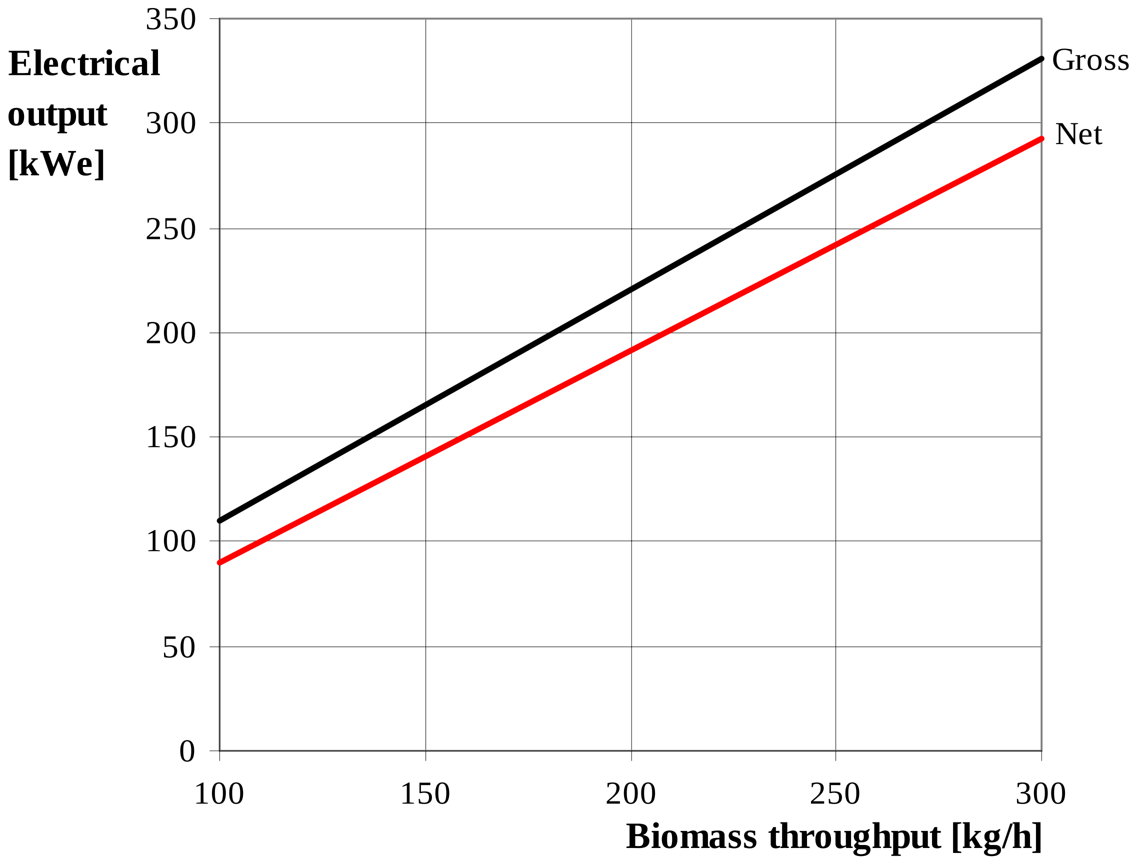
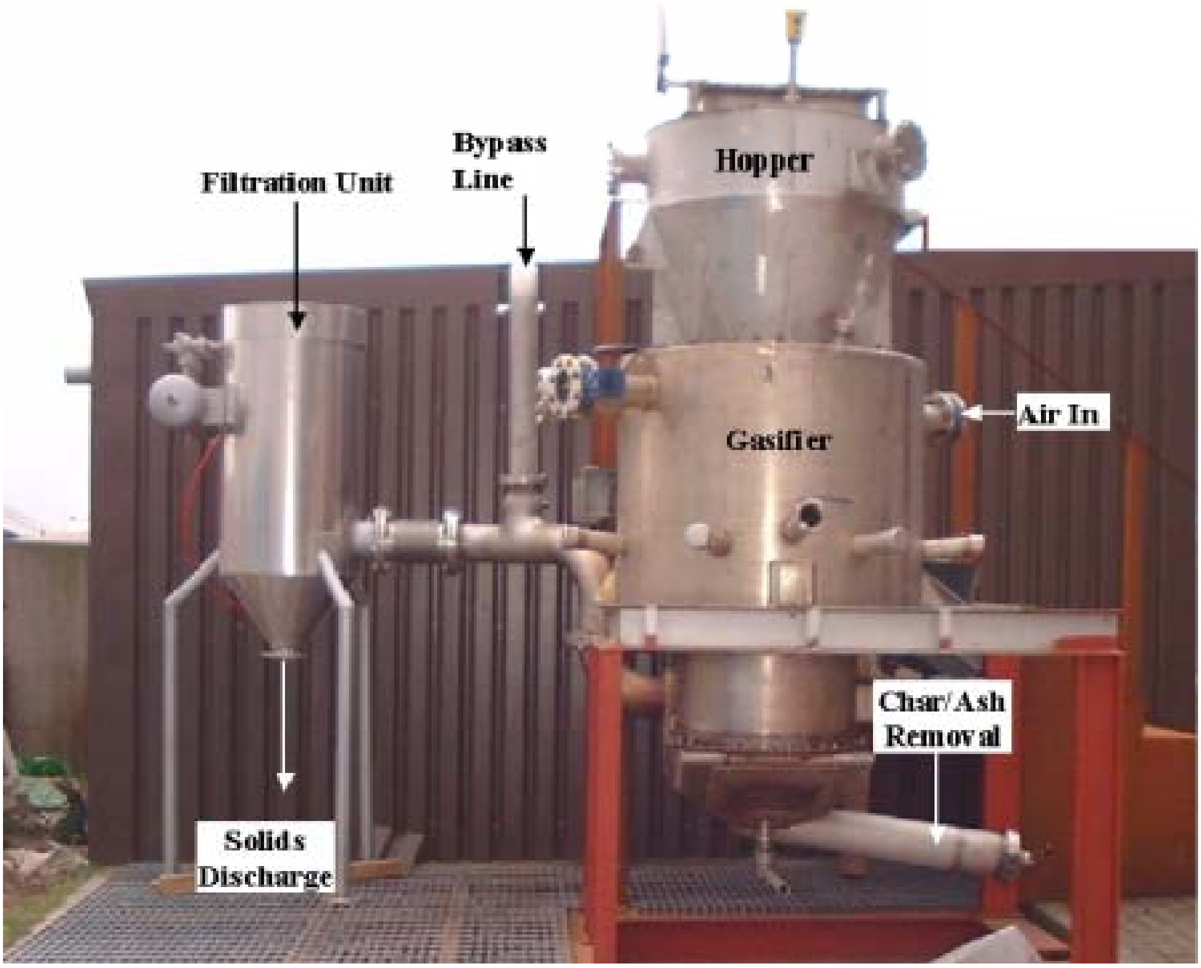


Figure 10. Gross and Net electrical output v's biomass throughput [gasifier efficiency 80%, engine efficiency 30%]

PHOTOGRAPH



Photograph 1. Gasifier and Test filtration unit

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