Anaerobic Digestion: Overall Energy Balances – Parasitic Inputs & Beneficial Outputs

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Abstract

Energy based on fossil fuels is a limited resource. The area of land available to produce alternatives is also limited. As a result any forms of energy produced from land based biomass have to be both renewable and sustainable. Waste materials, often placed in landfill with the associated environmental problems, have to be minimised and considered as resources. Anaerobic digestion (AD) is a highly efficient process for producing energy from biomass and other organic materials including wastes. In determining the sustainability of an energy source the overall energy balance must be taken into consideration including parasitic inputs and beneficial outputs. The parasitic inputs include energy required for feedstock growth, collection and preparation. In the case of AD the outputs are energy in the form of biogas and digestate, a bio-fertiliser. With most organic feedstock materials the energy available in the biogas exceeds that of producing and processing the feedstock. The biogas produced has a range of uses including heat, electricity through combined heat and power units and as a vehicle fuel. The bio-fertiliser replaces mineral fertilisers with the associated saving in energy and greenhouse gas emissions. The energy balances and yields compare favourably with other biomass based fuels.

Key words

Anaerobic digestion, energy balance, renewable, sustainable, co-digestion, parasitic energy

Introduction

The definition of renewable fuels is a broad one and includes those that return more energy than they consume from fossil fuel sources (for example wind or wave power) and those that are sourced from biomass which has consumed the carbon dioxide (CO_2) that is later released as the fuel is used (carbon neutral). Some of the early forms of biomass based fuel production however consumed more energy in the form of fossil fuel than they produced. For a renewable energy source to be beneficial it has to also be sustainable, it has to consistently produce more energy than is consumed in producing it. For a biomass fuel source to be sustainable it has to enrich the land it is grown on and produce new crop every year. In order to determine sustainability and to compare fuel sources it is necessary to conduct life cycle analyses including all sources of energy used in the production of feedstock for fuel production, the fuel production process itself, transport and any further modifications to the fuel produced.

Anaerobic digestion (AD) is a naturally occurring process which takes organic matter as a feedstock material and produces two forms of output; an energy source in the form of biogas, and a bio-fertiliser. In the UK AD has principally been used in the waste water industry as part of the process to clean up waste water into a form which can be reused. It helps to break down organic residues into a homogenous material suitable for application to land as a soil enhancer and fertiliser. More recently AD has been recognised as source of renewable energy, the biogas produced can be used to provide heat, heat and power, or upgraded and supplied as natural gas replacement or vehicle fuel. The materials used as feedstock can include organic wastes, for example the organic fraction of municipal solid wastes, farm wastes including animal slurries and farm yard manure, vegetable wastes and also crops grown specifically as feedstock material.

This paper examines an energy balance for AD, the parasitic inputs and beneficial outputs and compares a number of feedstock materials. These energy balances will determine if AD is ‘renewable’ and ‘sustainable’ as a source of energy. Similar methods can be used with any form of energy production and allow for a comparison of different fuel sources to determine their relative sustainability.

Parasitic inputs

Energy inputs into any production process can be divided into two types; direct and indirect. Direct energy inputs are those which involve the direct consumption of energy e.g. diesel fuel for vehicles, electricity for motors, gas for heat etc. Indirect energy is energy which has been invested in the production of materials and equipment used in the fuel production process. This may include fertilisers for crops, building materials and construction, vehicles etc. Direct energy requirements also include a certain amount of indirect energy which is involved in production of the energy source, for example diesel fuel has to be extracted from the ground, processed and delivered, electricity requires generation from a primary fuel source which has to be extracted and processed.

In determining the energy balance the system can be divided into three stages:

1. Feedstock production.
2. Conversion of the feedstock into primary fuel source.
3. Processing of the primary fuel source into usable energy.

Feedstock production involves all energy required to deliver and process the material which goes to produce the fuel. If something is produced specifically for the fuel production then this stage should include all energy inputs required. Conversion of the feedstock produces an energy source and potentially other by-products. Some of these primary fuels are available for use straight away, e.g. biogas can be burnt directly. Some need further processing or conversion to produce a useable fuel, for example biogas may need to be scrubbed of CO_2 and other impurities and then compressed for use as a vehicle fuel.

A boundary is required to determine which are inputs to the system and which are outputs. For a crop based energy system, the crop production is included within the system so inputs include fertilisers and fuel. For a waste based energy system the inputs include the transport of the material to the processing plant and any processing required to make the waste suitable for processing. If this waste is considered as a resource (the eventual target being to have no such thing as waste, all material is a resource for some process) then a proportion of the production energy can be attributed to the 'waste'. In this paper we will consider waste converted to energy production as being material diverted from landfill and therefore consider only the transport implications and pre-processing requirements. An outline of the system, indicating the inputs and outputs is shown in Figure 1.

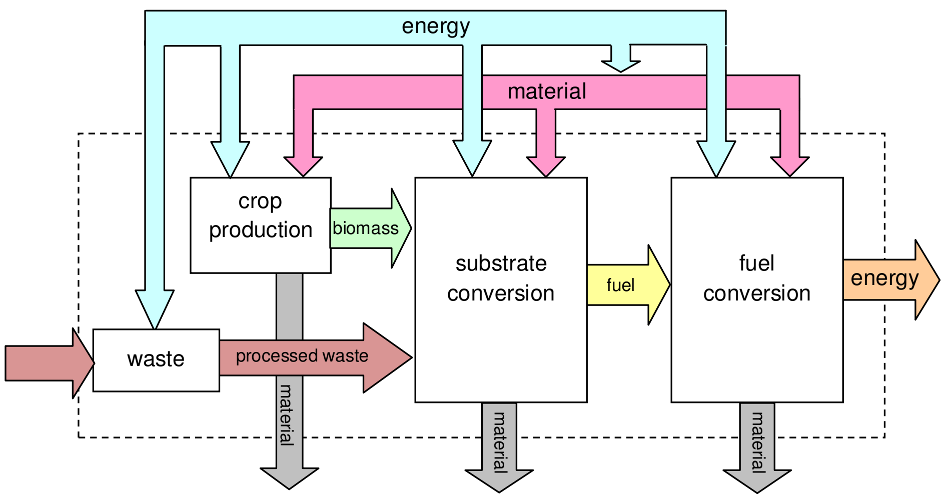

Figure 1: Inputs and outputs to a fuel production system

Conversion of feedstock into a primary fuel source

Anaerobic digestion occurs naturally but the process can be enhanced through the use of digesters which are heated and mixed. In addition to these direct energy requirements, indirect energy requirements can be calculated from the type and amount of materials used in the construction of the digester and any ancillary equipment required for repair and maintenance. The outputs from the digester consist of energy in the form of biogas and material in the form of digestate. The energy and material flows for an anaerobic digester are shown in Figure 2.

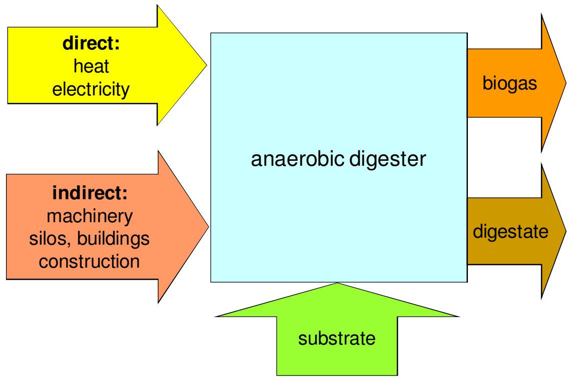

Figure 2: Energy inputs and outputs to digestion

It is possible to calculate energy requirements for anaerobic digestion based on the design of the digester and ancillary equipment attached. Calculation of the electrical energy requirement can be made through knowledge of electrical equipment used around the digester and the periods over which this equipment operates. The requirement for heat in the digestion process can be estimated from the calculation of heat loss through the walls of the digester and the heat required to raise the temperature of the feedstock to that of the digester. Heat requirement can be calculated using the formulae:

$hl = UA\Delta T$ where hl = heat loss, (kJ/s)
U = overall coefficient of heat transfer, (W/m^2.°C)
A = cross-sectional area through which heat loss is occurring, (m^2)
ΔT = temperature drop across surface in question, (°C).

$q = CQ\Delta T$ where C = specific heat of the feedstock (kJ/kg/ °C)
Q = volume to be added (m^3)

Total heat requirement for the process = $hl + q$.

The digester design and consequent heat losses will also be affected by the nature of the materials used as feedstock. Animal slurries and agricultural crops can be digested directly at mesophilic temperatures (30 - 45°C). Any organic wastes brought into the system are potentially contaminated with pathogens. In this case they must be treated in a manner which is compliant with the Animal By-Product Regulations (APBR 2005). This requires that the processing includes reducing the waste to a maximum particle size of 12mm and maintaining it at 70°C for at least one hour.

Processing of primary fuel

The final stage in the production of a renewable energy is the conversion of the primary fuel produced to a form of energy which can be used. Biogas has a range of possible uses which involve different degrees of processing:

1. The biogas can be burnt directly to provide heat.
2. The biogas can be provided to a combined heat and power (CHP) unit to produce electricity and heat.
3. The biogas can be used as vehicle fuel.

The various inputs and outputs for the different processing options are shown in Figure 3.

If the biogas is used to provide heat then little further processing is required, the gas is consumed in a boiler and will be converted into heated water at approximately 85% efficiency. If the biogas is consumed in a CHP unit a minimal amount of gas scrubbing may be required to remove Hydrogen Sulphide (H_2S) and other impurities. Approximately 85% of the energy value of the biogas will be converted to energy in the form of electricity (at approximately 30 to 40% efficiency) and heat at approximately (50 to 60% efficiency). If the biogas is used as vehicle fuel then it can be used after a minimal amount of gas scrubbing to remove impurities. However 40 to 50% of the biogas is carbon dioxide (CO_2) which cannot be combusted and so reduces the available range of the vehicle using fuel held in the tank. The biogas will therefore usually be scrubbed of the CO_2, to leave methane enriched biogas, and then compressed to further increase the amount which can be carried in a vehicle. Both of these processes consume electricity. For example upgrading of the biogas may require up to 0.75 $kWh_{electricity}/m^3$ upgraded biogas (Murphy et al. 2004).

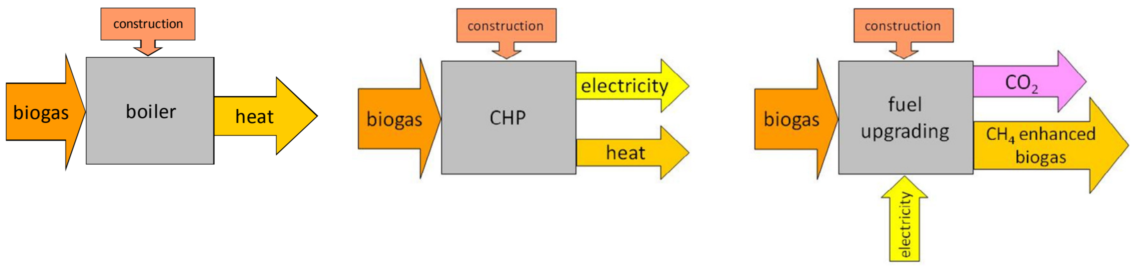

Figure 3: Energy and material inputs and outputs post digestion

Beneficial Outputs

Anaerobic digestion is a process with dual outputs, the second product being the digestate which can be used as a bio-fertiliser. The digestate contains the majority of the nutrients which were in the original feedstock, and will usually be stored after digestion in a separate container. If this container is enclosed then any further generation of biogas will also be captured. The digestate (usually in a form with less than 6% solids) can be used directly in the form in which it comes out of the digester or can be separated into liquid and fibre components, both of which can be returned to the ground. The fibre, which contains the majority of the phosphate and potash can be used as a soil conditioner or further composted and then bagged for gardens. The separated liquor will have a high nitrogen content and can be applied as a liquid bio-fertiliser. Separation of the digestate requires the application of parasitic energy, usually in the form of electricity.

The use of bio-fertiliser reduces the requirement for mineral fertiliser and as such the digestate has an energy value. Most fertilisers, in particular nitrogen are currently supplied based on fossil fuels and require considerable amounts of energy to produce them along with the associated CO_2 release. Examples of the energy requirements for "average European production processes" of fertiliser components are shown in Table 1 adapted from Kongshaug (1998).

Table 1: Energy requirements for fertiliser production

fertiliser component		
Ammonium nitrate (NO_3)	triple Super Phosphate	Potash
38.7 GJ/t N	5.3 GJ/t P_2O_5	5 GJ/t K_2O

AD is a suitable process for enhancing animal slurries and anaerobic digesters have been installed in seven locations in Scotland for the purpose of processing slurry to reduce pollution (Greenfinch 2008). Anaerobic digestion of the slurry reduces pathogens and odours and makes the nutrients in the slurry more readily available for plant uptake. The slurry is also converted into a substance which is more homogenous, easier to spread and gives a more uniform fertiliser application. Examples of nutrient contents and availabilities for slurry and digestate are shown in Table 2. Digesters have been used in waste water processing for a similar purpose, the biogas being a secondary output which has started to be utilised.

Table 2: Nutrient availability

	whole cow slurry	Whole mixed digestate	Separated liquor
DM %	7	4	1
Total N – kg/t	5.47	5.15	4.49
Phosphate – kg/t	1.02	1.16	0.37
Available N : total N	60.1%	80.0%	92.0%

In a closed energy production system, using only energy crops as feedstock for the digester, it is unlikely that digestate will provide a complete replacement for mineral fertiliser. The nutrient recycling is not complete, as there are some losses in the system, volatilisation of ammonia (NH_3) for example. Some of the nutrients added to the crops will not be included in the harvested plant material as they are retained in the soil or lost through leaching. The use of leguminous crops can enhance the amount of nitrogen in the system but there will still be a requirement for the addition of phosphate and potash in some circumstances. In terms of calculating the parasitic inputs therefore there will thus be energy requirement for both mineral fertiliser application and digestate application. Slurries and waste products brought in as feedstock for digesters will add to the nitrogen and other nutrients and may then provide enough digestate to fulfil the nutrient requirements of any crops grown for use as feedstock. An example of this can be found at the anaerobic digestion plant installed at Västerås in Sweden (Weiland and Ahrens 2006)

Example of a crop based energy balance

An example of an energy balance for crop based energy production using anaerobic digestion is given in Table 3. Scenario 1 involves the use of mineral based fertiliser and conversion of the biogas to heat and electricity via CHP. Scenario 2, shown in Figure 4, involves the production of vehicle fuel with some of the biogas used for CHP to fulfil the heat and electricity requirements of the digester and fuel upgrading. The efficiency of AD as an energy source is dependent on the use of the biogas, where it is used in CHP there must be a use for the heat generated or up to 55% of the energy is wasted.

Table 3: Energy balance for crop based anaerobic digestion

<table>
<tr><th>scenario</th><th></th><th>1</th><th>2</th></tr>
<tr><td>mineral nitrogen fertiliser</td><td>kg N/ha</td><td>160</td><td>0</td></tr>
<tr><td>area of crop required</td><td>ha</td><td colspan="2">492</td></tr>
<tr><td>crop production</td><td>GJ/yr</td><td>7429</td><td>4231</td></tr>
<tr><td>crop transport</td><td>GJ/yr</td><td colspan="2">274</td></tr>
<tr><td>digester embodied energy</td><td>GJ/yr</td><td colspan="2">2109</td></tr>
<tr><td>digestate transport & spreading</td><td>GJ/yr</td><td colspan="2">430</td></tr>
<tr><td>total deficit</td><td>TJ/yr</td><td>10.9</td><td>7</td></tr>
<tr><td>CH_4 (in biogas)</td><td>10^6 m^3/yr</td><td>1.94</td><td></td></tr>
<tr><td>CHP generated</td><td></td><td></td><td></td></tr>
<tr><td>Electricity</td><td>TJ/yr</td><td>20.8</td><td></td></tr>
<tr><td>Heat</td><td>TJ/yr</td><td>34.7</td><td></td></tr>
<tr><td>digester parasitic energy</td><td>TJ/yr</td><td>4.7</td><td></td></tr>
<tr><td>CH_4 required for CHP</td><td>10^6 m^3/yr</td><td></td><td>0.38</td></tr>
<tr><td>surplus</td><td></td><td></td><td></td></tr>
<tr><td>electricity</td><td>TJ/yr</td><td>20.1</td><td></td></tr>
<tr><td>heat</td><td>TJ/yr</td><td>30.6</td><td></td></tr>
<tr><td>CH_4 in upgraded biogas</td><td>10^6 m^3/yr</td><td></td><td>1.57</td></tr>
<tr><td>energy value</td><td>TJ/yr</td><td></td><td>55.9</td></tr>
<tr><td>energy balance</td><td>TJ/yr</td><td>39.9</td><td>48.8</td></tr>
<tr><td>energy ratio (out/in)</td><td></td><td>4.7</td><td>7.9</td></tr>
<tr><td>energy in diesel equivalent</td><td>10^6 l/yr</td><td></td><td>1.56</td></tr>
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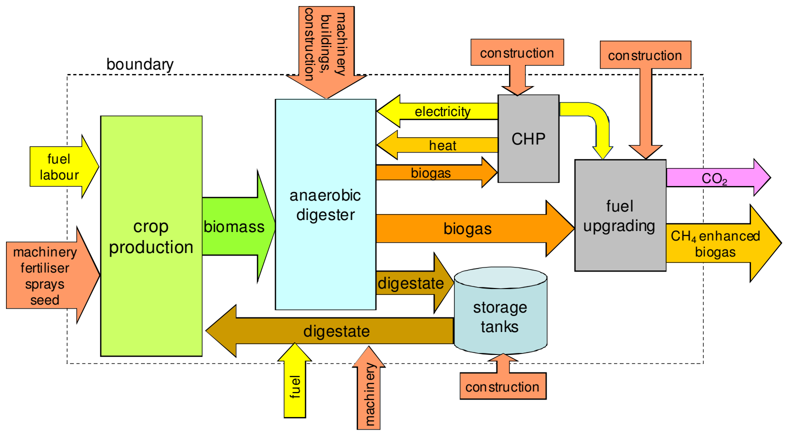

Figure 4: Crop based digestion for vehicle fuel - digestate recycled to crop

The use of energy balance analysis allows for the comparison of variable feedstock supplies. One advantage of a process which utilises most forms of organic material, such as AD, is that it can also incorporate and co-digest multiple feedstock materials at the same time. These often consist of animal slurries and manures but may include food waste. Currently food waste is often placed in landfill where it is responsible for greenhouse gas emissions, these can be captured in the AD process and then utilised.

A comparison of energy balances for some different feedstock combinations, maize (*Zea mays*) and cattle slurry as mono substrates and co-digestion of maize with cattle slurry and food waste is shown in Table 4. In these scenarios it is assumed that the digester is of a constant size (approx 3000 m^3) and the same amount of material is applied (16,000 tonnes per annum). This leads to a constant retention time and varying loading rate. All loading rates (the amount of volatile solids/organic dry matter which are digested to produce the biogas) are below 4kg VS_{added}/m^3/day which is a recommended operating loading. Heat loss through the digester walls is the same for each scenario as it is dependent on construction, operating and climate temperatures rather than feedstock. The electrical energy required for the digester can also be considered the same for each feedstock. For digestion of food waste extra energy is required for the pasteurisation digester both in the form of heat and electricity.

Table 4: Energy balances for various feedstock

feedstock (tonnes)	potential CH_4 (10^3m^3)	Biogas (t/year)	Digestate (t/year)	parasitic heat energy (GJ/year)	parasitic electrical energy (GJ/year)	digestate transport & spreading (GJ/year)	energy for crop production (GJ/year)	energy for crop production - recycled digestate (GJ/year)	waste transport (GJ)	electricty generated (GJ)	heat generated (GJ)	energy balance (GJ/year)	energy balance - recycled digestate (GJ/year)
maize (16,000)	1,759	2668.8	13,331	2,425	528	347	6680	3720		21,979	34,538	46,537	49,497
cattle slurry (16,000)	217	330.0	15,670	2,425	528	407				2,711	4,261	3,612	3,612
maize(8000) + slurry (8000)	988	1585.8	14,414	2,425	528	375	3340	1860		12,345	19,399	25,077	26,557
maize(8000) + food waste(8000)	1,578	2394.4	13,606	4,526	531	354	3340	1860	88	19,717	30,984	41,862	43,342

It can be seen from Table 4 that cattle slurry does not provide a high energy output, the feedstock having had most of its energy value removed by the cow. The major benefit of slurry digestion is as a process for conditioning the slurry to improve its use as a fertiliser. In terms of the digestion process slurry provides a stabilising substrate which can be used to balance other inputs to the feedstock. Maize provides a good source of energy for digestion and with the use of digestate as fertiliser the energy balance can be improved by up to 3,000 GJ per year. Maize however is also a food crop and as such is a valuable resource. Food waste provides a substrate which produces as much energy as the maize but has the advantage that it requires no energy for its production, only transport to the digester site. There are approximately 6.7 million tonnes of food waste generated each year in the UK

(WRAP 2007), if all of this was digested and converted to electricity it could supply 2,031,683 MWh, equivalent to the supply for 524 thousand homes.

Comparison of fuels

The same energy balance methods can be used to compare alternative fuel sources as shown in Table 5. The figures for bio-ethanol and bio-diesel, both from first generation plants, are taken from Elsayed *et al*. (2003). The final two columns compare the effect of using digestate as bio-fertiliser on whole crop triticale, a cereal crop like wheat which has been harvested while still green. The bio-fertiliser reduces the requirement for mineral fertiliser with the subsequent reduction in energy demand. In this example half of the mineral fertiliser has been replaced with digestate.

Table 5: Comparison of fuel production

fuel	biodiesel	bioethanol		methane				methane
crop	OSR seed	sugar beet	wheat grain	sugar beet	wheat grain	maize	whole crop triticale	whole crop triticale
fertiliser (N kg/ha)	195	147	150	147	150	150	160	80
crop yield (fresh yield t/ha)	3	56	8	56	8	40	38	38
crop yield (t DM/ha)	3	11.5	6.9	11.5	6.9	12.6	15	15
energy for crop production (GJ/ha)	12.7	11.9	12.8	11.9	15.5	16.7	16	11.6
energy for processing (GJ/ha)	9.2	41.4	13.2	10.8	8	8	8.3	8.3
energy of fuel produced (GJ/ha)	40.4	117	61.1	124.8	89	157.1	166	166
energy ratio (output/input)	**1.84**	**2.20**	**2.35**	**5.50**	**3.79**	**6.36**	**6.83**	**8.34**
net energy produced (GJ/ha)	**18.5**	**63.7**	**35.1**	**102.1**	**65.5**	**132.4**	**141.7**	**146.1**
potential electricity generated MWh/ha				9.4	6.1	12.2	13.1	13.5
energy to convert to vehicle fuel (GJ/ha)				5.3	3.7	6.6	7	7
energy of vehicle fuel produced (GJ/ha)				96.8	61.8	125.8	134.7	139.1
equivalent litres of diesel.	**517**	**1779**	**980**	**2704**	**1726**	**3514**	**3763**	**3885**

With the limited availability of land it is vital to maximise energy production per hectare, this can be partly achieved through the use of high yielding crops but also through the use of processes with low parasitic energy requirements and maximised beneficial outputs.

Conclusions

Anaerobic digestion is a highly efficient process which can make use of a range of feedstock materials including organic wastes. Many of the parasitic energy requirements can be covered within the boundary of the process, reducing the requirement for use of fossil fuels and the associated emissions. The parasitic inputs of electricity and heat required to operate the AD process can be provided by a CHP unit running on the biogas produced. The digestate provides a source of bio-fertiliser which can be used for crop growth and feedstock production. If waste is used as feedstock then it could be collected in vehicles running on biogas fuelled engines. A system of this type can therefore be self-sufficient in energy and at least carbon neutral if not better.

Acknowledgement

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