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D18: Quantification of energy deficits and surpluses for a staged approach to crop energy production

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D18: Quantification of energy deficits and surpluses for a staged approach to crop energy production

Introduction

In determining the energy efficiency of a renewable energy source consideration needs to be taken of all the energy inputs and outputs. Different stages in the production process will have positive or negative energy requirements, if a renewable energy source is to be viable then its net energy output must be positive. This deliverable sets out methods for identifying the deficits and surpluses in crop based energy production by anaerobic digestion. Results of the application of these methods can be found in deliverable **D19**.

In order to determine the energy balance, the boundaries of the system must be established. In producing renewable energy from crops and agrowastes, the system can be divided into three parts (which will be the same for any crop based fuel):

1. crop production
2. conversion of biomass into primary fuel source
3. processing of the primary fuel source into usable energy

On this basis a number of boundaries can be drawn including an overall boundary and internal system divides between the three parts, as shown in Figure 1.

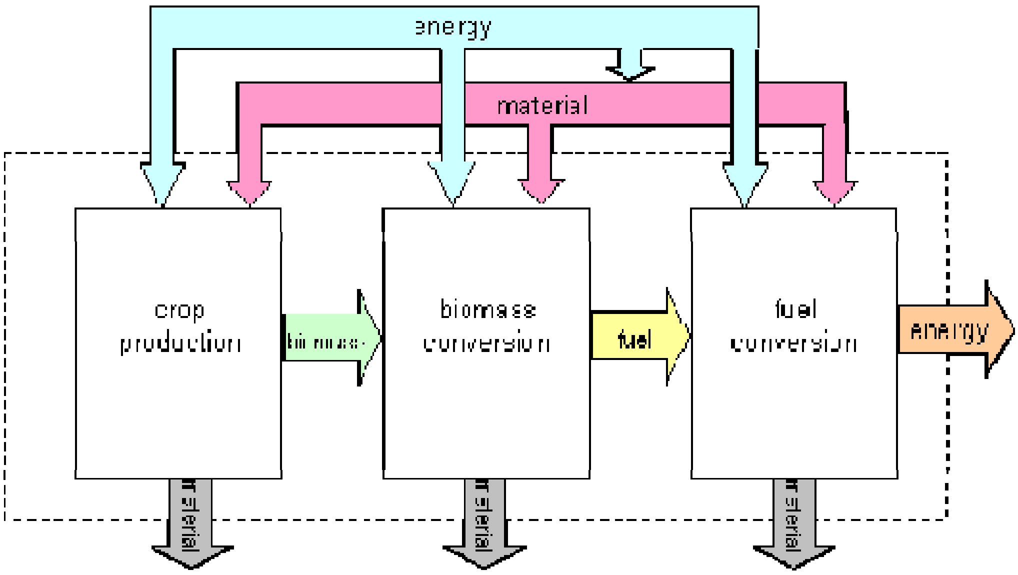


Figure 1: system boundaries

An energy production system involving the use of crops needs to be considered at more than one level in terms of its effectiveness as there is considerable difference in the amount of crop produced from each hectare of land used. The amount is affected by crop type, stage of crop growth at harvest etc, these factors were outlined in **WP1**. In terms of final energy efficiency the energy yield must be considered on a per hectare basis as it is important to maximise the yield potential of any area of land. Whereas plant yields can still be increased through crop development, the area of land surface available is fixed.

The same system boundaries can be used for both the analysis of energy and for mass balances. Examples of mass balances are given in the report for cropgen **WP4**. When considering the energy balance material is also considered. Equipment, machinery and buildings all require energy for the extraction and processing of materials and for construction, repairs and maintenance. Thus in conducting an energy balance in order to determine energy deficits and surpluses, the balance considers both direct energy requirements – in the form of fuels directly consumed such as diesel in tractors and indirect energy – the energy for machinery construction, maintenance etc. Indirect and direct energy requirements can be identified for all the stages of crop based energy production.

1. Crop production

Crop production requires energy, in a crop based anaerobic digestion system this part of the process generates material in the form of biomass (which has calorific value) but involves only energy consumption. The amount of energy required is directly affected by the type of crop grown. This affects the amount of direct energy required – proportional to the number of operations carried out in the field, and the indirect energy which is used in the production of nutrients and pesticides added to the crop.

The energy requirement for the production of a number of crops has been reported in detail in deliverable **D25**. The results of the energy analyses are shown in Table 1.

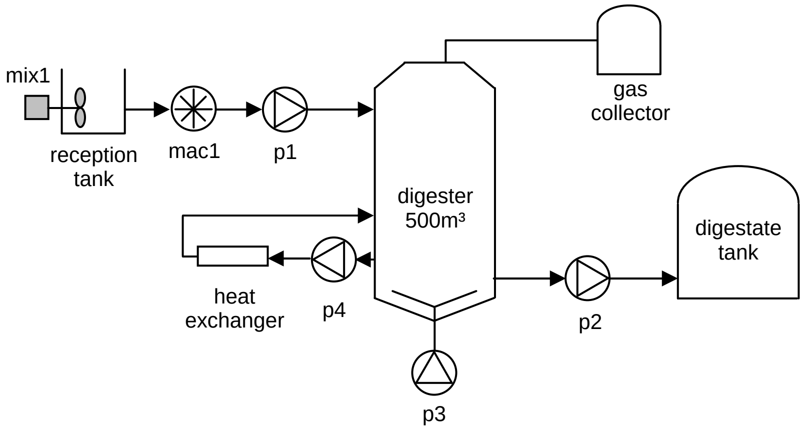
Table 1: Energy requirements for a number of crops (from D25)

crop	sowing period	energy requirement (GJ/ha) indirect	fuel (l/ha)	fertiliser & sprays	total	yield (tFM/ha)	energy (GJ/tFM)
annual crop							
maize	spring	1.92	2.78 (71)	11.8	**16.7**	40	0.42
wheat	winter	1.84	2.26 (57)	12.7	**17.0**	36.5	0.46
fodder beet	spring	3.76	3.38 (86)	14.4	**21.8**	80	0.27
triticale	winter	1.84	2.26 (57)	11.6	**16.0**	38	0.42
sunflower	spring	1.85	2.26 (57)	10.9	**15.3**	35 (est)	0.44
lupin	spring	1.81	2.20 (56)	4.3	**8.6**	30 (est)	0.29
field bean	winter	1.64	2.05 (52)	3.83	**7.8**	35 (est)	0.23
perennial crop							
	year						
perennial ryegrass	1	2.4	2.62 (67)	12.1	**17.7**	33	0.54
	2,3	4.2	4.62 (117)	12.1	**21.1**	42	0.5
Timothy grass	1	2.3	4.2 (105)	13.5	**20.4**	37	0.55
	2,3,4	1.4	2.1 (54)	13.5	**17.0**	36	0.47
Clover	1	2.1	2.37 (60)	7.3	**12.3**	42	0.29
	2	2.3	2.59 (66)	7.3	**12.2**	40	0.31
Lucerne	1	2.1	2.37 (60)	6.4	**11.5**	42	0.27
	2+	3.7	3.9 (100)	6.4	**14.1**	45	0.31

2. Conversion of biomass into primary fuel source.

The principal method of biomass conversion in cropgen is anaerobic digestion, the fuel being in the form of biogas. Anaerobic digestion does occur naturally but the process can be enhanced through the use of digesters which are maintained at a constant temperature (either mesophilic or thermophilic). Stirring of the contents of the digester also enhances biogas production and as the systems are usually run in a continuous way mixing and pumping are required which involve the use of energy in the form of electricity. Energy is produced in the form of biogas which can be combusted to produce energy.

It is possible to calculate theoretical 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. An example of the electrical equipment required for a simple digester system is shown in Figure 2 with the size of equipment of time periods over which these operate.



mix1	reception tank mixer	3.0 kJ s^{-1}	0.64 hrs d^{-1}
mac1	feedstock macerator	2.2 kJ s^{-1}	1.75 hrs d^{-1}
p1	digester feed pump	3.0 kJ s^{-1}	1.75 hrs d^{-1}
p2	digester discharge pump	3.0 kJ s^{-1}	1.75 hrs d^{-1}
p3	digester mixing pump	2.2 kJ s^{-1}	7.25 hrs d^{-1}
p4	digestate heating pump	0.5 kJ s^{-1}	8.0 hrs d^{-1}

Figure 2: electricity requirement for a simplified digester system

In order to maintain the temperature of the digestion process the digester must be either heated (which is generally the case) or cooled (which has been shown to be a requirement for some crop based digesters in Austria (Lindorfer *et al.*, 2006). The heat requirement can be estimated from the 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 loss from the digester takes place at its surfaces and can be calculated from knowledge of the dimensions of the digester and the heat transfer coefficients of the materials of which it is constructed, using the formula:

$hl = UA\Delta T$

where hl = heat loss, (kJ s^{-1})

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).

The energy required for heating the feedstock is calculated based on the specific heat of the feedstock C, the volume to be added Q, and the temperature difference ΔT:

$q = CQ\Delta T$

Thus, for a 500 m^3 digester built of 300 mm insulated concrete, with a floating, insulated cover as shown in Figure 3, the heat loss through the digester surfaces can be calculated as:

walls: hl_w = 0.8 W m^2.°C * (132 m^2) * (35 - 2 °C) = 3.48 kJ s^{-1}

floor: hl_f = 1.7 W m².°C * (126 m²) * (35 - 5 °C) = 6.43 kJ s^{-1}
roof: hl_r = 1.0 W m².°C * (113 m²) * (35 - 2 °C) = 3.73 kJ s^{-1}
Total heat loss *hl* = 13.64 kJ s^{-1} = 1.18 GJ d^{-1}

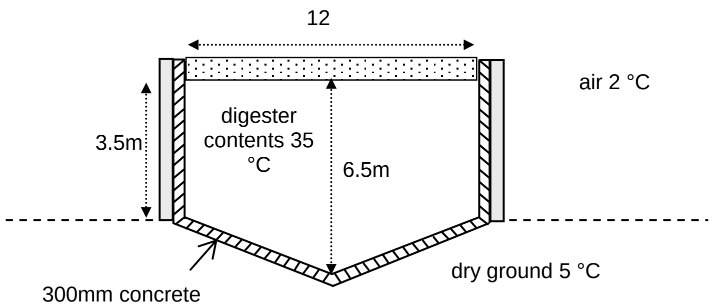


Figure 3: a simple digester structure used in calculation of energy loss.

If the digester operates at a 30 day retention time, the amount of feedstock added per day (*Q*) = 500 / 30 = 16.7 m³. If the feedstock has a low solids concentration then the specific heat can be assumed to be similar to that of water *C* = 4.2 MJ t^{-1} °C. If the incoming feedstock has an initial temperature of 10 °C and the digester works at 35°C then the heat required: q = 4.2 * 16.7 * (35 – 10) = 1.75 GJ d^{-1}

The total heat requirement for the digester under these conditions is therefore:

$hl + q$ = 1.18 + 1.75 = 2.93 GJ d^{-1}

A detailed method for the calculation of energy requirement in the AD process is outlined in deliverable **D14** and **WP8**.

In addition to these direct energy requirements, indirect energy is calculated from the type and amount of materials used in the construction of the digester and ancillary equipment and for the repair and maintenance.

3. 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. In the cases of biodiesel and bioethanol, the fuels produced can be directly used in vehicles or added to fossil fuels. Biogas has a range of possible uses which involve different degrees of processing.

1. The biogas can be burnt directly with no further processing to produce 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.

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 heat at approximately 85% efficiency.

If the biogas is consumed in a CHP unit a minimal amount of gas scrubbing may be required to remove H_2S and other impurities. The gas will be converted to electricity at approximately 30% to 40% efficiency and heat at approximately 50% to 60% efficiency. Approximately 85% of the energy value of the biogas will obtainable as electricity or heat.

If the biogas is used as vehicle fuel then it can be used after a minimal amount of gas scrubbing to remove impurities such as H_2S. However 40 to 50% of the biogas is CO_2 which cannot be combusted so reduces the available range of the fuel held in a vehicles tank. The biogas will therefore usually be scrubbed of the CO_2 to leave methane enriched biogas and compressed to further increase the amount which can be carried in a vehicle. Both of these processes consume electricity. Upgrading the biogas requires between 0.3 kWh/m^3 upgraded gas plus 0.2 kWh/m^3 compression (deliverable **D22**) to 0.75kWh/m^3 upgraded biogas (Murphy et al., 2004). Further details on energy requirements for processing primary fuel are detailed in deliverable **D22** and **WP8**.

Material removal and processing

Figure 1 indicates that each part of the process involves the production of material as well as energy. In the case of crop production may be straw or other materials not consumed in fuel production. In the conversion to primary fuel there may be secondary products such as glycerol and rapeseed cake in biodiesel production or distillers grains from bioethenol production. In the case of anaerobic digestion for energy the secondary product is the digestate which can be used as a biofertiliser. In processing the primary fuel the material products may include CO_2 from upgrading.

In the case of anaerobic digestion the main secondary product is the digestate, the material remaining which is not converted into biogas. The digestate contains the majority of the nutrients which were in the original feedstock and will be stored after digestion in a separate container. The digestate can be used directly in the form which 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 can be used as a soil conditioner with some nutrients and the liquor as a bio fertiliser containing nutrients such as nitrogen, phosphate and potash. Separation of the digestate requires energy, usually in the form of electricity. Both components can be used to reduce the requirement for mineral fertiliser. The digestate therefore has an energy value in that it replaces mineral fertiliser which has a high indirect energy requirement. Energy is required for the transport and spreading of the digestate as fertiliser and examples of these energy requirements as given by Berglund and Börjesson (2006) are shown in Table 2.

Table 2: Energy requirements for transport and spreading of digestate from (Berglund and Börjesson, 2006)

vehicle	load (tonne)	energy input (MJ/tonne km)		material
		incl empty return	excl empty return	
truck	30	1.1 (1.0-1.2)	0.7 (0.6-0.8)	ley crops, tops and leaves of sugar beet
tractor	8	3.5		solid digestate
tractor	15	2.5		liquid digestate
truck	16	1.6 (1.5-2.3)	1.0 (0.8-1.3)	digestate
digestate	Energy input (MJ/tonne)			
	loading	spreading	total	
liquid phase	2.5	17	25	
solid phase	7	14	28	

It is unlikely that digestate will provide a complete replacement for mineral fertiliser. The nutrient recycling is not complete, there are some losses in the system (volatilisation of NH_3 for example). Some nutrients added to the crops will be not be retained in the harvested plant material being 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. There will thus be energy requirement for both mineral fertiliser application and digestate application.

Quantifying the energy - identifying the boundaries

Figure 1 gave an example of the boundaries for generalised crop based fuel production – this boundary allows the comparison of different fuel types and production methods.
Determining the energy requirements, deficits and surpluses, for energy production using anaerobic digestion depends on the specifics of the process and in particular the use of the biogas and digestate. Once a system boundary has been determined then anything going into the system is a deficit, anything coming out of the system is a surplus.

Various scenarios of energy use can be considered:

1. crop production using mineral fertiliser, all energy for AD unit imported, biogas exported (Figure 4).
2. crop production using mineral fertiliser, biogas used in CHP, heat and electricity from CHP used for AD plant, electricity exported.
3. crop production using mineral fertiliser, biogas used in CHP, heat and electricity from CHP used for AD plant, biogas exported as vehicle fuel.
4. as scenario 1 but digestate used as fertiliser.
5. as scenario 2 but digestate used as fertiliser (Figure 5).
6. as scenario 3 but digestate used as fertiliser.

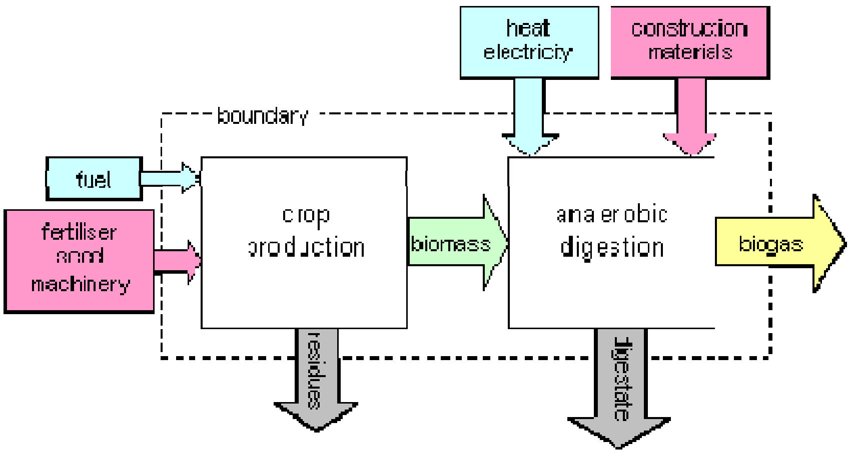


Figure 4: energy boundaries for scenario 1

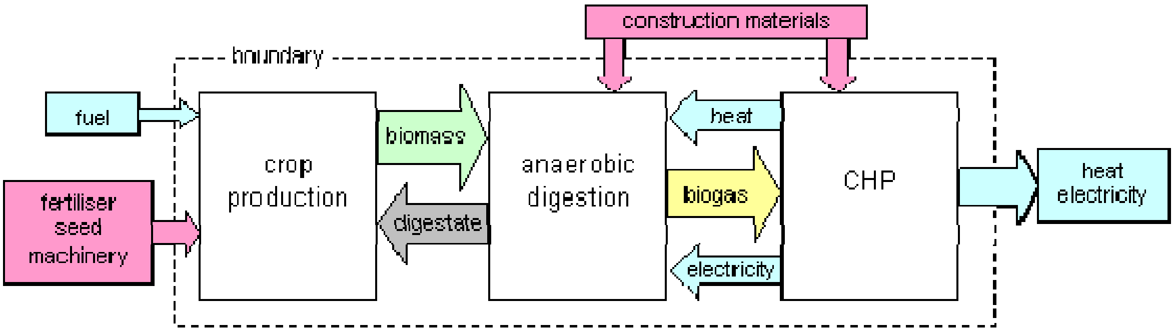


Figure 5: energy boundaries for scenario 5

The sources and sinks of energy in a staged approach to crop based energy production including energy type and whether the energy can be regarded as a source of deficit and surplus are identified in Table 3.

Table 3: Sources of Deficit and Surplus energy

energy source/sink	direct/indirect	energy deficit/surplus
crop production		
fertiliser	indirect	deficit
sprays	indirect	deficit
tractor fuel	direct	deficit
machinery	indirect	deficit
seed	indirect	deficit
anaerobic digestion		
digester	indirect	deficit
heat	direct	deficit
electricity	direct	deficit
biogas	direct	surplus
digestate *(a)*	indirect	surplus
digestate use (a)		
machinery	indirect	deficit
transport fuel	direct	deficit
mineral fertiliser replacement	indirect	reduces deficit in crop production
fuel processing		
CHP machinery	indirect	deficit
heat	direct	surplus
electricity	direct	surplus
biogas upgrading equipment	indirect	deficit
electricity	direct	deficit
CH_4 enhanced biogas	direct	surplus

From Table 3 it can be seen that crop production is entirely deficit in energy. This is because the model does not take into account the energy absorbed from the Sun by the crop. The object of these analyses is to determine if the process of anaerobic digestion is more efficient in energy production that other comparable forms of crop based energy production. If the process is to be compared to forms of solar energy collection and utilisation, such as photovoltaic cells, then the energy absorbed form the Sun must also be included. The crop production energy deficit can be greatly reduced through the use of digestate as a bio-fertiliser or the use of leguminous crops which have the ability to fix atmospheric nitrogen. Table 1 indicates that crops of lupins, field beans, clover or

Lucerne have approximately half of the energy requirements of other crops, due principally to their reduced nitrogen requirements.
The stage of anaerobic digestion has an energy surplus in the form of biogas which can be considered in terms of calorific value based on its CH_4 and CO_2 composition. If CHP and/or CHP/upgrading is included as part of the process then the biogas is taken as an energy carrier and the electricity, heat and vehicle fuel are taken as the energy surplus.
As with any renewable fuel productions system, the use of anaerobic digestion is only worth considering if the energy surplus is greater than the energy deficits. Energy balances and details of surplus/deficit for a range of crops and digestion options are given in deliverable **D19**.

The scenarios have been simplified in order to illustrate the concept of energy and material movement within a crop based AD system. In reality the systems will be more complex as they are governed by the design, mode of operation and location of the digester. A more complete example of the system boundaries, sources and deficits of energy is shown in Figure 6. This example, based on the Kalmari farm in Jyväskylä Finland, is developed in greater detail in deliverable **D22**. There are two boundaries on this system depending on where the dairy unit is considered.

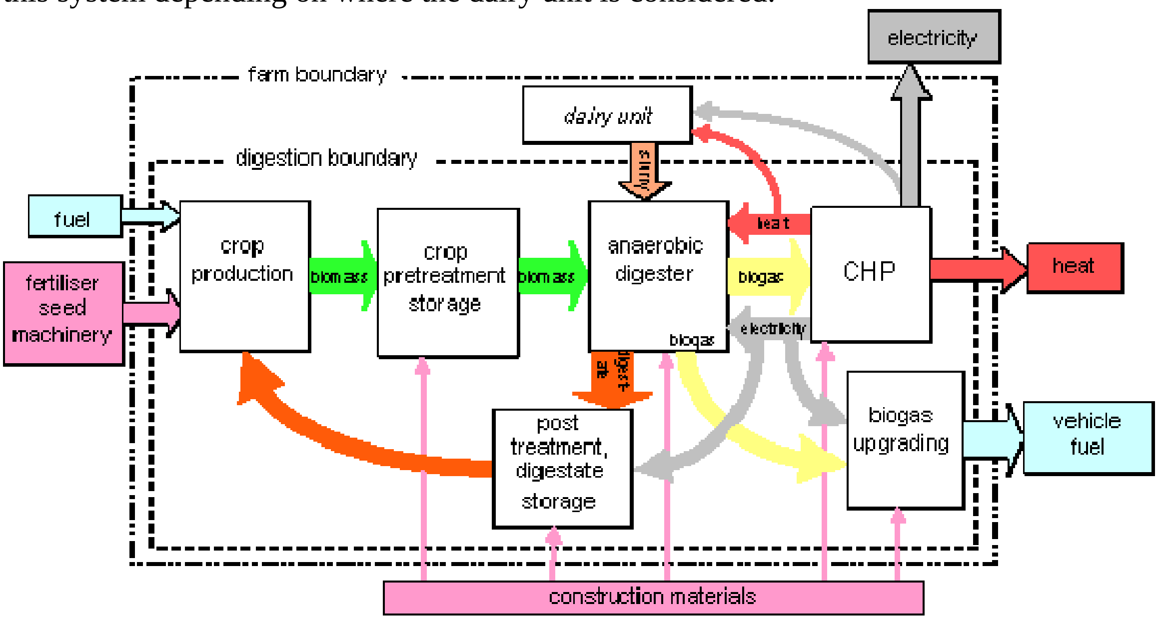


Figure 6: Boundaries for a mixed arable/livestock farm based digester

Conclusion

For any 'renewable' fuel source to be considered viable, the energy surplus must be greater than the energy deficit and this ratio must be greater than for other comparable fuels. In order to determine the surpluses and deficits it is necessary to identify system boundaries and thereby what energy is entering the system (the deficits) and what is being produced (the surplus). Energy requirements must be considered both in terms of the direct energy requirements – fuels used directly, and indirect energy requirements – energy used in fabrication, repair and maintenance of buildings and equipment.

For a system based on the anaerobic digestion of crop material the energy requirements must be considered for crop production, biomass conversion and final use of the biogas. The crop production will consume a considerable part of the energy required, particularly in the form of mineral fertiliser added to the crop, and various ways can be taken to reduce these energy requirements. These include the use of digestate as a biofertiliser and choice of crops to reduce fertiliser requirements. Energy requirement for the anaerobic digestion plant and ancillary equipment will be in the form of electricity and heat which can be obtained externally to the system or by the use of boilers and CHP within the system.

Examples of the overall energy balances for energy production taking into account energy inputs associated with farming are given in deliverable **D19**, examples of AD plants and associated requirements are given in deliverables **D22**, **D24** and **D29.** Detailed examples of energy requirements for crop production are given in deliverables **D14** and **D25,** methods for determining energy requirements for anaerobic digestion are developed in deliverable **D15.**

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