GHG assessment of Bore Hill Farm Biodigester (Malaby Biogas Ltd)

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Summary

This study takes the Bore Hill Farm Biodigester (BHFB) facility as a case study to explore the sources of Greenhouse Gas (GHG) emissions associated with commercial Anaerobic Digestion (AD), and some of the factors affecting them. With access to extensive operational data from a commercial food-waste site, it provides robust analysis of the onsite activities.

The work is based upon Lowe's (2020) Final Year Project report with additional refinements and expansion.

On the basis of the parameters and boundaries in this study, operation of BHFB causes annual emissions of almost 2000 tCO_2e but causes the avoidance of approximately 4100 tCO_2e elsewhere. Its overall effect is therefore a net GHG benefit of around **2100 tCO_2e.** This is equivalent to a net saving of over 300 gCO_2e per kWh of electricity exported.

The impact of switching from electricity generation to biomethane production is examined and found to present the potential to more than double the overall GHG benefit; increasing the total benefit to over **4360 tCO_2e**.

Centre for **Sustainable** **& Circular** Technologies

Supergen Bioenergy

Goal and scope

Aim

The aim is to assess the GHG emissions associated with Bore Hill Farm (Anaerobic) Biodigester (BHFB). This is to determine both the overall impact on GHG emissions that an AD facility might achieve, but also where the emissions and savings occur. As such, the assessment is intended to act as a guide to increasing the GHG emissions benefits at the BHFB site as well as helping others prioritise areas for improvement and develop appropriate assessments for other facilities.

Impact categories

The environmental impact category considered in this study is climate change. Climate change impacts are presented in terms of CO_2 equivalent mass using GWP100 characterisation factors from IPCC AR5.

Throughout, the convention of “positive” emissions being to atmosphere and “negative” emissions being from atmosphere or avoided counterfactual emissions to atmosphere is adopted. Biogenic CO_2 emissions are noted in the accounting throughout for clarity and because they present a potential scope for emissions reduction, but they are not included in the totals.

Functional unit.

The functional unit of the process is the **annual operation of BHFB**.

To assist in comparison, the results are also presented normalised to:

- The electricity (kWh) that is net-exported from the site (i.e. generation, less on-site consumption). Note that 1kWh = 3.6 MJ.
- The food waste (ton) processed by the site (total mass including liquid feedstocks).

These “normalised” results should be used with care as they still represent the total effect on GHG emissions of the annual operation of BHFB. That is, the results include credits from the avoided activities that would typically be excluded if the functional unit related to that activity (see “System Perspective”, below).

System perspective

AD plants are well positioned to provide a range of products and services within a circular economy context (Mezzullo 2010). They can provide energy (as electricity, heat or biomethane), recycle organic wastes and residues, provide organic fertilizer and potentially achieve negative GHG emissions. The different nature of these products and services, and their variable values, can be a challenge for meaningful allocation of impacts between them. In this study, the entire system is assessed in terms of both emissions and credits due to avoided activities. This is generally consistent with a “system expansion” / “substitution” approach to co-products and a “consequential perspective” to Life Cycle Assessment (LCA).

The “total” results include **credits for all** avoided impacts within the study boundaries. This is consistent with assessing the impact of operating the AD facility and questions around the overall desirability (in terms of GHG emissions) of encouraging their operation rather than the alternatives by all incentives. That is, if support or incentives designed to reduce GHG emissions are applied to the co-products (waste treatment, energy, organic fertilizer etc.), then the incentive for each co-product should relate to a portion of this overall benefit.

If assessing the impact of a particular co-product, it is more conventional to **not include the credit** for avoiding the counterfactual production route for that co-product. For example, if considering electricity production, it is conventional to compare different generation options without any of them being given credit for avoiding emissions due to displacing average grid generation.

GHG sources / system boundaries

This assessment considers the following GHG emissions due to operation of BHFB:

+ GHG embodied in equipment and site construction
+ Transport
    - food waste to digester
    - digestate to farms
+ Engine exhaust emissions
+ Methane slip (unburnt fuel) through engines
+ Biogas leakage from AD operation
+ Additional emissions due to digestate application and use

And the following GHG emissions that are avoided through the operation of BHFB:

− Conventional (inorganic) fertilizer production

− Alternative food-waste treatment

− Grid (average) electricity generation

Note that biogenic CO_2 emissions are included in the accounting throughout for clarity but are not included in the totals.

The uncertainties for each of these GHG sources / sinks vary in their nature and magnitude. They are also affected by the actions of different actors: the AD operators, the food waste suppliers, the site construction firm, etc. In the following results section, they are provided separately so that the reader can assess their relative significance. More detail of the approaches taken to assess them are then provided in the “Methods” section.

Overview of Bore Hill Farm Anaerobic Digester.

Malaby Biogas operates a commercial anaerobic digestion (AD) facility located at Bore Hill Farm in Warminster. It opened in 2012 and has been nominated as finalists in three categories in the Anaerobic Digestion & Bioresources Association (ADBA) awards and was the 1st plant in England to be accredited under the AD Certification Scheme which certifies industry best practice and underpins the facility's ability to demonstrate GHG emissions benefit. BHFB is a food waste digester, providing an environmentally friendly disposal option for waste producers and suppliers in the surrounding areas and around the country. Additionally, the site promotes sustainable energy production to the local community and academic researchers across the world. Since opening, they have processed over 155,000 tonnes of waste, generating 47,500 MWh of electricity and 145,000 tonnes of low-carbon biofertilizer. The site consists of a single buffer tank, 2 digesters, 2 Combined Heat and Power Units (CHPs) and operational equipment for managing the incoming / outgoing waste.

The digester receives food waste feedstock from clients across the U.K., up to 320 km away, transported to the site via tanker, freight or refuse lorries. The current annual feedstock supply is approximately 31,500 tons, of which 85% is in liquid form, arriving at site already separated and not requiring a further step within the pre-treatment process; agreeing with the EU recommendation of separate collection of biowaste. The plant produces approximately 61% methane biogas at a rate of 445 m^3/hr, under a mesophilic regime at 35 - 37°C, with CHP units providing energy for maintaining temperature throughout the process, the office building and providing electricity similarly. Furthermore, an estimated 28,800 tons of digestate is produced and transported to farms up to 250km away.

Figure 1: Bore Hill Farm Biodigester

Results

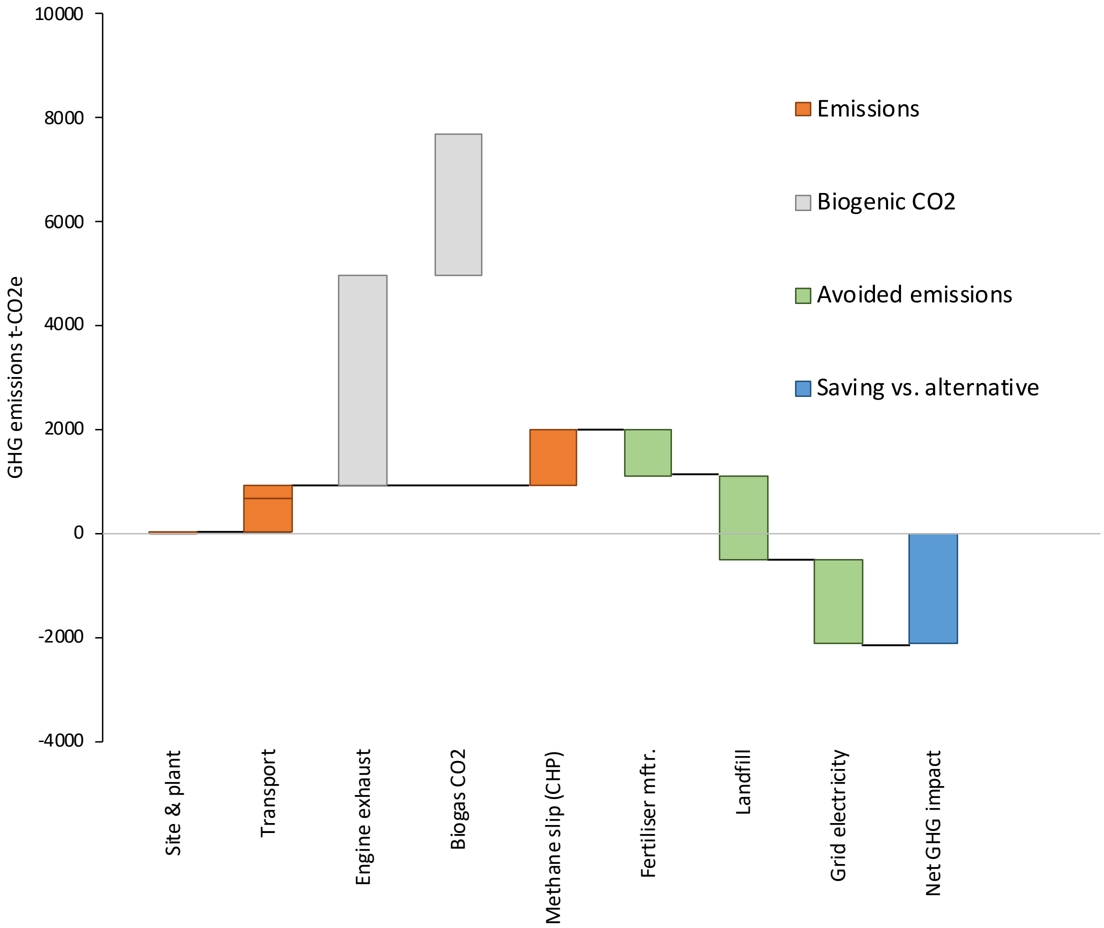

Figure 2: Effect of BHFB on GHG emissions

Table 1: Effect of BHFB on GHG emissions

Source	GHG (tCO_2e)	GHG (gCO_2e/kWh)	GHG ($kgCO_2e/t$-waste)
Site & Plant	38	5	1
Transport	896	129	28
Food waste	632	91	20
Digestate	264	38	8
Engine – combustion biogenic CO_2	*4027*	*581*	*128*
Biogas biogenic CO_2 content	*2740*	*395*	*87*
Methane slip (engines)	1064	154	34
Avoided fertilizer manufacture	-878	-127	-28
Avoided landfill	-1606	-232	-51
Avoided grid electricity	-1616	-233	-51
NET IMPACT	**-2102**	**-303**	**-67**

Total annual GHG emissions were 1998 tCO_2e.
Total emissions avoided elsewhere were 4100 tCO_2e.
Net GHG benefit was 2102 tCO_2e.

Methods and calculations

This section describes the approach taken to assess each of these GHG sources. Calculations relate to the period 23/07/2019 to 22/07/2020.

Where results are presented normalised to the throughput of the site, this relates to either net electricity exports of **6,930 MWh**, or to total feedstock input of **31,530 tons**.

Within each subsection below, emissions are highlighted red, savings are highlighted green, and the overall net benefits are highlighted blue.

GHG embodied in equipment and site construction materials

The GHG emissions embodied in on-site equipment and construction materials are relevant to questions relating to the decision to ***build and then*** operate an AD facility (rather than to *continue* operating). These emissions were assessed by estimating the quantity of materials – this was done through calculations based on the size of equipment and Ordnance Survey mapping of the site, accounting for the two CHP generators, and discussion between Cooper and Minter. Factors supplied in Ecoinvent 3.7 (Wernet et al. 2016) were then used (and scaled in the case of the CHP engines):

Table 2: Embodied GHG associated with BHFB

Item	Quantity	Unit	Ecoinvent product flow used	GHG intensity	Embodied GHG $kgCO_2e$
Floorpan:					
Concrete floor	750	m^3	concrete production 20MPa | concrete, 20MPa | Cutoff, S	198	149000
Aggregates	4800	t	market for gravel, crushed | gravel, crushed | Cutoff, S	0.0151	73000
Other concrete	900	m^3	concrete production 20MPa | concrete, 20MPa | Cutoff, S	198	178000
Reinforcing steel	22500	kg	reinforcing steel production | reinforcing steel | Cutoff, S	1.96	44000
Weighbridge - steel	10000	kg	market for section bar rolling, steel | section bar rolling, steel | Cutoff, S	2.15	21000
Building:					
Skin	28000	kg	market for sheet rolling, steel | sheet rolling, steel | Cutoff, S	2.34	65000
Structure	23000	kg	market for section bar rolling, steel | section bar rolling, steel | Cutoff, S	2.15	50000
Base	22	m^3	concrete production 20MPa | concrete, 20MPa | Cutoff, S	198	4000
Digester:					
Digesters & digestate storage tank	52500	kg	market for sheet rolling, steel | sheet rolling, steel | Cutoff, S	2.34	123000
Buffer, other tanks & pipework	24700	kg	market for sheet rolling, steel | sheet rolling, steel | Cutoff, S	2.34	58000
CHP:					
Generator / electrical	5	#	heat and power co-generation unit construction, 200kW electrical, components for electricity only | heat	15600	78000

Gas engine	3.46*	#	and power co-generation unit, 200kW electrical, components for electricity only | Cutoff, S heat and power co-generation unit, 200kW electrical, common components for heat+electricity	84100	292000
TOTAL					1113000

Totals might not match due to rounding. *Sizing exponent of 0.6 used.

This gives a total of 1,113 tCO_2e embodied in the site and equipment. Of this total, approximately a third is embodied in the concrete used to support the site, a third is embodied in the CHP equipment and a third is embodied in the AD tanks, building and other equipment.

Assuming a 30-year plant lifespan with operation at the same level, the annual emissions embodied in the site and equipment are **38 tCO_2e** (5 gCO_2e/kWh or 1 $kgCO_2e/t$).

Note that emissions associated with the construction of the site and its end of life are not included in this figure.

Emissions due to Transport

Emissions due to transport of food waste to BHFB and of digestate from BHFB to farms are assessed in this section. From a consequential perspective (i.e. considering the change due to operation of the AD) this is a conservative approach as there would probably otherwise be transport of the food waste to an alternative treatment facility and there would be transport of the (albeit lighter) inorganic fertilizer from production facilities to farms. These emissions are kept in this study in order to provide some clarity over the scope of these emissions and the potential to abate emissions by reducing them.

Food waste to the site

Lowe (2020) analysed the location of the food waste suppliers to BHFB and determined the following average transport distances.

Table 3: Feedstock types and transport distances

Feedstock Type	Range of Transport Distance (km)	Average Transport Distance (km)	Annual mass delivered (t)
Liquid Waste	16 – 193	104	26236
Loose Waste	32 – 129	80	4970
Packaged Waste	3 - 321	162	323

Taking lifecycle emissions factors from Ecoinvent 3.7 and assuming a 50:50 split between 7.5-16 ton and 16-32 ton EURO5 lorries, this gives annual emissions of **632 tCO2e**.

Digestate to farms

Lowe (2020) analysed the location of the farms to which digestate was delivered. Average distances were calculated as follows:

Table 4: Digestate transport distances

Lorry size	Average Transport Distance (km)	Annual mass delivered (t)
7.5 – 16 t	66	7664
16 – 32 t	41	21168

Taking Ecoinvent 3.7 emissions factors for EURO5 lorries, this gives annual emissions of **264 tCO_2e**.

The total transport-based GHG emissions are therefore 896 tCO_2e (129 gCO_2e/kWh or 28 $kgCO_2e/t$).

It is worthwhile to consider options for reducing them. Of these emissions, almost 90% correspond to tailpipe emissions (with the remainder being manufacture and maintenance of the vehicle, and construction of the road). These emissions could potentially be reduced by securing more localised feedstocks (where available) or dewatering (partially drying, evaporating or filtering) feedstocks prior to transport. It is possible that further processing of digestate could also enable more efficient transport to additional markets (Rehl and Müller 2011; Vázquez-Rowe et al. 2015). However, these might not be viable options in the near term without further research, development, and commercialisation.

Another option is the use of lower emissions vehicles (perhaps electrified or using biomethane). CNG is available as a fuel for HGVs and can achieve some GHG savings; Speirs et al. (2019) give a range of results with a central estimate of around 10% GHG saving through switching from diesel to CNG. This saving is less than the 25% reduction in CO_2/energy ratio that CNG exhibits relative to diesel; this is due to a range of factors but notably reduced average engine efficiency. However, switching to CNG enables the use of biomethane. This could achieve a reduction in non-biogenic tailpipe emissions of around 90% (highly dependent on vehicle, engine and operational characteristics). If achieved, this would reduce the total annual transport GHG emissions due to operation at BHFB from 896 tCO_2e to **170 tCO_2e.** This total is indicative and should not be added to the GHG results in this study without further analysis as the biomethane production would either reduce other avoided impacts (if sourced from BHFB) or else embody other activities. The use of biomethane for transport potentially provides synergistic opportunities and so Malaby Biogas is exploring its use at BHFB.

CO_2 in CHP engine exhaust

Operational plant data supplied by Malaby Biogas was used to calculate these emissions. The metered data provides the biogas volume supplied to the two CHP engines, boilers and flare. Average daily temperature and methane fraction (by volume) enabled calculation of the total methane combustion as 1,464 t. Combustion of this methane resulted in emissions of **4027 tCO_2** (including 72 tCO_2 due to methane flared), i.e. 581 gCO_2/kWh or 128 $kgCO_2/t$.

The rated electrical efficiencies of both CHP engines are 41%. This implies nominal combustion emissions of 483 gCO_2/kWh. Clearly, real world conditions (e.g. not being run at optimum point), on-site electricity use, and occasional flaring have increased the emissions per kWh of net exported electricity.

In addition to the combustion emissions, **2740 tCO_2** (395 gCO_2/kWh, 87 $kgCO_2$/t) are released as the CO_2 content of the biogas.

Note that the combustion and biogas CO_2 emissions that this subsection relates to are biogenic, i.e. they are not included in the total GHG emissions as they were recently absorbed from the atmosphere but are noted as they might represent a potential for other abatement.

Methane slip through CHP engine

Stack emissions testing data for the two CHP engines at BHFB was supplied. This data includes exhaust concentrations of organic compounds, organic compounds excluding methane, and oxygen. The oxygen content suggests air:biogas input ratios of approximately 9.7:1 and 8.8:1 for CHP1 (Edina) and CHP2 (Coopers) respectively.

Converting the organic compounds concentration to a mass/mass proportion of the input methane indicates that 3.6% and 1.8% of methane entering CHP1 and CHP2 respectively, is not burnt. This results in a climate change impact of **1064 tCO_2e** (154 gCO2e/kWh or 34 kgCO2e/t). Fruergaard and Astrup (2011) provide comparable results, with a climate change impact equivalent to 140 gCO2e/kWh when converted to same basis.

This is striking as reducing the slip through CHP1 just to the level of CHP2 would reduce the overall climate change impact associated with methane slip by about a third. However, while it seems worthwhile from a climate change perspective, it is unlikely that support that targets the electricity generation (i.e. based on energy output) will be effective at incentivising changes to methane slip.

Biogas leakage from AD operation

Some studies have suggested that leakage of biomethane from the digester tanks, ancillary tanks or other pipework could occur. Bakkaloglu et al. (2021) estimate losses as between 0.4% and 3.8% (but note that smaller farm-based sites are typically responsible for the higher rates). This was identified as a key potential sensitivity in Lowe's (2020) project. Further work was therefore conducted in the summer of 2020 to investigate the extent to which this might occur at BHFB. Several potential sources of leaks were investigated and in each case, it was found that **good practice has largely eliminated the incidence of methane leakage**:

- Digestate storage emissions are typically associated with open-air storage. At BHFB, the digestate storage is covered and tested for leaks and residual biogas potential of stored digestate is significantly lower than the certification threshold for PAS110/ADQP compliance.
- Pressure Relief Valves operate when flaring is not available and when operation of the facility results in temporary overproduction of gas (Reinelt, Liebetrau, and Nelles 2016). At BHFB, neither of these is the case. The valves are tested regularly for leaks and seal integrity.

- Flaring. Management of the digester means that only a very small fraction of the biogas is flared. Even a pessimistic assumption that 1% of the flared gas escapes unburnt, this would be equivalent to less than 8 tCO2e.
- Feedstock preprocessing. Feedstock at BHFB is a mix of liquids, loose and packaged waste. Some preprocessing of the packaged waste is required and undertaken in a sealed building. Negligible methane was detected in the surrounding air and it is therefore assumed that no significant anaerobic decay to methane occurs before this waste is enclosed.
- Pipes and jointwork. This is designed not to leak as part of ATEX compliance. A selection of joints are checked daily with a methane detector. A comprehensive leak test is conducted every 6 months. No leaks have been detected since the site was opened in 2012.

The relatively high GWP of methane means that any leakage could have a significant effect on the site's overall GHG performance. For example, 2% leakage of methane produced would be equivalent to additional GHG emissions of **835 tCO2e.** Therefore, despite the lack of emissions at BHFB, potential sources of methane leakage at other sites should be investigated and monitored and, where possible, operational procedures and facilities should be managed to control leakage.

Emissions due to digestate application and use

Emissions from the application and spreading of the digestate are subject to large ranges of values due to the differences in application practice, types of crop, soil and weather conditions. In particular, ammonia emissions can be higher and studies (e.g. Lukehurst, Frost, and Al 2010) have recommended good application practice (e.g. applying in spring / summer and minimising air exposure to reduce volatilisation of ammonia) to partially address this.

However, it is not clear that GHG emissions are actually greater than those associated with inorganic fertilizers (Petersen 1999). Nitrous oxide emissions are potentially lower than those assumed in the IPCC standard (1% vs. 0.45 +/- 0.15%) (WRAP 2016).

The digestate might affect soil carbon in longer-term but this will also depend upon agricultural practice and the crop production over an extended period.

Within this study, net GHG emissions due to digestate application and use are therefore assumed to be zero. However, this does not mean they will always be zero – it is possible that a positive or negative value is appropriate and further study relating to this component is recommended.

Avoided emissions due to displaced fertilizer production

The digestate contains nitrogen, phosphate, and potash (potassium) macronutrients. These can displace the demand for inorganic fertilizer. The nutrient content of the BHFB digestate and estimates of the lifecycle GHG associated with manufacturing these as inorganic fertilizer are given in the following table.

Table 5: GHG embodied in inorganic fertilizer

Nutrient	% of digestate (m/m) BHFB	GHG kgCO2e/kg Ecoinvent 3.7	NNFCC (2007)	Williams et al 2006	Boldrin et al (2009)
Nitrogen (N)	0.796%	4.627	7.11	6.8	8.9
Phosphate (P2O5)	0.0789%	1.965	1.76	1.2	1.8
Potassium (K2O)	0.1324%	2.358	1.85	0.5	0.96

With 70% availability for the nitrogen, the annual digestate production of 28832 t (year ending 23 July 2020) has the potential to displace manufacture that causes emissions of -878 tCO_2e. This is equivalent to 127 gCO_2e/kWh or 28 $kgCO_2e$/t.

Avoided emissions from alternative food waste treatment.

If AD is not used to treat the food waste, then an alternative process must be used. This alternative will have an impact that is avoided if AD is used. However, while this is a real consideration, the choice and performance of the alternative avoided food-waste treatment is hypothetical; by definition it is a process that **doesn't** occur because of the AD. This means that there are significant uncertainties associated with it. These include the choice of the alternative process, the performance of this process, and other uncertainties associated with the data relating to the alternative (e.g. how representative is any emissions data of the conditions that would occur if the alternative were used).

For this study, covered landfill is assumed to be the default alternative technology. Different approaches can be taken to assess this. While landfill is a reasonable default alternative, it should be noted that crediting AD with the benefit of avoiding landfill is dependent on that being the default alternative; this may not be valid in the future.

Manfredi and Christensen (2009) estimate total emissions of 85.5m^3 methane per ton of wet domestic waste. Of this, it is estimated that 60m^3 could be collected but 4.7m^3 (5.5% of gas generated) would still be released to atmosphere (with the remainder oxidised organically in the cover soil etc.). The waste assessed in their study is different to that used at BHFB – while wet, it has a far lower water content (around 83% of feedstock delivered to BHFB was tankered) but the mixed domestic waste potentially has a lower specific methane potential (on a solids basis) than the food waste processed by BHFB. At BHFB, around 70m^3 of methane are generated per ton of waste input (including water content); this is around 200m^3 methane per ton of "wet" (15% water) food waste. Clearly the conditions in the AD are designed to maximise methane production.

Assuming the food waste processed at BHFB would otherwise be landfilled, it is estimated that this would release between 86m^3 and 140m^3 per "wet ton" (i.e. between 43% and 70% of the total methane generated by the AD facility). Of this, 5.5% might escape to atmosphere.

This gives avoided emissions of **-981 tCO_2e** to **-1606 tCO_2e.**

This does not include avoided benefits from using captured landfill gas for energy recovery. Landfill gas has poorer combustion characteristics compared to biogas from AD due to increased gas contamination by other combined, non-food waste landfill fractions. It should also be noted that landfill waste treatment brings a range of additional environmental impacts that are outside the scope of this study.

Some landfills will have greater unabated methane emissions (e.g. see Lee, Han, and Wang 2017; Yang et al. 2013). If methane were not captured at all, this could have a GHG emissions impact of over 29000 tCO_2e/yr! By comparison, Lowe (2020) provided a linear scaling to data relating to landfill across the country. BHFB treats around 31 kt/yr of food waste, equivalent to just under 11 kt/yr on a “wet solids” mass balance basis. This is 0.15% to 0.44% of the 7.2 Mt of biodegradable municipal waste that was landfilled in the UK in 2018. This suggests avoided emissions of 935 tCO_2e to 2715 tCO_2e based on the total UK landfill emissions (NAEI).

In this study, the **-1606 tCO_2e** figure is used (232 gCO_2e/kWh or 51 $kgCO_2e$/t). However, it is clear that there is a large range of uncertainty associated with this result and that apart from enabling an effective alternative to landfill, this is outside the control of the AD operator.

Grid electricity generation emissions

Defra reporting guidelines (defra 2021) give a GHG intensity of 233 gCO2e/kWh-electricity for 2020. BHFB operates consistently and so it might be that the grid intensity that it should be compared to has a higher proportion of combustion-based generation and a higher emissions factor. Detailed analysis of this is beyond the scope of this report. It is likely that a greater premium will be placed on dispatchable generation in the future. However, it is also likely that the UK grid generation mix will continue to decarbonise.

The net electricity exports from BHFB were 6,930 MWh. The grid generation emissions avoided were therefore **-1616 tCO_2e** (i.e. 233 gCO_2e/kWh or 51 $kgCO_2e$/t).

On-site electricity use was around 749 MWh; 9.8% of the total generation. This reduces the credit for avoided electricity generation by around (10%).

Additional savings through alternative energy outputs

District heating

BHFB uses around 3200 MWh/yr of heat. The heat generated by the CHP engines is not metered, but based upon their nominal efficiency (41% electrical efficiency, 42 – 44% thermal efficiency), this will be just over 8000 MWh/yr. If a third of the excess heat could be used (i.e. to account for losses and temporal mismatch between supply and demand) and displaces heat that would otherwise be generated by boilers with 85% efficiency, then this would provide a further GHG saving of -350 tCO_2e/yr.

Economic and commercial conditions make this unviable at present, but this result provides some perspective on the scope for emissions savings in other developments. Note that this potential benefit would be reduced if low-carbon heating (e.g. heat pumps with low-carbon electricity) were displaced.

Biomethane production

In light of the reducing GHG intensity of grid electricity, Malaby Biogas is developing the ability to diversify its energy products to include compressed biomethane for transport. Inspired by this development, this subsection investigates the hypothetical GHG impact of BHFB switching all of its energy output from electricity to compressed biomethane.

It is assumed that biomethane displaces fossil methane. That is, the impact that is considered here is the effect of fuelling CNG vehicles with biomethane rather than fossil methane; the additional impact of replacing diesel vehicles with CNG vehicles is excluded. There are some additional advantages to moving from diesel vehicles to CNG vehicles (see transport subsection, above). However, while greater availability of biomethane fuelling facilities might encourage wider switching to CNG, this is a separate decision for transport operators and outside the scope of this assessment.

Biomethane production would be achieved by feeding the biogas into a water scrubber that separates the methane and carbon dioxide and then compresses the biomethane. The CO_2 stream from this separation is currently vented to atmosphere. This is biogenic CO_2 that does not contribute to the total GHG emissions within the accounting here. However, it will contain some methane. Numerical modelling of a scrubber by Ravina and Genon (2015) suggests that this could be as high as 4% of the original methane content of the biogas if no flash-expansion tank is used to remove methane absorbed by the water. However, with a flash expansion tank this can be reduced to 1.4% (operating at 5 bar) or even 0.05% (operating at 2 bar). The proposed equipment at BHFB has a flash tank operating at this lower pressure and so the lower methane content is provisionally assumed. If released to atmosphere, this would have an annual GHG emissions effect of 21 tCO_2e (i.e. 2 gCO_2e/kWh_{BCNG}[1] or 1 $kgCO_2e/t$).

[1] Note that where results are normalised to energy output in this section, this relates to the hypothetical bio-CNG output (16670 MWh/yr) rather than the current net electricity exports (6930 MWh/yr)

However, it should be noted that the higher rates of methane emissions would have a significant impact: from **584 tCO_2e** at 1.4% slip, up to **1669 tCO_2e** at 4% slip. Clearly, minimising the methane content of the scrubbed CO_2 stream from the biomethane upgrade is critical for maximising the climate change benefit.

As the CHP units would not be needed, their emissions could be eliminated. However, the facility currently uses heat and electrical power that are supplied by the CHP units. The demands over the year were 3119 MWh of heat and 749 MWh of electricity. At a power consumption of 0.38 kWh per Nm^3 of biogas processed, the scrubber would require an additional 1337 MWh of electricity.

This heat and power could be supplied by either:
Option #1. A smaller CHP unit (or potentially a larger one operated intermittently or at reduced output), supplying the requisite heat. Electricity would be imported or exported to match net demand. Combined with the eliminated emissions from the original CHP operation, this results in a reduction in GHG emissions of **-965 tCO_2e**, (plus an additional reduction in biogenic CO_2 emissions of 2624 tCO_2).
Or:
Option #2. A gas boiler to supply heat and grid supplied electricity. The boiler is assumed to be 85% efficient and electricity supplied with UK 2020 grid GHG intensity (233 gCO_2e/kWh). Combined with the eliminated emissions from the original CHP operation, this results in a reduction in GHG emissions of **-503 tCO_2e**, (plus an additional reduction in biogenic CO_2 emissions of 3300 tCO_2).

However, this is not the full story. Although the GHG emissions per kWh of fossil CNG used (204 gCO_2e/kWh) are currently lower than the emissions per kWh of grid generated electricity (233 gCO_2e/kWh), more biomethane than electricity could be supplied. This is mainly due to the avoidance of efficiency losses in the CHP engines. For option #1, 1.9 times as much energy is supplied, for option #2, 2.4 times as much energy is supplied. This means that in this case the supply of biomethane would actually displace more emissions than the supply of electricity originally did. Option #1 would annually displace emissions due to CNG use of **-2700 tCO_2e** while option 2 would displace **-3396 tCO_2e** (rather than originally displacing 1616 tCO_2e from avoiding electricity generation).

This then achieves an overall net system benefit of either **-4130 tCO_2e** (option #1) or **-4365 tCO_2e** (option #2, equivalent to -262 gCO_2e/kWh_{BCNG} or -138 $kgCO_2e/t$). Although option #2 has higher emissions associated with the supply of energy, it achieves a greater overall GHG benefit because it supplies more biomethane.

There is clearly a large GHG advantage in producing biomethane rather than electricity. This **advantage will increase as the GHG intensity of the electrical grid decreases**. For example, if the GHG intensity of the grid were reduced to 10 gCO_2e/kWh, then the net GHG benefit for option #2 would increase to **-4830 tCO_2e**, while the net GHG benefit of the current / original electrical generation scheme would reduce to **-556 tCO_2e**.

Note that this hypothetical value is based on the premise that emissions associated with grid electricity will decrease while the displaced emissions (e.g. due to landfill) will remain the same.

However, it does illustrate that there is significant scope for additional GHG benefits if the full potential of the AD process is realised.

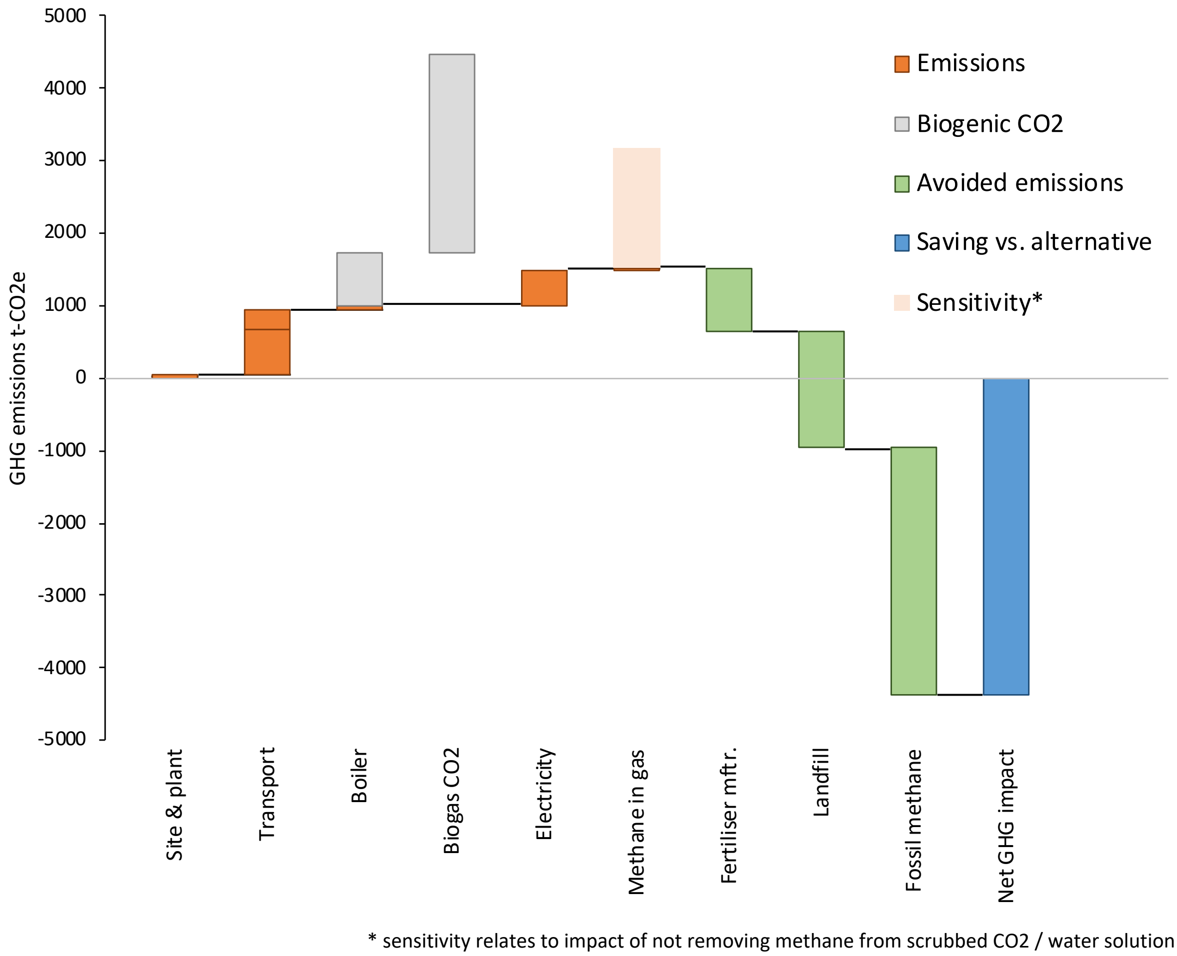

Figure 3: Effect of BHFB on GHG emissions if biomethane produced rather than electricity

Capturing CO_2 from biogas.

As the scrubbing process to produce biomethane provides a relatively pure CO_2 stream, it might also enable this CO_2 to be captured for storage once appropriate infrastructure and arrangements are available.

If compression of the CO_2 requires 120 kWh/ton-CO_2 and the CO_2 needs to be transported 300km by road tanker (i.e. the distance from BHFB to Merseyside) then the additional emissions would be approximately 219 tCO_2e. However, as this would transport 2740 tCO_2 to the sequestration site, the total emissions associated with operating BHFB would be reduced to **-1027 tCO_2e**. Including emissions avoided elsewhere, this would bring total GHG emissions benefits of -6886 tCO_2e (i.e. -413 gCO_2e/kWh_{BCNG} or -218 $kgCO_2e/t$). Note that this hypothetical benefit assumes that the impact of the avoided activities (landfill, inorganic fertilizer, CNG) remains the same.

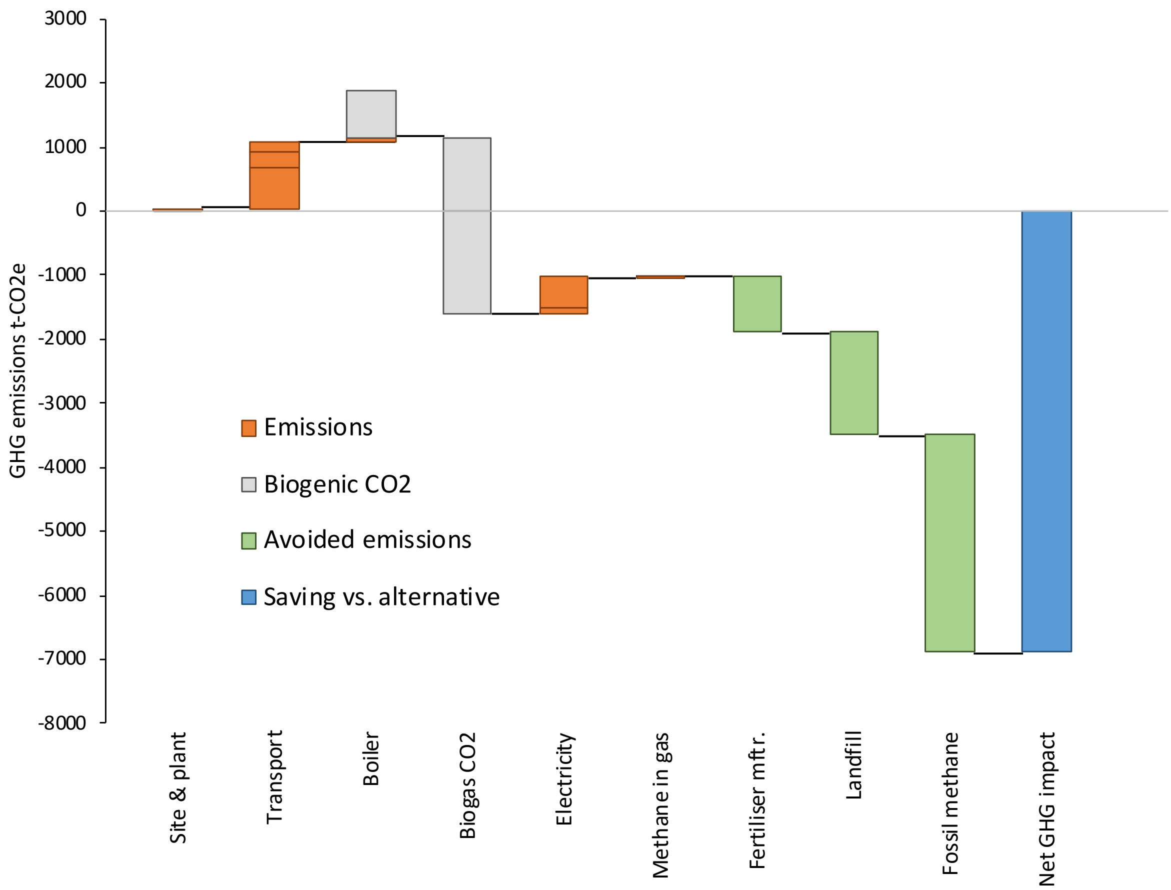

Figure 4: GHG benefits if CO_2 is captured and sequestered

Capturing and sequestering the biogas CO_2 has demonstrable potential for significant GHG benefits. However, neither the necessary economic mechanisms nor physical infrastructure are in place to incentivise it at present. Commercial or industrial uses of CO_2 that are currently satisfied with non-biogenic CO_2 could offer a cost-effective and more immediate alternative to geological storage. The food and drink industry presents some opportunities; while these tend to offer only temporary storage of the CO_2, displacing other non-biogenic CO_2 that would otherwise be released is still beneficial. Cement curing is an option that potentially presents a large-scale and long-term solution; it is currently at a relatively early stage of adoption, but initial work is promising. Other applications involving synthetic hydrocarbon fuels and platform chemicals present the scope for even greater utilisation but are at a lower technical maturity and their application is contingent on several prerequisites. These considerations and opportunities have implications far beyond the GHG benefits of AD, and resolving them will require policy and investment at the appropriate levels. However, when the facilities and market to deal with CO_2 become available, AD has the potential to be an important supplier of CO_2.

Conclusions

- AD can achieve significant GHG savings and potentially "negative emissions".
- These benefits are derived across the products and services that it provides: waste treatment, digestate and energy provision.
- AD also provides other benefits through these products and services. These are not assessed here but should form a key a consideration when assessing the overall desirability of AD.
- The savings relate to avoided counterfactuals. These are subject to activities outside the scope and control of the AD operator. This is made clear in the results.
- The overall savings are greater because of the accredited good practise employed at the BHFB site used as the basis for this case study. In particular, these relate to operational activities to prevent the escape of methane from the AD and ancillary activities.
- There are further opportunities for savings. Looking to the future, these particularly relate to the use of biomethane as a replacement for fossil natural gas (or other fossil fuels, e.g. for transport).
- Refining the biogas to biomethane also presents the opportunity for the captured CO_2 to be sequestered, this would further increase the GHG savings. However, it relies on the availability of either appropriate transport and storage infrastructure, or, more immediately, applications that displace commercial and industrial CO_2.
- This study differentiates between the sources of emissions and avoided-emissions but treats them quantitatively the same in presenting **net** emissions impacts. If AD operators are incentivised to reduce the direct emissions that they drive (i.e. excluding consideration of avoided impacts) then attention to transport and either electricity imports or CHP engine slip is likely. Technology options are available to minimise these emissions. However, it is also possible that a more holistic approach that includes the benefit of avoided emissions will maximise these benefits and lead to the greatest overall net GHG saving.

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