Life Cycle Assessment of Bioenergy Systems

Introduction

Part of the work carried out in Work Package 1 involved life cycle assessment of the chosen bioenergy systems. This was carried out at the University of Manchester in conjunction with and in order to inform the social assessment which Manchester also completed.

The principle of life cycle assessment is that it looks at the entire bioenergy system from crop establishment and growth, through harvesting, processing, transport and delivery through to utilisation in the power station. The Supergen bioenergy group aimed to take a holistic approach to looking at the entire bioenergy system, incorporating the interfaces that frequently define the boundary points in studies that consider only crop growth or only power production. The benefits of this approach are that it allows a realistic assessment of the impact of the entire bioenergy system, making it clear which steps in the bioenergy system contribute most to the impact of the overall system e.g. is there any real value in attempting to minimise agrochemical application to energy crops or are the typical quantities used so small as to be insignificant alongside the chemical consumption of the power generation plant? The disadvantage is that it is impossible to conceive an entire bioenergy system that all stakeholders would agree is typical or representative. It has been endeavoured to address this via consultation with growers, power producers and local authority representatives on what to model: what is likely to be built and how is fuel supply most likely to be implemented; but, inevitably, a degree of common sense and flexibility are required when interpreting the results presented here.

At the outset of the project it was intended to approach the life cycle assessment by considering a set of balances (inflows and outflows) over the entire system. The system boundaries would be defined and calculations carried out to quantify the flows across the boundaries with respect to the following “dimensions”:
Energy balance
Greenhouse gas balance
Materials balance
Economics balance
The extent to which this was completed is discussed below.

System Definition

The same physical system is modelled for each of the balances performed and this comprises the following elements:

Agricultural elements

The system modelled in each case begins with fields previously used for grassland or arable cultivation. The pre-existing growth is eradicated and the field prepared as appropriate for the crop. Crop establishment is included and the cuttings, rhizomes or seeds used are considered as a material flow into the system with an embodied energy which represents the specialised cultivation of the material, modelled specifically for the Supergen work. Similarly all agrochemicals required are quantified as materials entering the systems with an associated energy cost, which is included in the energy and carbon balances. A particular agronomic regime is defined for the base case for each crop and this has been based on consultation with Supergen partners and others within the industry. Inevitably the regime will be site-specific and this is impossible to replicate with desk-top modelling; but efforts have been made to make the steps included as representative as possible and appropriate to the size and type of farming being undertaken e.g. small arable farmers supplying a local gasifier may wish to return to food crops in the future and so might be more reluctant to spread sewage sludge on previously arable land. Harvesting of the material has been included utilising appropriate specialised machinery. The base case model involves simultaneous harvesting and chipping of short rotation coppice; mowing and baling of miscanthus and straw.

At the end of the planation lifetime it is returned to its original state by appropriate eradication of the energy crop.

Transport and logistics

Following harvest the system mdoel continues seamlessly with material collection, processing and storage appropriate to the size of installation being served. The table below summarizes the assumptions about transport made in the base case models.

Base case for short rotation coppice (winter harvest & chip)		
Leave piles of chips in field to dry to 30% moisture content		
< 2 MWe	**> 2 MWe**	
Transport to power plant by tractor/trailer	Transport to covered storage area by tractor/trailer	
	Reclaim from storage area with front-end loader	
	< 5 MWe	**> 5 MWe**
	Transport to plant in 60 m3 rigid trucks	Transport to plant in 120 m3 articulated tricks

Base case for miscanthus		
Winter harvest & bale at 25% moisture content		
Cart 5 km to satellite bale store		
Stack up to 7 bales high		
< 2 MWe	2-5 MWe	> 5 MWe
Transport to plant by tractor	Transport to plant by 60 m3 rigid trucks	Transport to plant in 120 m3 articulated trucks

Appropriate account is taken of dry matter losses during processing and storage based on published data.

Electricity production

The fuel delivered to the powerplant is appropriately stored at an appropriate level. The analysis incorporates consideration of power plant construction, operation and decommissioning. For construction the energy and carbon impacts are estimated, but there is not a detailed breakdown of material flows through the construction phase. During power plant operation key material inflows are quanitified that could differentiate bioenergy systems. These include items such as start-up fuel, abstracted water, chemical process reagents. A fully detailed inventory of all items required for operation has not been attempted. The power plant operation that is considered takes account of typical operating patterns for a plant of that type and size in estimating load factors, requirements for start-up fuel etc.

Scope of balances

Energy balance

Three types of energy consumption are considered for each step in the process:-

- Fossil fuel consumed directly by equipment e.g consumption of diesel oil by agricultural machinery or oil used as start-up fuel in furnaces
- Energy used in production of machinery utilised in the process e.g. energy used to produce steel used to manufacture tractors or concrete used for foundations of power plant. Where it is clear that not all of the machinery is used in the process this figure is weighted based on the operating hours associated with its use in the bioenergy system compared to its expected overall useful operational lifetime.
- Energy invested or embodied in materials utilised by the bioenergy system e.g. energy used in manufacture of fertiliser consumed in crop growth or energy used in nursery production of cuttings used in establishment of energy crops. This includes energy required to supply/transport materials for use in the bioenergy system. In general this is included as part of a referenceable figure that incorporates transport and distribution, but in some instances e.g. the application of digested sewage sludge to energy crops specific calculations have been undertaken to calculate the energy expended in the transport process.

Carbon balance

The carbon balance considers the same three sectors as the energy balance and the scope and assumptions are consistent with those above. Therefore it includes the following:

- Carbon emissions associated with the direct consumption of fossil fuel in agricultural machinery, transport vehicles etc.
- Carbon emissions associated with the production of machinery wholly or partly for use in the process (the same weighting factor is used as for the energy balance, based on operating hours)
- Carbon emissions associated with the production of the materials consumed in the process.

Additionally it is recognised that some of the agricultural activities taking place may add to the greenhouse gas emissions. This could happen by cultivating land, causing carbon in the soil to be released. The rate of release is complex, variable and difficult to predict. Calculation of this impact is beyond the scope of this work. However, it is noted that the tillage associated with energy crops is generally much less than that associated with conventional arable farming. Therefore, if comparing to an arable farmland scenario there will be no increase in carbon emissions. However, if comparing to grassland there will be increased carbon emissions which it has not been possible to quantify.

There are some areas where it has been possible to quantify the additional greenhouse gas emissions and these have therefore been included. First of all, it is not possible to ensure 100% efficient utilisation of an energy crop; there will inevitably be release of some biomass matter to the ecosystem that would not otherwise taken place. Provided that aerobic conditions dominate plant matter will degrade to CO2 , which has been recently sequestered and can be ignored. This is the case for leaf litter arising from senasence of the crop, residual root systems after cultivation and biomass left in the field due to harvesting inefficiencies. However, the leaves also contain a proprortion of nitrogen, which degrades to the powerful greenhouse gas nitrous oxide and this has been accounted for as its CO2 equivalent in the carbon balance. Secondly where nitrogen based fertilisers are applied to assist crop growth there will be associated releases of nitrous oxide, which have been quantified. It should be noted in this respect, though, that, even for the cases where nitrogen-based fertilisers are used (cases 1 and 2) the bioenergy system utilizes very much less fertilizer than conventional arable cropping would and so this is only really an incremental CO2 emission compared to grasscover.

In all cases the CO2 equivalent factor is calculated for the various greenhouse gases considered.

Material balance

The physical and activity scope of the system material balance is the same as for the carbon and energy balances. There are a very large number of inflows and outflows of material through the bioenergy system. For many of these the effort required to quantify them would not be justified by the benefits obtained by being able to compare them for different systems. Therefore certain material flows have been prioritised and efforts have focused on attempting to quantify these through every step of the bioenergy system. The choices of materials for tracking through the system are informed by those identified as of importance or interest through stakeholder dialogue. These comprise the agrochemicals used in energy crop production, chemicals used in power production, materials required for crop establishment, sewage sludge being treated and airborne pollutants. The work has focused on 4 key airborne pollutants: CO, NOx, particulates and VOC’s, which have been tracked across every step in the bioenergy system from field to power plant. Ash and effluent discharging from the power production process have also been quantified.

Employment

Each bioenergy system modelled has been analyzed in terms of its job creation utility. A step by step assessment has been carried out of the actual manhours expended in energy crop cultivation, harvesting and processing. For the power plants manning and shift patterns have been calculated specific to each plant technology and size and estimates made of the manpower required to undertake the relevant development and construction work. Previous work completed by Mott McDonald on behalf of the DTI has then been used to quantify the supply chain employment impact of each bioenergy system and finally the jobs created by induced economic activity associated with the new bioenergy system have been calculated in association with HM Treasury’s green book guidelines.

Life Cycle Assessment Indicators

The point of taking a life cycle approach to work within WP1 is to recognise that bioenergy is different to other new and renewable technologies in that a novel feedstock must actually be produced and this production (whether a crop or a waste material) has impacts on the local and global environment. Uncertainties related to these upstream activities are frequently a source of confusion and concern for stakeholders and the general public when considering bioenergy plants. Traditionally agronomists focus on the upstream activities, engineers look at the plant design and the interface between the two is marginalised. By taking a whole systems life cycle approach we aim to address the data uncertainaty by directly evaluating the performance of the entire system including agricultural and engineering components. Additionally it is recognised that each stage of the bioenergy system impacts not just on the technical performance but also has environmental, economic and social impacts. It is important therefore to be able to quantify important figures such as carbon savings over the entire system, but it is also important to simultaneously assess other softer parameters, such as visual impact and resultant employment opportunities.

This work has therefore, used the life cycle approach, to quantify a series of life cycle assessment indicators, the choice of which has been guided be dialogue with stakeholders and the general public. The indicators are intended to provide information on the aspects of an entire bioenergy system that are actually of concern/interest to a more general audience, rather than simply reflecting technical performance. This allows trade-offs to be examined when looking at different bioenergy systems that might be implemented in the UK. The actual indicators are derived from the life cycle balances performed, which, in turn utilise the outputs from the techno-economic assessment. They offer a consistent, independent analysis of the complete "end-picture" bioenergy system based on detailed and rigorous calculations. The calculations behind the chosen indicators are discussed below:

Landtake

The land requirement for bioenergy systems is frequently cited as a concern by local people when new facilities are proposed. There is often concern at the extent of the change in land use pattern that the bioenergy facility will cause and sometimes disbelief or distrust that developers' figures for the land area required are actually sufficient. Two figures are given here: the proportion of the local area that is to be utilised for production of biomass and the total area of land from which biomass will be drawn.

The calculation is a simple demand driven assessment of the total physical area from which biomass is drawn for a particular facility. The as-received biomass for plant operation is taken from the technical mass energy balance and scaled up to cover continuous operation over lifetime, accounting for moisture contents, availability factors, frequency of harvest etc. Allowances are made for losses of material related to harvesting inefficiencies, losses during each stage of drying, transfer and transit in the logistics chain to the power plant. Assumptions of crop yield are made based on data obtained from Supergen partners, which allow calculation of land area planted. The total land area affected is then calculated by taking into account a defined assumption for the percentage of the area that is actually planted. This has been varied from high (50%) for small systems to low (10%) for larger systems to reflect possible acceptable ranges for different scales of facility.

These figures are used later in calculating transport distances for feedstock, as well as the area of land that is cultivated in the carbon, material and energy balances.

Transport

The transport of bioenergy material to the plant is an area where the plant interfaces significantly with the surrounding area and is another frequent area of concern during plant development. The indicators presented give the type of vehicle used for transport and its capacity – this is set as one of the logistics assumptions referred to above. A calculation is then used to determine the number of road journeys likely each day. This incorporates assumptions regarding the density of the feedstock, the plant demand for biomass and the number of delivery days.

The mean length of journey for delivery vehicles to the plant is calculated taking into account the mean distance between the biomass loading point and the plant, weighted by tortuosity factos appropriate to the size of the facility. The assumption is that larger plants with longer distances to travel will utilise primary routes; whereas small plants in rural areas will generally be faced with less direct routes.

Physical setting

Possibly the most significant interaction between local communities and biomass plants are how they physically appear once they are built: how large and obtrusive are they? The detail of this is obviously site-specific but it is useful to offer stakeholders some idea of how different plants are likely to compare to each other in terms of scale and this is what is offered here.

Noise limits for all new bioenergy developments are set by its planning permission generally to ensure that new developments do not cause undue disturbance within their localities. Perception of noise can be very subjective and also depends on a plant’s setting. For this reason many noise limits are set relative to the pre-existing background noise level. It is of course possible to add sound attenuation measures to any new plant that will reduce the noise heard nearby and, where noise sensitivity is a particular issue this is what is done in practice. However, there is a cost attached with this noise attenuation so that generally it is not undertaken unless it is deemed necessary. Also, it is generally true that certain categories of system are likely to be intrinsically noisier than other categories fo system with the same degree fo abatement employed. On this basis it was considered appropriate to offer some guideline noise levels at the site boundary to allow discernment between different scales and technologies, while recognizing that these need not be constraints for any particular development, where noise is of particular concern. The noise levels quoted have been, as far as possible, based on planning permission limits issued and achieved at typical similar plants.

While recognizing that the dimensions of a particular facility depend on the detailed design of that plant, which will be linked to its environment, it is, nevertheless, useful to offer some guideline dimensions to guide stakeholders seeking to establish general trends such as whether a doubling of plant capacity equates to a doubling of footpint or stack height. A typical height for the main building has been given in each case. This height is generally determined by boiler configuration for larger plants and heights appropriate for similar reference facilities have been used as far as possible. The stack height is determined by the requirement to disperse pollutants adequately to limit resulting ground level concentrations. This will therefore depend upon the flue gas composition, the pre-existing ambient levels and the local topography. Obviously this is site-specific, but, once again, typical heights from previous similar installations have been used as far as possible. The footprint or area occupied by a plant is determined by creating typical layouts for different technologies that are sufficient to accommodate all of the appropriately dimensioned key plant items. The fuel storage area generally represents a significant proportion of the overall plant footprint and, in general, allowance has been made for 3 days fuel storage at the larger plants with 2-3 days at the smaller plants.

For each plant an existing reference plant has been cited which could be similar in terms of physical appearance to the proposed plant. This is intended to give at least some idea of what a completed plant of this type might look like.

Employment

A full analysis of the number, origin and types of jobs has been carried out for each system studied and a selection of key indicators related to employment are given.

Full time jobs on plant during operation are quoted. These are full-time equivalent positions available for the lifetime of plant operation. They are based on our own calculations of typical manning levels and shift patterns for each plant size and type, incorporating an assessment of the different job functions required to keep each plant operating.

Two figures have actually been arrived at for each plant: one base case which takes a cautious approach with regard to health and safety for smaller plant – it assumes that single man operation is not allowed, in case of an emergency incident, but does facilitate unmanned operation for very small facilities, which could be remotely monitored. A second figure represents the minimum staffing level that could be achieved if single man operation were allowed, management could be shared across sites and staff could be redeployed from CHP plants during non-operational periods (mainly summer). For brevity only the base case figures has been quoted in these tables as "Full time jobs on plant during operation".

Full time agricultural jobs for crop growth related to the plant are quoted. These are based on the detailed assessment of the hours and men required to complete every stage in the agricultural process. In order to facilitate comparison between different systems and with the agricultural activities that bioenergy could be replacing the agricultural jobs have also been convereted into full-time equivalent positions per hectare, based on the area of land cultivated. Because of the particular interest in bioenergy as a means of diversification for rural communities the figures for agricultural jobs have also been quoted as full time equivalent positions per unit of land farmed to facilitate comparison with other crops and agricultural activities.

Full time transport jobs during operation are quoted. These are based on detailed assessments of the required number and length of delivery journeys to keep the plant supplied.

The above three figures quantify the employment specifically related to the bioenergy plant.

A more comprehensive overview of the employment impact of bioenergy plant is then given by taking into account upstream activities and wider economic impacts. First of all there are jobs related to development and construction of the plant, which are available only for a fixed period. These have been quantified for each plant based on experience and consultation within the Supergen consortium.

Additionally there are jobs created in the supply chain upstream e.g. in manufacture of wood processing plant or boilers. A detailed study of this supply chain effect was carried out by Mott McDonald for the DTI in [2004] and the results from this study for bioenergy and waste plants have been adjusted and adapted to quantify the supply chain jobs related to each of our cases. It should be noted that these jobs would not necessarily be local.

There is also an induced economic effect in the locality caused by development and construction of the plant. In essence, building the plant brings investment into the area so that additional money is spent locally, resulting in an enhanced local induced economic effect. This has been calculated in line with recommendations in HM Treasury’s Green Book.

These factors are taken into account for each phase of the project: construction, development and operation. As these periods vary in length the total number of jobs has been calculated in man years for each period. The results are comprehensive figures for the total number of jobs during development, construction and operation of the plant in man years. These jobs may not all be local or directly traceable to the plant concerned, but represent a robust method of identifying the actual economic impact of a new bioenergy plant. The final figures have been given as total number of jobs during each phase (development, construction and operation) and total over plant lifetime. This latter figure has also been expressed per unit of electrical output, again to facilitate comparison across systems.

Key characteristics of each system studied

	1	**2**	**3**	**4**	**5**	**6**	**7**
Capacity (MWe)	0.25	0.25	2	2	5	5	5
Technology	Gasifier/engine	Gasifier/engine	Gasifier/engine	Gasifier/engine	Gasifier/engine	Gasifier/engine	Gasifier/engine
CHP	No	Low grade space heating	No	Low grade space heating	No	Low grade space heating	No
Fuel	Willow SRC	Willow SRC	Willow SRC	Willow SRC	Willow SRC	Willow SRC	Miscanthus
Proportion of region planted	50%	50%	20%	20%	10%	10%	10%
Proportion of planted area fenced	50%	50%	25%	25%	25%	25%	100%
Fertilizer use	N at establishment and after harvest	N at establishment and after harvest	None	None	None	None	P, K every 5 years
Sewage sludge application	No	No	Yes	Yes	Yes	Yes	No
Drying	Uncovered piles of chips	Uncovered piles of chips	Covered in local barns	Covered in local barns	Covered in local barns	Covered in local barns	None
Storage	In field/at plant	In field/at plant	Local barns	Local barns	Local barns	Local barns	Sheeted bales
Transport to plant	Tractor	Tractor	Rigid 60 m^3 lorry	Rigid 60 m^3 lorry	Artic 120 m^3 lorry	Artic 120 m^3 lorry	Artic 120 m^3 lorry
Remediation	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate	Glyphosate

Key characteristics of each system studied

	8	**9**	**10**	**11**	**12**	**13**	**14**
Capacity (MWe)	5	25	25	25	25	2	5
Technology	Gasifier/engine	Atmospheric gasification combined cycle	Pressurized gasification combined cycle	Pressurized gasification combined cycle	Fluidized bed combustion	Grate	Grate
CHP	Low grade space heating	No	No	No	No	Low grade space heating	No
Fuel	Miscanthus	SRC willow	SRC willow	Miscanthus	SRC willow	SRC willow	SRC willow
Proportion of region planted	10%	10%	10%	10%	10%	20%	10%
Proportion of planted area fenced	100%	25%	25%	100%	25%	25%	25%
Fertilizer use	P, K every 5 years	None	None	P, K every 5 years	None	None	None
Sewage sludge application	No	Yes	Yes	No	Yes	Yes	Yes
Drying	None	Covered in local barns	Covered in local barns	None	Covered in local barns	Covered in local barns	Covered in local barns
Storage	Sheeted bales	Local barns	Local barns	Sheeted bales	Local barns	Local barns	Local barns
Transport to plant	120 m^3 artic lorry	120 m^3 artic lorry	120 m^3 artic lorry	120 m^3 artic lorry	120 m^3 artic lorry	60 m^3 rigid lorry	120 m^3 artic lorry
Remediation	Glyphosate	Scoring & glyphosate	Scoring & glyphosate	Glyphosate	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate

Key characteristics of each system studied

	15	**16**	**17**	**18**	**19**	**20**	**21**
Capacity (MWe)	5	25	25	2	25	25	5
Technology	Grate	Grate	Grate	Grate	Grate	Grate	Pyrolysis engine
CHP	Industrial process heat	No	Industrial process heat	Low grade space heating	No	No	No
Fuel	SRC willow	SRC willow	SRC willow	Miscanthus	Miscanthus	Straw	SRC willow
Proportion of region planted	10%	10%	10%	10%	10%	30%	10%
Proportion of planted area fenced	25%	25%	25%	100%	100%	n/a	25%
Fertilizer use	None	None	None	P, K every 5 years	P, K every 5 years	n/a	None
Sewage sludge application	Yes	Yes	Yes	No	No	n/a	Yes
Drying	Covered in local barns	Covered in local barns	Covered in local barns	None	None	None	Covered in local barns
Storage	Local barns	Local barns	Local barns	Sheeted bales	Sheeted bales	Sheeted bales	Local barns
Transport to plant	60 m^3 rigid lorry	120 m^3 artic lorry	120 m^3 artic lorry	60 m^3 rigid lorry	120 m^3 artic lorry	120 m^3 artic lorry	60 m^3 rigid lorry
Remediation	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate	Glyphosate	Glyphosate	None	Scoring & glyphosate

Key characteristics of each system studied

	22	**23**	**24**	**25**
Capacity (MWe)	5	5	5	25
Technology	Pyrolysis engine	Pyrolysis gas turbine	Pyrolysis gas turbine	Co-firing
CHP	Low grade space heating	No	Industrial process heat	No
Fuel	SRC willow	SRC willow	SRC willow	SRC willow
Proportion of region planted	10%	10%	10%	10%
Proportion of planted area fenced	25%	25%	25%	25%
Fertilizer use	None	None	None	None
Sewage sludge application	Yes	Yes	Yes	Yes
Drying	Covered in local barns	Covered in local barns	Covered in local barns	Covered in local barns
Storage	Local barns	Local barns	Local barns	Local barns
Transport to plant	60 m^3 rigid lorry	60 m^3 artic lorry	60 m^3 rigid lorry	120 m^3 rigid lorry
Remediation	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate	Scoring & glyphosate

Life cycle assessment indicators for each system studied

	Units	1 250 kWe engine wood PO	2 250 kWe engine wood CHP	3 2 Mwe engine wood PO	4 2 Mwe engine wood CHP	5 5 Mwe engine wood PO	5 Mwe woo
Landtake							
Area of land being considered	***ha***	1,150	511	18,160	8,546	84,271	
% of that area which is farmed		50%	50%	20%	20%	10%	
Transport							
Mode of transport for fuel deliveries		Tractor/trailer	Tractor/trailer	rigid lorry	rigid lorry	artic lorry	artic lo
Capacity of delivery vehicle	***m3***	45	45	60	60	120	
Number of round trip deliveries per day		1	1	5	2	6	
Mean length of round trip road journey	***km***	3	2	14	10	26	
Physical setting							
Typical noise level at site boundary	***dBA***	45	45	45	45	40	
Typical height of main building	***m***	4	4	10	10	15	
Typical height of stack	***m***	5	5	15	15	30	
Typical footprint of building	***acres***	0.11	0.11	0.40	0.40	2	
Example of implementation		Biomass engineering	Biomass engineering	Biomass engineering	Biomass engineering	Gussing	Gussin
Employment							
Full time jobs on plant during operation	***FTE***	0.375	0.375	3	3	11	
Full time agricucltural jobs for crop growth	***FTE***	0.58	0.26	3.61	1.70	8	
Full time transport jobs during operation	***FTE***	0.018	0.004	0.61	0.26	2	
Development period jobs	***Man Years (MY)***	1.25	1.25	2.50	2.50	3	
Construction period jobs	***MY***	2.54	2.54	35.15	35.15	87	
Operational period jobs	***MY***	55.68	45.87	398.05	338.10	998	
Agricultural jobs per unit of land farmed	***FTE/ha***	0.001	0.001	0.0010	0.0010	0.0010	
Total jobs	***MY***	59.47	49.66	436	376	1088	
Total jobs	***MY/Gwhe***	1.16	2.18	1.21	2.21	1.28	

Life cycle assessment indicators for each system studied

	Units	1 **250 kWe engine wood PO**	2 **250 kWe engine wood CHP**	3 **2 Mwe engine wood PO**	4 **2 Mwe engine wood CHP**	5 **5 Mwe engine wood PO**	**5 M w**
Greenhouse gas reductions (ignoring sewage sludge decomposition)							
CO2 produced by bioenergy system	***kg/kWh***	0.058	0.058	0.041	0.053	0.040	
CO2 saved compared to grid electricity	***kg/kWh***	0.37	0.37	0.39	0.38	0.39	
CO2 saved compared to grid electricity and natural gas heat - CHP only	***kg/kWh***	n/a	0.24	n/a	0.26	n/a	
CO2 saved compared to grid electricity and oil heat - CHP only	***kg/kWh***	n/a	0.29	n/a	0.29	n/a	
CO2 saved per unit of energy embodied in biomasss at point of harvest	***kg/MJ***	0.027	0.059	0.031	0.067	0.032	
CO2 saved per unit area of land farmed	***t/ha***	33	73	39	83	39	
Emissions to air over lifetime per unit electricity generated							
CO emissions	***g/kWh***	12.77	12.77	7.73	7.73	7.30	
Nox emissions	***g/kWh***	3.17	3.17	1.99	1.99	1.89	
Particulate emissions	***g/kWh***	0.18	0.18	0.11	0.11	0.10	
VOC emissions	***g/kWh***	0.18	0.18	0.11	0.11	0.11	
HCl emissions	***g/kWh***	0.00	0.00	0.00	0.00	0.00	
Agrochemical consumption per hectare farmed							
Total agrochemical application over lifetime	***kg/ha***	559	559	79	79	79	
Additional glyhposate used(-saved) cf wheat	***kg/ha***	27	27	27	27	27	
Additional fertilizer used (-saved) cf wheat	***kg/ha***	-5120	-5120	-5600	-5600	-5600	
Additional pesticide used(-saved) cf wheat	***kg/ha***	-80	-80	-80	-80	-75	
Material consumption and waste produced per unit electricity generated							
Water treatment chemicals consumed	***t/GWh***	0.00	0.00	0.00	0.00	0.00	

Life cycle assessment indicators for each system studied

Water abstracted during plant operation	***t/GWh***	0	0	0	0	0	
Inert (bottom) ash produced	***t/GWh***	10	10	11	11	11	
Fly ash (hazardous waste) produced	***t/GWh***	0.5	0.5	0.6	0.6	0.6	
Sewage sludge treated	***t/GWh***	0	0				
Effluent produced	***t/GWh***	214	214	0	0	0	
Operational mode							
Mode of operation		baseload	heat led	baseload	heat led	baseload	hea
Capacity factor		90%	40%	85%	40%	80%	
Technology risk (1 - proven), 5 unproven)		3	3	3	3	3	

Life cycle assessment indicators for each system studied

	Units	8 **5 Mwe engine misc CHP**	9 **25 Mwe atmos GCC wood PO**	10 **25 Mwe press GCC wood PO**	11 **25 Mwe press GCC misc PO**	12 **25 Mwe FBC wood PO**	13 **2 Mwe grate wood CHP**
Landtake							
Area of land being considered	***ha***	13,449	314,494	260,591	74,604	462,926	16,860
% of that area which is farmed		10%	10%	10%	10%	10%	20%
Transport							
Mode of transport for fuel deliveries		artic lorry	artic lorry	artic lorry	artic lorry	artic lorry	rigid lorry
Capacity of delivery vehicle	***m3***	120	120	120	120	120	60
Number of round trip deliveries per day		4	21	18	23	32	5
Mean length of round trip road journey	***km***	18	51	47	43	62	14
Physical setting							
Typical noise level at site boundary	***dBA***	40	38	38	38	38	40
Typical height of main building	***m***	15	35	40	40	32	12
Typical height of stack	***m***	30	50	50	50	45	12
Typical footprint of building	***acres***	2	10	10	10	12	1.4
Example of implementation		Gussing	Winkleigh	Varnamo	Varnamo	Fife	Wartsila
Employment							
Full time jobs on plant during operation	***FTE***	11	25	25	25	20	11
Full time agricucltural jobs for crop growth	***FTE***	2	31	26	10	46	3.36
Full time transport jobs during operation	***FTE***	4	7	6	22	12	0.56
Development period jobs	***Man Years (MY)***	3	27	27	27	26	2.50
Construction period jobs	***MY***	86	855	863	860	863	70.68
Operational period jobs	***MY***	602	4423	428f4	2902	4907	450.62

Life cycle assessment indicators for each system studied

Agricultural jobs per unit of land farmed	***FTE/ha***	0.0014	0.0010	0.0010	0.0014	0.0010	0.0010
Total jobs	***MY***	692	5304	5174	3788	5796	524
Total jobs	***MY/Gwhe***	2.20	1.19	1.22	1.29	1.22	3.06

Life cycle assessment indicators for each system studied

	Units	8 5 Mwe engine misc CHP	9 25 Mwe atmos GCC wood PO	10 25 Mwe press GCC wood PO	11 25 Mwe press GCC misc PO	12 25 Mwe FBC wood PO	13 2 Mwe grate wood CH
Greenhouse gas reductions (ignoring sewage sludge decomposition)							
CO2 produced by bioenergy system	***kg/kWh***	0.042	0.034	0.031	0.025	0.039	0.0
CO2 produced by national grid for equivalent amount of electricity	***kg/kWh***	0.43	0.43	0.43	0.43	0.43	0.
CO2 saved compared to grid electricity	***kg/kWh***	0.39	0.40	0.40	0.4	0.39	0.
CO2 saved compared to grid electricity and natural gas heat - CHP only	***kg/kWh***	0.26	n/a	n/a	n/a	n/a	0.
CO2 saved compared to grid electricity and oil heat - CHP only	***kg/kWh***	0.3	n/a	n/a	n/a	n/a	0.
CO2 saved per unit of energy embodied in biomasss at point of harvest	***kg/MJ***	0.047	0.045	0.052	0.043	0.032	0.0
CO2 saved per unit area of land farmed	***t/ha***	201	56	65	159	40	
Emissions to air over lifetime per unit electricity generated							
CO emissions	***g/kWh***	7.38	0.20	0.17	0.18	0.07	3.
Nox emissions	***g/kWh***	2.19	0.60	0.51	0.66	1.58	3.
Particulate emissions	***g/kWh***	0.12	0.01	0.01	0.02	0.05	0.
VOC emissions	***g/kWh***	0.13	0.19	0.16	0.17	0.15	0.
HCl emissions	***g/kWh***	0.00	0.00	0.00	0.00	0.00	0.
Agrochemical consumption per hectare farmed							
Total agrochemical application over lifetime	***kg/ha***	251	79	79	251	79	
Additional glyhposate used(-saved) cf wheat	***kg/ha***	3	27	27	3	27	

Life cycle assessment indicators for each system studied

Additional fertilizer used (-saved) cf wheat	***kg/ha***	-824	-5600	-5600	-824	-5600	-56
Additional pesticide used(-saved) cf wheat	***kg/ha***	-77	-75	-75	-77	-75	-
Material consumption and waste produced per unit electricity generated							
Water treatment chemicals consumed	***t/GWh***	0.00	0.04	0.04	0.04	0.11	0.
Water abstracted during plant operation	***t/GWh***	0	45	40	41	131	8
Inert (bottom) ash produced	***t/GWh***	28	26	5	13	8	
Fly ash (hazardous waste) produced	***t/GWh***	1.5	1.4	0.3	0.7	0.9	1
Sewage sludge treated	***t/GWh***						
Effluent produced	***t/GWh***	0	0	0	0	0	
Operational mode							
Mode of operation		heat led	baseload	baseload	baseload	baseload	heat led
Capacity factor		40%	85%	80%	75%	90%	40
Technology risk (1 - proven), 5 unproven)		3	4	4	4	2	

Life cycle assessment indicators for each system studied

	Units	15 **5 Mwe grate wood CHP**	16 **25 Mwe grate wood PO**	17 **25 Mwe grate wood CHP**	18 **2 Mwe grate misc CHP**	19 **25 Mwe grate misc PO**	20 **25 Mwe grate straw PO**	**C**
Landtake								
Area of land being considered	***ha***	125,837	469,455	370,210	10,449	134,187	181,466	
% of that area which is farmed		10%	10%	10%	10%	10%	30%	
Transport								
Mode of transport for fuel deliveries		artic lorry	artic lorry	artic lorry	artic lorry	artic lorry	artic lorry	art
Capacity of delivery vehicle	***m3***	120	120	120	60	120	120	
Number of round trip deliveries per day		9	32	25	7	42	40	
Mean length of round trip road journey	***km***	32	62	55	18	58	67	
Physical setting								
Typical noise level at site boundary	***dBA***	40	38	38	40	38	38	
Typical height of main building	***m***	20	40	40	12	40	40	n/a
Typical height of stack	***m***	30	40	40	12	40	40	n/a
Typical footprint of building	***acres***	4	12	12	1.4	12	12	
Example of implementation		Wartsila	Elean	Elean	Wartsila	Elean	Elean	Dr
Employment								
Full time jobs on plant during operation	***FTE***	11	20	20	11	20	20	
Full time agricucltural jobs for crop growth	***FTE***	13	47	37	1	18	0	
Full time transport jobs during operation	***FTE***	2	12	9	3	41	39	
Development period jobs	***Man Years (MY)***	3	26	27	3	26	26	
Construction period jobs	***MY***	175	863	905	70	862	862	
Operational period jobs	***MY***	1133	4928	4775	348	3161	2741	

Life cycle assessment indicators for each system studied

Agricultural jobs per unit of land farmed	***FTE/ha***	0.0010	0.0010	0.0010	0.0014	0.0014	0.0000
Total jobs	***MY***	1311	5817	5707	420	4049	3630
Total jobs	***MY/Gwhe***	2.04	1.22	1.71	3.35	1.21	1.02

Life cycle assessment indicators for each system studied

		Units	15 5 Mwe grate wood CHP	16 25 Mwe grate wood PO	17 25 Mwe grate wood CHP	18 2 Mwe grate misc CHP	19 25 Mwe grate misc PO	20 25 Mwe grate straw PO
Greenhouse gas reductions (ignoring sewage sludge decomposition)								
	CO2 produced by bioenergy system	***kg/kWh***	0.073	0.039	0.045	0.066	0.028	0.009
s	**CO2 produced by national grid for equivalent amount of electricity**	***kg/kWh***	0.43	0.43	0.43	0.43	0.43	0.43
	CO2 saved compared to grid electricity	***kg/kWh***	0.36	0.39	0.39	0.36	0.40	0.42
	CO2 saved compared to grid electricity and natural gas heat - CHP only	***kg/kWh***	0.22	n/a	0.30	0.22	n/a	n/a
	CO2 saved compared to grid electricity and oil heat - CHP only	***kg/kWh***	0.27	n/a	0.33	0.27	n/a	n/a
	CO2 saved per unit of energy embodied in biomasss at point of harvest	***kg/MJ***	0.055	0.032	0.038	0.046	0.027	0.027
	CO2 saved per unit area of land farmed	***t/ha***	85	40	52	208	100	27
Emissions to air over lifetime per unit electricity generated								
	CO emissions	***g/kWh***	2.36	1.19	1.34	2.47	1.18	1.08
	Nox emissions	***g/kWh***	3.06	1.55	1.75	3.67	1.76	1.46
	Particulate emissions	***g/kWh***	0.03	0.02	0.02	0.06	0.03	0.02
	VOC emissions	***g/kWh***	0.19	0.10	0.11	0.24	0.12	0.10
	HCl emissions	***g/kWh***	0.00	0.00	0.00	0.27	0.13	0.12
Agrochemical consumption per hectare farmed								
	Total agrochemical application over lifetime	***kg/ha***	79	79	79	84	251	n/a
	Additional glyhposate used(-saved) cf wheat	***kg/ha***	27	27	27	3	3	n/a

Life cycle assessment indicators for each system studied

Additional fertilizer used (-saved) cf wheat	***kg/ha***	-5600	-5600	-5600	-824	-824	n/a
Additional pesticide used(-saved) cf wheat	***kg/ha***	-75	-75	-75	-77	-77	n/a
Material consumption and waste produced per unit electricity generated							
Water treatment chemicals consumed	***t/GWh***	0.72	0.10	0.39	0.40	0.10	0.10
Water abstracted during plant operation	***t/GWh***	826	119	449	466	118	118
Inert (bottom) ash produced	***t/GWh***	17	8	9	50	24	52
Fly ash (hazardous waste) produced	***t/GWh***	1.8	0.9	1.1	5.6	2.7	5.8
Sewage sludge treated	***t/GWh***						
Effluent produced	***t/GWh***	0	0	0	0	0	0
Operational mode							
Mode of operation		heat led	baseload	heat led	heat led	baseload	baseload
Capacity factor		60%	90%	60%	40%	85%	90%
Technology risk (1 - proven), 5 unproven)		2	2	2	2	2	2