
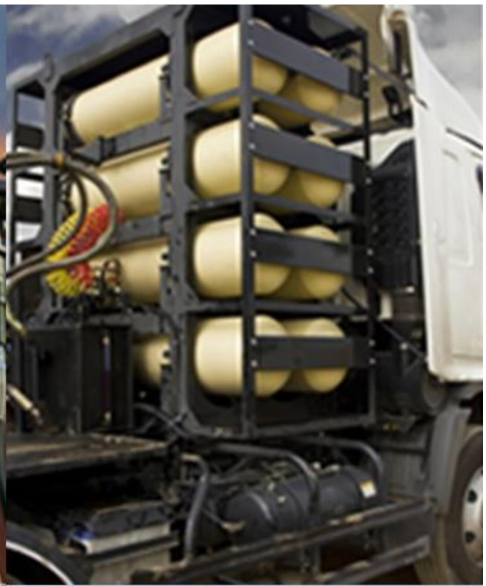

Biomethane for Transport from Landfill and Anaerobic Digestion

Final report

Report for the Department for Transport

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Executive summary

There is growing interest in the use of gaseous fuels in the transport sector, with advocates pointing to the energy security benefits of diversifying supplies of transport fuel and potential carbon and air quality benefits. A previous study by Ricardo-AEA for the DfT (Ricardo-AEA, 2014) found that the use of biomethane in vehicles could deliver substantial greenhouse gas savings, compared to the use of petrol and diesel or of natural gas. However at present, only a very limited amount of biomethane (0.1 Peta Joules, PJ) is produced for supply to the transport sector (DfT, 2014). This biomethane is 0.2% of total biofuels supplied to road transport, 0.006% of total fuels supplied for road transport (DECC, 2014a), and 0.1% of the 85 PJ of biogas produced from landfill sites and the anaerobic digestion of wastes in 2013 (DECC, 2014a).

DfT therefore commissioned this further study from Ricardo-AEA to assess what potential exists to increase the supply to the transport sector of biomethane produced from biogas from landfill sites and from the anaerobic digestion of wastes. Only biomethane produced from waste feedstocks is considered, as under the Renewable Transport Fuel Obligation (RTFO), this is 'double counted' i.e. it is eligible for double the number of RTFC certificates available to biomethane produced from non-waste feedstocks e.g. from the anaerobic digestion of energy crops[1].

As biogas can also be used to generate electricity and/or heat, as well as upgraded to biomethane for injection into the gas grid, the assessment of potential supply in this study evaluates not only the future biogas resource, but also the economic attractiveness to developers or operators of supplying into the transport sector rather than the heat or power sectors. The assessment is based on the current incentive structures for biomethane in all sectors.

Two policy scenarios are considered in the assessment. The first is based on the current incentives for biomethane in the transport sector, where only biomethane supplied directly from the source to the transport sector (e.g. to an on-site filling station, or delivered by road tanker to a filling station) qualifies under the Renewable Transport Fuel Obligation (RTFO) for Renewable Transport Fuel Certificates. The second, hypothetical policy scenario assumes that policy is changed to allow biomethane injected into the gas grid which is destined for transport use to qualify for RTFCs. Both scenarios assume that the incentive structures for biomethane in the heat and power sector remain at current levels.

Potential biogas supply

About 85 PJ of biogas were produced in the UK in 2013, and used predominantly for electricity generation. About two-thirds (61PJ) of biogas supply came from landfill sites, and the remainder (24 PJ) from anaerobic digestion.

In the case of landfill sites, about 61 PJ of landfill gas was collected from over 300 sites in 2013, and used to generate electricity, providing about 10% of the UK's renewable electricity (DECC, 2014a). 0.1 PJ at one site was converted to liquefied biomethane and supplied to the transport sector as part of an LNG/LBM mix known as "bio-LNG". Landfill gas available for collection and use in the future will decline, as quantities of waste landfilled have declined significantly in the last few years and will decline further into the future. It is estimated that by 2020, landfill gas that could feasibly be available for transport fuel use (if economic) is 29 PJ in 2020, approximately half of the total estimated landfill gas resource, dropping to 6 PJ in 2030. It is expected that almost all of this landfill gas resource will be at existing landfill sites, as the decline in waste being landfilled means that there is little incentive to open new sites. Exceptions may be areas where there is a local shortage of landfill void space.

In the case of anaerobic digestion, about 24 PJ of biogas was produced (DECC, 2014a) at about 240 sites in 2013[2] and was used to produce electricity and a small amount of heat. More than half of the biogas produced was from anaerobic digestion of sewage sludge. The potential resource, based on estimates of feedstock available for AD, is much higher than this (between about 90 and 210 PJ), although estimates of the feasible resource that could be developed by 2020 are significantly lower,

[1] Energy crops e.g. maize, or maize silage may be used as the sole feedstock of an AD plant, or added to other waste feedstocks in order to improve biogas production rates and 'smooth' out any fluctuations in the supply of waste feedstocks.
[2] Based on data from OFGEM's FIT Installations Statistical Report (https://www.renewablesandchp.ofgem.gov.uk/Public/ReportManager.aspx) and information from OFGEM ROC register (https://www.renewablesandchp.ofgem.gov.uk/)

ranging from about 31 to 77 PJ. The main contribution to the increase in biogas production will be from the AD of wastes rather than sewage sludge. Encouraged by incentives available under the Renewable Heat Incentive (RHI), an increasing proportion of the biogas output is likely to be upgraded to biomethane for injection to the grid, a trend already evident in 2014 (DECC, 2014d).

Total potential biogas supply could thus be up to 30% higher in 2020 than 2013 (at 106 PJ or 2.2 Mt biomethane) but more pessimistic forecasts of the development of anaerobic digestion (AD) suggest it could be up to 30% lower (at 60 PJ or 1.3 Mt of biomethane).

Producing biomethane for the transport sector

Biomethane produced from biogas at landfill sites or anaerobic digestion plant can be delivered to the transport sector in a number of ways. It can be:

- liquefied to produce liquefied biomethane (LBM), which can then be loaded on to tankers for delivery to a dispensing station
- compressed to produce compressed biomethane (CBM), which can then either be dispensed to vehicles on-site, or transported by road in pressurised containers to dispensing stations off-site
- further conditioned and injected into the gas grid via a pipeline; if no suitable gas grid injection point is available close to the site, the biomethane can be compressed and taken by road to a suitable injection point (a 'virtual pipeline')

The profitability of producing transport fuels from biogas via each of these production routes was estimated based on typical operating characteristics and capital and operating costs for each route. An allowance was made in estimating production costs of LBM and CBM, for the revenue available from Renewable Transport Fuel Certificates (RTFCs) when these fuels are sold into the transport market. In addition, a hypothetical policy scenario, was examined where biomethane injected into the gas grid which is destined for transport use would also qualify for RTFCs. As RTFCs are a market mechanism, their price can fluctuate considerably. Over the range of prices seen recently for RTFCs (7 to 12 pence per certificate) the economic analysis showed that:

- Production of **LBM** from **landfill gas** and from **biogas** from **anaerobic digestion plant** is generally **profitable**.
- Upgrading biogas and dispensing as **CBM** is **profitable** for the case of an **existing sewage sludge digestion** plant (where only the additional costs of upgrading and dispensing are considered) when all the biogas is used as at transport fuel. Diverting only a proportion of the biogas to service a small dispensing station is not profitable under any of the main scenarios considered and is marginal even with a very high RTFC price (of 18p per certificate).
- Upgrading biogas produced from a **new anaerobic digestion plant** and dispensing as **CBM** is **not profitable** under any of the scenarios considered.
- Upgrading **landfill gas** and injecting into the grid via a virtual pipeline could be profitable if RTFC prices were 10 pence per certificate or above.
- Upgrading biogas from a **new anaerobic digestion plant** using waste as a feedstock for injection to the grid for use in transport is not profitable under all of the core scenarios, and is still marginal at the very high RTFC price (of 18 per certificate).

However, in most cases operators could receive better returns by using biogas to produce electricity and receiving support under the Renewables Obligation, or, in the case of biomethane injected to grid from AD plants, receiving RHI payments.

The only option which is potentially more profitable than use of the biogas for heat and power is the production of LBM from landfill gas. Even then, the option is only more profitable under favourable conditions: at a price of 10 pence per RTFC, the results suggest that the liquefaction plant needs to operate at full capacity for at least 10 years, and ideally for longer. Even at a higher RTFC price (of 12p per certificate), levels of landfill gas generation need to be maintained for the option to be attractive.

This suggests that the option might only be considered at sites which will still be receiving waste for several years. In addition, landfill gas generation should be high enough now, that even as it declines in the future, there is still sufficient gas produced to run the liquefaction plant at close to full capacity[3].

An additional barrier to the development of such projects is the 'unbankability' of RTFC income, which, as it is traded rather than fixed, has fluctuated widely in the past.

Overall it is therefore considered unlikely that, at under current levels of RTFC prices, and current levels of support available in the heat and power sector (from ROCs, FITS and RHI) that the supply of biomethane into the transport sector will increase by 2020. In a more optimistic scenario, it is considered that perhaps two landfill sites might convert from electricity production to LBM production, delivering an additional 0.6 PJ of LBM (equivalent to 13 kt of LBM) for transport by 2020. This could fuel almost 1,000 dual fuel HGVs running on a mixture of 60% LBM and 40% diesel; this is about 0.2% of the total current HGV fleet (DfT, 2014a). Supply in 2030 is likely to be lower than this.

[3] It is assumed that surplus biogas in earlier years could still be used for generation of electricity.

Units Conversion
1 PJ is 1 million GJ
1 PJ is 0.28 TWh
1 PJ is 21 kilotonnes (kt) of biomethane

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1 Introduction

There is growing interest in the use of gaseous fuels in the transport sector, with advocates pointing to the energy security benefits of diversifying supplies of transport fuel and potential carbon and air quality benefits. A previous study by Ricardo-AEA for the DfT (Ricardo-AEA, 2014) found that the use of biomethane as a transport fuel could deliver substantial greenhouse gas savings, compared to natural gas, petrol and diesel. However at present, a very limited amount of biomethane is produced for the transport sector. DfT therefore commissioned this further study from Ricardo-AEA to examine what potential exists to increase the supply of biomethane for use as a road transport fuel by 2020 and to 2030.

DfT requested that this study focussed on the potential future **supply** of biomethane to transport from landfill and anaerobic digestion of wastes, including sewage sludge, under two policy scenarios. The first policy scenario reflects current legislation and policy where, for the purpose of the Renewable Transport Fuels Obligation (RTFO), biomethane can only be regarded as a transport fuel and receive renewable transport certificates (RTFCs) if it is directly supplied to the vehicle. The second, hypothetical policy scenario assumes that policy and legislation are changed, so that biomethane destined for transport use, which is injected into gas grid, and uses the gas grid to transport the biomethane to the point where it is dispensed to vehicles, could also qualify for RTFCs. The supply of biogas from anaerobic digestion of energy crops was not included in the study (see Section 2).

The potential demand for biomethane as a transport fuel is being investigated as part of broader government analysis of options for reaching the 2020 10% renewable energy in transport target and for meeting longer term economy-wide CO_2 targets. For the purposes of this study, it is assumed that a demand will exist for both compressed biomethane (CBM) and liquefied biomethane (LBM) as part of an increased demand for gaseous fuels in the transport sector.

This study firstly examines potential routes for producing transport fuels from both landfill gas and biogas from anaerobic digestion and assesses which production routes may be technically feasible given the characteristics of landfill gas sites, and anaerobic digestion plant (Section 2 and 3). For each of these production routes, a ‘case study’ is defined based on typical sizes and operating characteristics, and capital and operating costs collected (Appendix 1). These costs are then used to model the profitability of producing transport fuels via each of the production routes. The profitability of transport fuel production is then compared with the profitability of other options for use of the biogas such as production of electricity, to assess whether transport fuel production would be commercially attractive to operators (Section 4). The broader benefits of using biogas to produce transport fuels in terms of meeting 2020 Renewable Energy Directive targets, and carbon targets are assessed in Section 5. Finally, given the evidence on the commercial attractiveness of producing transport fuels and an assessment of the potential future biogas resource, an assessment is made of the potential increase in the supply of biomethane to the transport sector (Section 6).

2 Producing biomethane for transport from biogas

This study considers two sources of biomethane, derived from biogas produced from waste feedstocks:

- biogas (landfill gas) produced from the decomposition of waste in landfill sites; and
- biogas produced from anaerobic digestion of organic waste material such as food wastes, animal wastes and sewage sludge in dedicated digesters.

Under the RTFO, biomethane produced from waste feedstocks is 'double counted' i.e. it is eligible for double the number of RTFC certificates available to biomethane produced from non-waste feedstocks e.g. from the anaerobic digestion of energy crops[4]. This study focusses on the production of biomethane from waste feedstocks, as the higher level of income available from RTFCs due to this 'double counting' means that these production routes are the most likely to be economically viable. In addition, pending the conclusion of European Commission negotiations on factors to account for greenhouse gas emissions caused by indirect land use change (ILUC), it is possible that the greenhouse gas savings attributable to biogas produced from anaerobic digestion of energy crops may be reduced.

Biogas produced from landfill typically contains 50% methane and 50% carbon dioxide (CO_2) and a number of trace gases. To be suitable for use as a transport fuel, the biogas must be upgraded to biomethane, which involves removing some of the trace gases and the carbon dioxide. A number of technologies (membrane separation, chemical scrubbing, water scrubbing and pressure swing adsorption) can be used to remove CO_2. Biogas produced from the anaerobic digestion of organic material typically has a higher methane content (60%) but must go through the same upgrading process. The biomethane produced may be supplied as transport fuel, as either liquefied biomethane (LBM) or compressed biomethane (CBM). Biomethane can deliver substantial greenhouse gas savings compared to both the use of petrol and diesel and conventional gaseous fuels (Box 2.1).

Box 2.1 Greenhouse gas savings from use of biomethane

The greenhouse gas emissions associated with production of biomethane from waste feedstocks, and the savings achieved from using biomethane in different vehicles, were examined in detail in a previous study on the use of gaseous fuels in transport (Ricardo-AEA, 2014). The study found that emissions associated with the production, dispensing and use of biomethane in vehicles were between 74% and 88% lower than those associated with conventional gaseous fuels, compressed natural gas (CNG) and liquefied natural gas (LNG) (**Error! Reference source not found.**). Compared to using petrol and diesel in vehicles, the tudy found that biomethane delivers greenhouse gas savings of between 60 and 90%.

Table 2.1 Comparison of emissions from use of biomethane and conventional gaseous fuels

	Biomethane [1] (kg CO_2 eq/GJ)	Conventional gaseous fuels[1] (kg CO_2 eq/GJ)	% saving in GHG emissions
CBM from AD	18 to 19	67 to 69	74%
CBM from landfill	8 to 9	67 to 69	88%
LBM from AD	19	75	74%
LBM from landfill	10	75	87%

(1) Excluding methane emissions occurring during use of (bio) methane in vehicle as these are vehicle dependent. They will however be identical from use of biomethane or conventional fossil fuel

[4] Energy crops e.g. maize, or maize silage may be used as the sole feedstock of an AD plant, or added to other waste feedstocks in order to improve biogas production rates and 'smooth' out any fluctuations in the supply of waste feedstocks.

Potential routes for converting biogas into a transport fuel are summarised below together with an indication of their suitability for use at landfill sites or anaerobic digestion plants. In the case of injection to the grid, the gas grid is used as the storage and transport medium for the biomethane, with dispensing stations extracting gas from the grid and compressing it to refuel vehicles. Under the present RTFO legislation, biomethane transported via the gas grid would not qualify for RTFCs. However, such routes are included in the study, to examine whether potential supply would be increased under a hypothetical policy scenario where policy is changed to allow biomethane transported via the gas grid to qualify for RTFCs.

2.1 Liquefaction to LBM

After upgrading, the biomethane is converted to a liquid via a cooling process and stored in large cryogenic insulated tanks, prior to transportation by road tanker to the dispensing point. This process is already implemented in the UK, at the Albury landfill site by GasRec. The smallest liquefaction plant available is typically designed to produce about 20 tonnes per day of liquefied biomethane, but can be operated at lower throughput (down to 10 tonnes per day). Liquefaction plants have high capital costs (about £4M), so running at as close to the design capacity as possible is important in maximising the cost efficiency of the liquefaction process. It also reduces energy (electricity) requirements and fugitive losses of biomethane per tonne of LBM produced, so reducing the greenhouse gas emissions associated with production of the LBM.

Production of 20 tonnes/day of LBM requires about 2300 m^3/hr of biogas production from a landfill site, or 1900 m^3/hr of biogas production from an AD plant. Liquefaction is therefore most suited to large landfill sites with high biogas production, and large AD plants. As LBM is transported by road to the dispensing station, there is no restriction on the location of the site.

2.2 Compression to CBM

The biomethane produced after upgrading can be dispensed as CBM either by:

1) Using it to directly supply a dispensing station on the site. The biomethane from the upgrading plant is compressed to high pressure (250 bar) and stored ready for dispensing at a filling station point. The high pressure storage enables transfer of CBM to the vehicle fuel tank.
2) Compressing the gas into a trailer which is then taken by road to a dispensing station. At the dispensing station, the trailer also acts as a storage facility. CBM is transferred at high pressure (250 bar) from the trailer directly into the vehicle fuel tank by way of a filling point.

A typical size for such plant might be 10 tonnes/day. In the case of an on-site filling station, the main restriction is likely to be location of the site – particularly for commercial vehicles, operators will not wish to make detours to refuel and dispensing stations need to be close to main trunk routes or depots. This means that this option is unlikely to be suitable for landfill sites. A variation on option 1 above, is rather than utilising all of the biogas output for transport fuel production to divert only a small amount of the biogas produced to a small upgrading plant, and to use this in a smaller dispensing station which services only a small number of vehicles. These could be located in depots close to the anaerobic digestion plant, or be vehicles associated with delivery of waste to the plant. This option could be particularly suitable for AD plant at waste water treatment plants which are treating sewage sludge. Such plant are often located on the periphery of urban areas, and may have vehicle fleets located on site.

The location of the biogas production site is not an issue if the biomethane is transported by road to the dispensing station. In this instance, a round trip of 100 km is considered economic from the biogas production site to the CBM dispensing station. The minimum size is considered to be in the order of 10 tonnes/day. There are different options to transport and store the CBM; a traditional trailer constructed of steel can carry around 5 tonnes of CBM, of which approximately 4 tonnes can be delivered under sufficient pressure at the dispensing site (assuming no use of a pump). This equates to just over 2 HGV trips per day. A lightweight composite trailer is more costly to purchase but can hold approximately 10 tonnes of CBM of which 8 tonnes can be delivered at pressure at the dispensing site. This equates to just over one HGV trip per day. The choice of trailer will be dependent on the most economic choice for the development. Road transport of compressed gas is already being used with natural gas, at the Crewe virtual pipeline filling point, where natural gas is compressed and transported in trailers for delivery to customers located off-grid'.

2.3 Injection to grid

At present, for the purpose of the Renewable Transport Fuels Obligation (RTFO), biomethane can only be regarded as a transport fuel (and receive renewable transport certificates) if it is directly supplied to the vehicle. Injection of biomethane in to the gas grid, to allow the use of the gas grid to transport the biomethane to the filling system, using a tracking system such as 'Green Gas Certificates' to provide a link between supply and dispensing mechanism, does not at present qualify. However, as discussed in Section 1, DfT wishes to explore whether an additional supply of biomethane could be available if policies were changed to allow gas injected to the grid to qualify, so this option is included in the study.

Injection to the grid requires that once biogas has been upgraded to biomethane, it is further conditioned, metered and compressed before injection. Conditioning includes odorisation, and adjustment of the calorific value by the addition of propane to meet gas quality standards.

There are several AD plants which are currently injecting gas to the grid (encouraged by incentives available under the Renewable Heat Incentive), and several more are planned. As the technology has developed, the minimum size at which conditioning and injection of the gas is considered viable has fallen to about 5 tonnes/day of biomethane (about 3 MW of biogas output). However, gas to grid injection projects coming forward under the Renewable Heat Incentive (RHI) are typically larger than this with an average size of about 7.5 MW of biogas output.

Apart from size, the main limitation for this route is access to a suitable gas grid injection point. Pipeline costs are high (approximately £1M per km, dependent on the pipeline route) and so a suitable injection point needs to be available close (within five hundred metres) to the biogas source. This means that this option is unlikely to be suitable for landfill sites, which are typically located in more rural areas, and will not be suitable for all AD plant.

A concept which can be used for sites where direct injection to the grid is not possible, is the 'virtual pipeline'. In this concept, gas is compressed into storage vessels on trailers, which are then driven to a suitable gas grid injection point. This could be a shared facility servicing several biogas sources. The transport of CBM to the shared injection point would be similar to that described above for the CBM dispensing station located away from the biogas production source, where either steel or composite trailers can be used. In addition, for injecting into the gas main from the tanker, a pressure reducing system would be needed to reduce the pressure from 250 bar to the pressure of the gas pipeline. This concept could be used with both AD plant and landfill sites, and there are plans to use such a virtual pipeline system at Crouchlands Farm AD plant.

2.4 Production routes chosen for evaluation

From an assessment of the technical characteristics of the production options, and in consultation with stakeholders, the production options shown in Table 2.2 were chosen for evaluation of economic viability. For LBM production the output size represents the minimum that is likely to be economically viable. For gas to grid routes, the size is above the technically feasible minimum, and more representative of gas to grid projects coming forward under the RHI.

Table 2.2 Production routes chosen for evaluation

Biogas source	Production route	Output (tonnes/day of biomethane)
Policy Scenario 1 (existing policy and legislation)		
Existing landfill site	Liquefaction to LBM	20
New anaerobic digestion plant with waste feedstock	Liquefaction to LBM	20
New anaerobic digestion plant with waste feedstock	CBM transported by road to dispensing station	10
Existing anaerobic digestion plant treating sewage sludge	Liquefaction to LBM	20
Existing anaerobic digestion plant treating sewage sludge	All of biogas goes to onsite station dispensing CBM	10
Existing anaerobic digestion plant treating sewage sludge	Some of biogas goes to onsite station dispensing CBM	0.5
Additional routes considered in policy scenario 2 (RTFCs extended to biomethane injected to grid)		
Existing landfill site	Injection to gas grid via 'virtual pipeline'	10
New anaerobic digestion plant with waste feedstock	Injection to gas grid on site	10
New anaerobic digestion plant with waste feedstock	Injection to gas grid via 'virtual pipeline'	10

3 Biogas Resource

3.1 Landfill gas

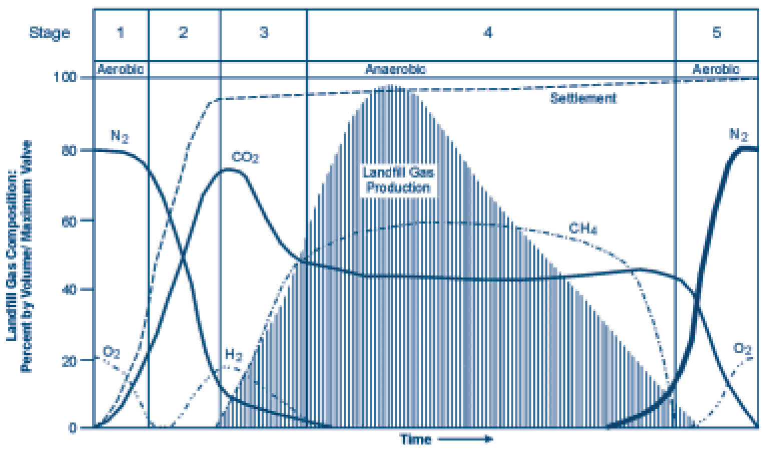
Landfill gas arises from the decomposition of biodegradable waste within the landfill mass. As indicated in Figure 3.1, initially matter is broken down in aerobic conditions producing carbon dioxide whilst consuming available oxygen, then when oxygen levels have been depleted anaerobic conditions arise and hydrolysis and acetogenic processes take over (producing carbon dioxide and displacing nitrogen). The next phases are defined as the balance into and then process of methanogenesis (methane producing bacterial breakdown) producing methane. Then the substrate required for methanogenesis becomes depleted (after around 30 years) and methane and carbon dioxide production reduce to minimal levels. As the landfill meets maturity in the methanogenic phase, typical gas levels (as set out in Table 3.1) are observed which then drop off as indicated in Figure 3.1. Substantial landfill gas production normally occurs within a couple of years of depositing waste in the landfill.

Table 3.1 Typical range of bulk components in landfill gas[5]

Bulk landfill gas	Typical value (% v/v)	Observed maximum (% v/v)
Methane	63.8	88.0
Carbon dioxide	33.6	89.3
Oxygen	0.16	20.9#
Nitrogen	2.4	87.0#
Hydrogen	0.05	21.1
Water vapour (typical % w/w, 25˚C)	1.8	4.0

Note: # derived entirely from the atmosphere.

Figure 3.1 Indication of the fluctuations in landfill gas composition over the lifetime of a site[6]



Factors that influence landfill gas production rates include rainfall infiltration, the percentages of organic waste in the waste mix, the geological situation of the site and the seasonal atmospheric temperature

[5] Environment Agency (2004), *'Guidance on the management of landfill gas, LFTGN 03'*, Table 6.1 pp51, 2004.
[6] Environment Agency (2004), *'Guidance on the management of landfill gas, LFTGN 03'*, Figure 6.1 pp56, 2004.

and pressure conditions (high pressure systems suppress gas release, low pressure systems encourage gas release). Landfill gas emission and extraction rates are influenced by the design and maintenance of the landfill gas extraction system affecting the effectiveness of gas capture and then the use of flares and/or engines for burning off or utilising the gas collected. A certain proportion will also be released to atmosphere, the extent of which depends on the nature of final cover and the age and maintenance of that cover and other infrastructure or post-closure land uses.

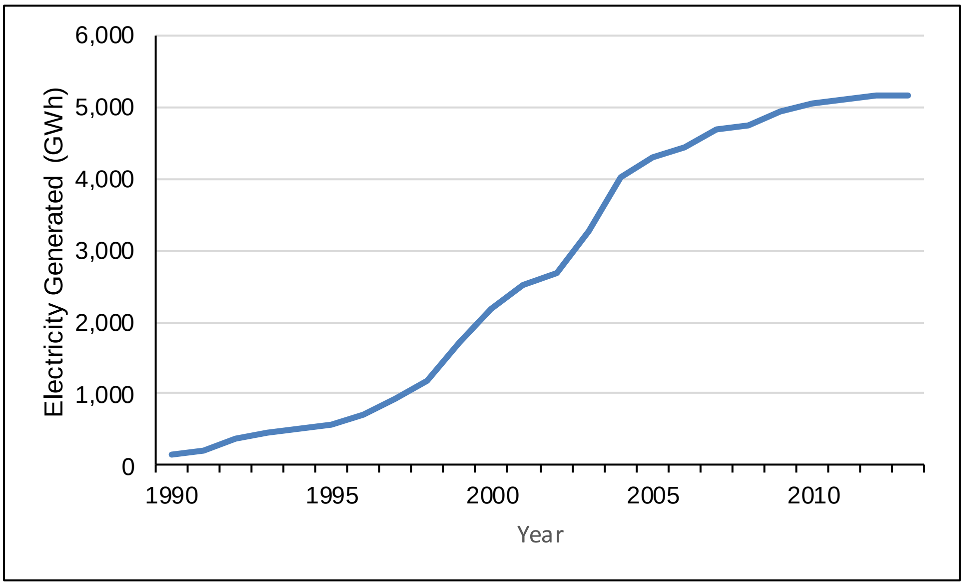
Landfill gas also contains a proportion of hydrogen and oxygen which originate from the atmosphere and are pulled into the site from processes of biodegradation and poor surface cover (and often through over-extraction).

Landfill gas also contains around 550 trace compounds which, among others, include compounds such as hydrogen sulphide and siloxanes that can be harmful to landfill infrastructure (reducing gas control effectiveness) and to gas utilisation equipment (such as engines). These must be removed before the gas can be burnt and impacts upon the choice of materials and components in infrastructure and the cost of installation and maintenance to reduce corrosion. Carbon dioxide dissolved in water can also produce acidic condensate, damaging pipework.

3.1.1 Current resource and utilisation

All operational landfill sites are required to collect and manage landfill gas produced at the site. Typically this is collected and combusted in a gas engine to generate electricity; landfill gas which cannot go to a gas engine is flared. Electricity generated from landfill gas has been encouraged under the Renewables Obligation, and has grown steadily since 1990 (Figure 3.2). Generation occurs on over 300 sites and 18.6 PJ (5,169 GWh) of electricity was produced from about 61 PJ of landfill gas in 2013 (DECC, 2014a)[7]. This was approximately 10% of the UK's renewable electricity supply in 2013. In contrast, only 0.1 PJ of landfill gas (at one site) was converted to LBM (DECC, 2014a).

Figure 3.2 Electricity generation from landfill gas



Source: DECC, 2014a

[7] This assumes an efficiency for landfill gas engines of 30%. The Digest of UK Energy Statistics (DEC, 2014) assumes a much lower efficiency for gas engines (of 26%) in calculating the gas quantity necessary to produce this quantity of electricity, whereas the UK Greenhouse Gas Inventory assumes an efficiency for landfill gas engines of 36% (based on Golders Associates, 2014). In the calculation of supply in this study, an average of these two values of 30% is used.

3.1.2 Future potential resource

As landfill gas is generated from waste which is landfilled now for a period of several years, the future supply of landfill gas is determined both by the quantities of biodegradable waste which have been landfilled historically as well as future quantities of waste which have yet to be landfilled. The Landfill Directive sets a target for the UK that biodegradable municipal waste (BMW) landfilled in 2020 should be 35% of the BMW landfilled in 1995[8]. Quantities of waste going to landfill have been declining rapidly, as waste is managed via other options such as anaerobic digestion, composting, and combustion in energy from waste plant, and BMW to landfill in 2012 was already only 29% of that landfilled in 1995 (Defra, 2014). Assessment by Defra of future quantities of BMW to landfill, given other waste management plant which are under development, suggest that quantities of BMW landfilled in 2020 could fall by 60% between 2012 and 2020 (Defra, 2014a). There are currently no targets for policies on the quantities of waste which may be landfilled post 2020, but it seems likely that they will be more stringent. The European Commission suggested in the summer of 2014, as part of its move towards a zero waste, circular economy that landfilling of all recyclable waste shall be prevented by 2025, and that Member States should endeavor to virtually eliminate landfill by 2030. These proposals are currently being reformulated, but revised proposals are still likely to seek to restrict future landfilling of waste beyond the levels set out in the landfill directive.

The most recent estimate of the future landfill gas resource found in the literature was by AEA for DECC in 2010, as part of a study on the UK's bioenergy resource. This estimated that the landfill gas supply would fall from 141 PJ in 2010, to 86 PJ in 2020 and 42 PJ in 2030[9], based on 25% of waste being landfilled in 2020, and 20% in 2025 and thereafter. As discussed above, the fall in biodegradable waste to landfill looks set to be more rapid than this, and others have suggested a more rapid decline in landfill gas supply is likely. For example, the Renewable Energy Association and the Environmental Services Association, in their response to a consultation on the inclusion of heat produced from landfill gas in the Renewable Heat Incentive (REA and ESA, 2012) estimated that the quantity of heat available (mainly recovered from gas engines at landfill sites used for electricity production) would fall by about 90% between 2012 and 2020, suggesting a rapid decline in the amount of landfill gas captured. However other sources foresee a slower decline. For example the National Grid, in work to support the electricity market reforms (National Grid, 2013) estimated potential production of electricity from landfill gas in 2020 to still be about 80% of generation from landfill gas in 2013.

It is clear that in the light of current developments in waste management, the estimates of future biogas supply by AEA in 2010 are likely to be too high, as quantities of waste landfilled have fallen more rapidly than was foreseen at the time of the projection. A revised forecast of the potential supply is shown below, based on the decline in landfill gas production occurring five years earlier than in the original forecast to reflect the acceleration in diversion of waste from landfill.

This potential supply is the total amount of landfill gas which could be captured at sites. In reality, the actual quantity captured and utilised for electricity generation is significantly less than this. In 2013, 5169 GWh of electricity were produced from landfill gas (DECC, 2014a), equating to the use of 61 PJ of landfill gas[10]. This is assumed to be a realistic estimate of the quantity of landfill gas that could be diverted into transport, and a similar proportion of the potential supply identified is assumed to be available in future years, giving a 'feasible' supply that could be made available for transport fuel use (if economic) of 29 PJ in 2020 and 6 PJ in 2030.

It seems probable that most of this landfill gas supply will be at existing landfill sites. Due to the decline in waste going to landfill, there is several years' capacity at existing sites, and the industry reports that new sites are unlikely to open unless there are regional shortages. Only thirteen potential new sites

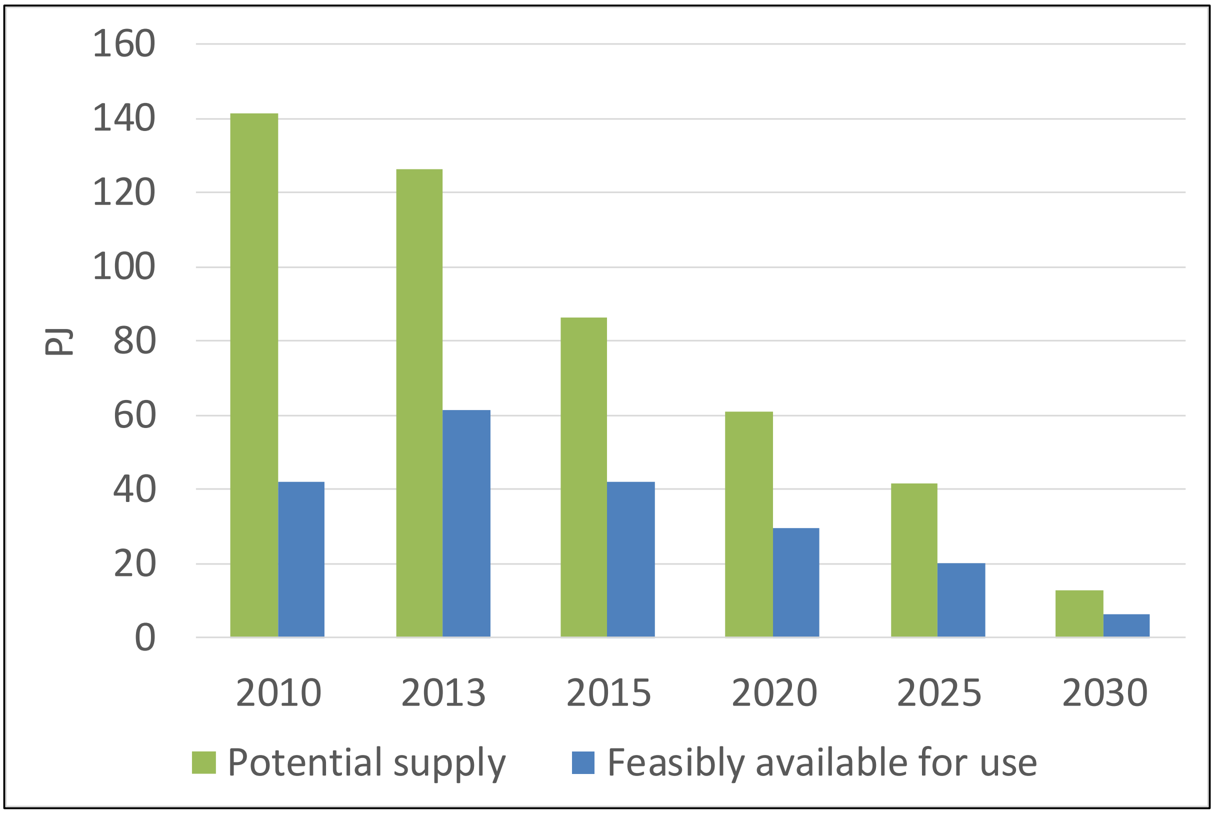
[8] There will be additional sources of biodegradable waste to landfill from commercial and industrial waste. Some commercial waste does enter the municipal waste stream, and the remainder is generally managed in the same way as municipal waste. It can therefore be reasonably assumed that quantities of commercial

[9] Based on available resource at £10//GJ with easy and medium constraints overcome.

[10] This assumes an efficiency for landfill gas engines of 30%. The Digest of UK Energy Statistics (DEC, 2014)assumes a much lower efficiency for gas engines (of 26%) in calculating the gas quantity necessary to produce this quantity of electricity, whereas the UK Greenhouse Gas Inventory assumes an efficiency for landfill gas engines of 36% (based on Golders Associates, 2014). In the calculation of supply in this study, an average of these two values of 30% is used.

are listed in the Renewable Energy Planning Database; some are now operational but the status of others could not be confirmed.

Figure 3.3 Landfill Gas Resource



3.1.3 Options for producing biomethane from landfill gas

Due to their space requirements and the nature of their operations, many landfill sites are located in rural areas or in brownfield areas. As discussed in Section 2, this means that they are unlikely to be located close to the gas grid to allow direct injection of upgraded gas to the grid, or location of a filling station on the site. The most likely production routes suitable for landfills are therefore considered to be liquefaction or injection to the grid via a virtual pipeline.

Data was made available to the study by the Environment Agency and Scottish Environmental Protection Agency on the volumes of gas flared and utilised in gas engines at landfill sites. The data covers all sites still receiving waste, but not all older closed sites[11]. Such sites are however unlikely to be of interest for the supply of biomethane due to their declining gas generation profile. The variation in total volume of landfill gas combusted (either in flaring or gas engines) in 2013 at sites in England, Wales and Scotland covered by the data is shown in Figure 3.4. The data can also be used to identify the number of sites with a gas output in 2013 suitable for the production routes discussed above. It is assumed for liquefaction options, sites should have enough landfill gas generation to produce 20 tonnes/day of biomethane. Gas grid injection, if carried out using a virtual pipeline concept, could be done at a range of sizes; based on experience in the AD sector of current and proposed plants, it is

[11] The data only includes those sites within the current environmental permitting regime (EPR) that are obliged to report annual volumes of gas flared. Closed landfills (i.e. those no longer receiving waste) that were not transferred to the EPR are unlikely to be of interest as they are older sites, which will have a declining gas generation profile.

considered that while a desirable size (economically) might be 10 tonnes/day of biomethane, a minimum economic size might be 7 tonnes/day.

Figure 3.4 Volume of landfill gas utilised for generation or flared

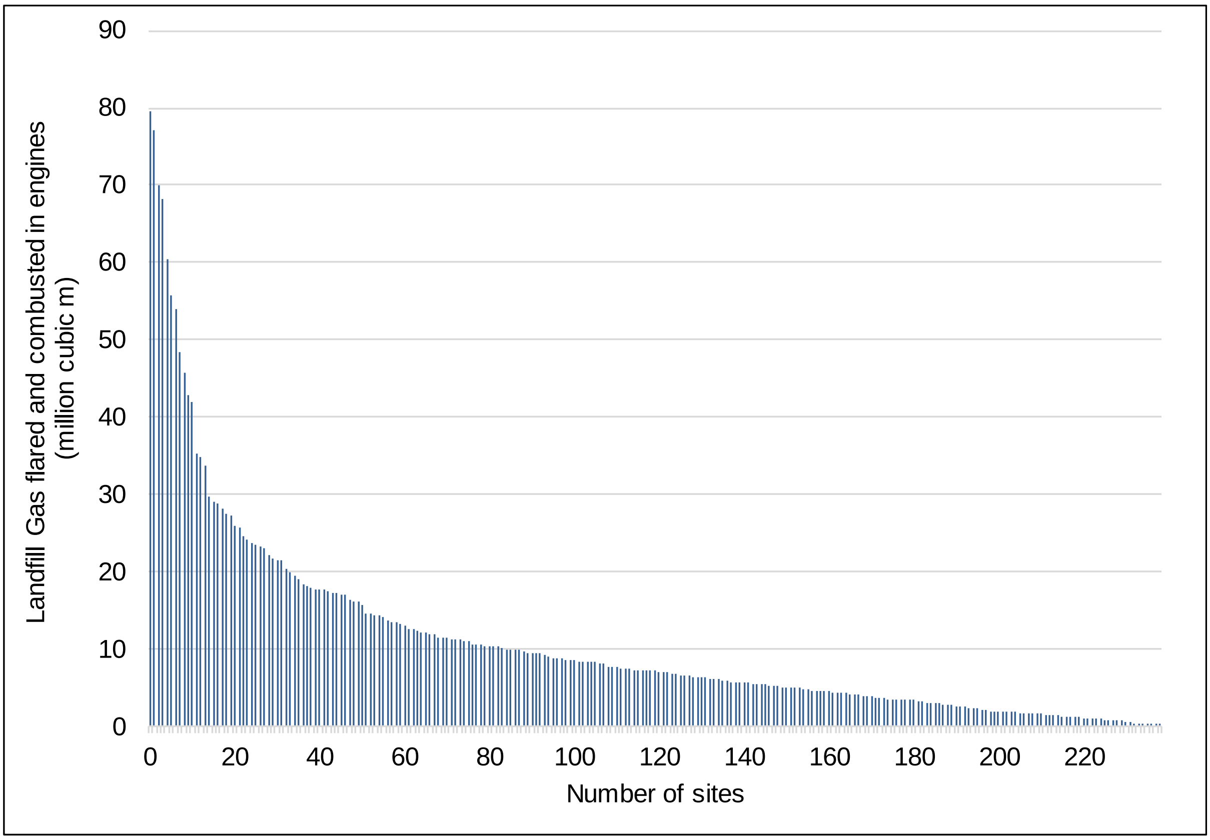


Table 3.2 Number of sites with specified biogas generation (2013)

Biomethane output (tonnes/day)	Biomethane output (kt/year)[1]	Required biogas generation (approximate) (million m^3/year)	Number of sites with required biogas generation
40	13.9	40	11
20	6.9	20	34
10	3.5	10	84
7	2.4	7	121

[1] Assuming 95% availability

3.2 Biogas from anaerobic digestion

3.2.1 Current resource and utilisation

The use of biogas from AD is shown in Table 3.3. Most existing installations use sewage sludge or food or animal wastes as a feedstock, and combust the biogas in gas engines to produce electricity, typically recovering heat for use in the AD process or in some cases for other uses (such as heating of buildings as well). In the future, upgrading and injection into the grid, encouraged by the Renewable Heat Incentive, is likely to increase. In 2012 there were two AD plant (both waste based) injecting 0.03PJ (9

GWh) of biomethane into the grid[12]; this was 0.001% of total gas supply (DECC, 2014a). In 2014 there were six operational biomethane plants in the UK, with a combined capacity to inject 1,700 m^3/hr biomethane into the gas grid (Green Gas Grids, 2014). RHI statistics show that in September 2014, three biomethane installations were receiving payment, and had generated a total of 0.266 PJ up to September 2014, with 0.24 PJ of this being generated between September 2013 and September 2014 (DECC 2014). Several of these new installations are using energy crops as a feedstock, either in combination with animal and food wastes or as the sole feedstock.

Table 3.3 Use of biogas from AD in 2013

	Total biogas supply (PJ)	Used for electricity generation (PJ)	Electricity produced (PJ)	Used for heat generation (PJ)	Heat produced (PJ)
Anaerobic digestion of wastes and energy crops	10.5	9.7	2.5	0.8	0.5
Sewage sludge digestion	13.3	10.5	2.7	2.9	2.0
Total from AD	23.8	20.2	5.3	3.6	2.5

Source: DECC, 2014a

3.2.2 Future potential resource

Table 3.4 summarises estimates of the total future biogas resource from anaerobic digestion of waste feedstocks (regardless of end use). Values from E4Tech (2013) are for the total potential resource i.e. not allowing for competing uses of feedstocks. The study by AEA (2010) estimated both the total available resource and the accessible resource. The accessible resource estimates allow for competing uses of the resource, barriers to development of the resource, and the influence of price on developing the resource. The key barriers to the development of anaerobic digestion identified in the study are summarised in Table 3.5. Since the study there have been a number of policy developments (e.g. introduction of Feed in Tariffs for electricity produced from AD plants and Renewable Heat Incentive payments for heat rom biogas and biomethane injected to the grid) and actions undertaken as a result of the DECC/DEFRA Anaerobic Digestion Strategy and Action Plan (DEFRA, 2011; DEFRA, 2013) which have begun to address some of these barriers.

The potential for biogas from food waste and animal wastes is large: up to 105 PJ in 2020 compared with current biogas production of 10 PJ in 2013. However, when barriers to development are considered, a more likely potential future biogas resource from these feedstocks is 64 PJ in 2020 and 68 PJ in 2030, assuming that all but the most difficult barriers to deployment are overcome.

Forecasts from the Anaerobic Digestion and Biogas Association (ADBA) in their Anaerobic Digestion Road Map of 2012 are more optimistic, suggesting that biogas production could be 76 PJ in 2020 and 108 PJ in 2020, with the total resource (based on feedstock availability) being 144 PJ. However other estimates are more pessimistic, with the DECC/DEFRA Anaerobic Digestion Strategy and Action Plan (DEFRA, 2011) concluded that *"based on current information available, and assuming that the real and perceived barriers are overcome through the actions undertaken, an estimated potential for AD deployment for heat and electricity could reach between 3 and 5 TWh by 2020."* This 3 to 5 TWh (10 to 18PJ) of electricity production is equivalent to about 31 to 51 PJ of biogas production.

In the longer term, on the basis of current policy and payments available under the RHI, it is likely that biomethane injected into the gas grid is likely to increase as a proportion of total biogas generated. For example ADBA suggest that grid injection could account for at least 50% of total biogas generated by 2030 (ADBA 2012).

[12] Based on information from CNG services

Recently concerns have been raised about the availability of food waste, since segregated food waste collections are progressing more slowly than hoped. If this trend continues it would constrain the availability of waste food feedstock and thus AD plant development further than previously modelled. Eunomia estimates that 3.5 million tonnes food waste (13PJ) is the most that will be available in 2024 under assumptions of current policies (Eunomia 2014). This is similar to the Ricardo-AEA assumption of low biogas price and high levels of constraints, which gives 13 PJ in 2015 rising to 20 PJ in 2020. Such concerns over the availability of food wastes are one of the reasons for the interest in using energy crops as an additional feedstock.

The available resource from sewage sludge is shown to be fairly constant to 2030. This is because around 66% is already treated by AD, with a substantial current electricity production of 13 PJ (DUKES 2014)[13]. However, water companies are interested in converting to biomethane for grid injection because this enables better utilisation of the gas produced, particularly at times of the year when there is a low site heat requirement and they find electricity grid connections restrictive (Severn Trent 2013). It is also possible that the biogas potential from sewage AD treatment could increase if new efficient plant and advanced pre-treatment techniques are introduced (Severn Wye 2014). A recent review suggests yield increase of 10% to 80% depending on pre-treatment (Hanjie 2010).

Table 3.4 Estimates of future biomethane resource from anaerobic digestion (all units in PJ)

	Potential resource			Accessible resource		Baseline Scenario	Eunomia current policies	Resource which could be developed
	E4 Tech (2013)	National Grid (2009)	AEA (2010)	AEA (2010)	AEA (2010)	National Grid (2009)	Eunomia (2014)	Defra (2011)
	2020	2020	2020	2020	2030	2020	2024	2020
Food waste	155	47	80	47	49	26	13	-
Animal manures	43	18	25	17	19	9	-	-
Sewage sludge	10	22	15	13	14	10	-	-
Total from AD	**208**	**87**	**120**	**77**	**82**	**45**	**-**	**31 to 51**

Notes:
(1) Estimate is for biogas which could be produced from the total biodegradable content of MSW and commercial and industrial waste, so includes fractions such as paper as well as food waste.

(2) Study estimated resource which would be available under different price scenarios and different levels of effort are made to overcome barriers. Estimates reported here are for a price of £10/GJ assuming easy and medium barriers/constraints are overcome.

[13] The remainder goes to incineration or is spread to farmland

Table 3.5 Key barriers to development of biogas resource identifies in AEA (2010)

	Constraints that are easy to overcome	Constraints of medium difficulty to overcome	Constraints of high difficulty to overcome
Food waste	• Perception of risks and uncertainty, linked to bankability of AD projects. • Lack of market experience (would be overcome by successful demonstration of schemes) • Lack of standards • Planning and licensing requirements • Lack of processing facilities for wastes (Need to facilitate separate collection of food waste)	• Perception of market complexity (markets perceived as complex by financiers, particularly issues related to grid connection) • Difficulty in obtaining project finance (high return expected due to lack of experience with AD) • Regulatory and policy uncertainty (NIMBY issues). • Integration into energy supply markets (current use of biogas restricted by access to heat demands and energy markets).	• Competing cost-related feedstock uses (particularly where waste contracts in place already) • Returns insufficient (needs generous gate fee, energy return not sufficient). • Regulatory and policy uncertainty (Quality standards for after use of residue)
Animal waste	• Perception of risks and uncertainty	• Competing alternatives for disposal (e.g. management of waste on farm without AD) • Lack of collection and storage facilities (storage facility for livestock slurries) • Lack of transport infrastructure (road access needs to be sufficient and tankers must not transmit pathogens).	• Requirement for substantial upfront investment. • Difficulty in obtaining project finance (low returns) • Location of feedstock compared with fuel demand (farmers cannot use all the heat generally produced from CHP) • For remote farms: integration into energy supply markets.
Sewage sludge	• Returns insufficient (for all sewage sludge) • Perceptions of complexity of market (although there is some experience of use at sewage treatment plants) • Regulatory and policy uncertainty (changes due on Water Framework and Nitrate Directives)	• Location of feedstock compared with fuel demand (sewage sludge produced at remote locations where AD treatment may not be economic). • Meeting current and future sustainability standards (and sludge matrix)	• Cash flow issues (low payback on investment, restrictions placed on investment by OFWAT). • Lack of transport infrastructure (for remote and small quantities of sewage sludge).

3.2.3 Suitability of resource for producing biomethane for transport

Compared to landfill sites, a broader range of options is available for production of transport fuels from anaerobic digestion. Suitable options are considered to include liquefaction, direct injection to grid, injection to grid via a virtual pipeline, and upgrading to biomethane which is supplied via an onsite fuelling station, or compressed into containers which are then taken by road to a dispensing station. In particular it is considered that existing AD plants treating sludge may be suitable sites for onsite filling stations, as they are often located on the edge of industrial areas, or the urban periphery, and often have a stream of vehicles visiting the site.

Data on the size of current AD plants[14] which are receiving either Feed in Tariff (FIT) payments or Renewable Obligation Certificates (ROCs) is shown in Table 3.6. For comparison, an AD plant with a capacity of 4 MWe will have a biomethane throughput of about 20 tonnes/day (i.e. is of a suitable size for liquefaction). Of the sewage sludge AD plant receiving ROCs, six are greater than 4 MWe and 18 are greater than 2MWe. Of the other AD plant, none are greater than 4MWe and only two are greater than 2MWe.

Table 3.6 Size distribution of existing AD plant

	Size Range (MW)	No of plant	Average size	Total capacity (MW)
Receive ROCS (AD of sewage sludge)	0.08 to 12.1	110	1.1	126
Receive ROCS (other AD)	0.09 to 3	24	0.09	19.9
Receive FITS		107		75
Of which	<=250kW	19		2.7
	250-500kW	54		25.8
	500-5MW	34		47.0

[14] Based on data from OFGEM's FIT Installations Statistical Report (https://www.renewablesandchp.ofgem.gov.uk/Public/ReportManager.aspx) and information from OFGEM ROC register (https://www.renewablesandchp.ofgem.gov.uk/)

4 Cost and economic viability

4.1 Cost of producing biomethane

For each of the options identified as potential production routes for biomethane for transport, the costs of the biomethane produced were estimated based on capital and operating costs for the typical plant sizes shown in Table 2.2, together with data on plant characteristics and feedstock costs. These costs are summarised in Appendix 1, and were drawn from a variety of sources including the previous study by Ricardo-AEA (2014) for DfT which examined the costs of using gaseous fuels in transport, the recent consultation by DECC on biomethane grid injection RHI tariff review (DECC 2014, 2014b and 2014c), previous work by SKM Enviros (2010) on biogas production, and evidence from stakeholders.

The cost of producing a transport fuel from biogas is shown in Figures 4.1 to 4.3, for the production of liquefied biomethane, for biomethane injected into the grid (either directly or using a 'virtual pipeline'), and for biomethane supplied as CBM at either an on-site or off-site dispensing station. The figures show the levelised cost of production, i.e. the price that the operator would need to receive to 'break even' assuming a 12% discount rate, if:

a) the operator received no Renewable Transport Fuel Certificates (RTFCs) for the fuel produced, and
b) if RTFCs were received.

For this base case, it is assumed 3.8 RTFCs are received per kg biomethane (as it is derived from waste) and that the certificate price is 10 pence. These prices can be compared to the price (excluding taxes and duty) of the conventional fossil gaseous fuel for which biomethane would be substituting[15]. If the biomethane can be produced at, or below the price of the conventional fossil fuel it substitutes for, then the production of biomethane would be profitable for the plant operator. A discount rate of 12% was agreed with DfT for this initial assessment of production costs, as representative of rates typically required by operators for investment, and to give constancy with other assessments of biogas use. For example, a 12% discount rate was used by DECC in the biomethane grid injection RHI tariff review. In reality, under current policy where RTFCs are traded under a market mechanism and subject to considerable price volatility, the hurdle rate for projects producing biomethane as a transport fuel may be higher than 12%; this is discussed further in Section 4.2.3. In the case of existing landfill gas sites and existing sewage sludge plant only the additional costs of equipment to upgrade the biogas and produce the transport fuel were considered. In the case of new anaerobic digestion plant, the costs of the anaerobic digestion plant were also included. For options utilising landfill gas, a number of variants were considered as the profile of gas generation at individual sites may vary. As discussed in Section 2, the generation of landfill gas from landfilled waste declines over time, and while in a landfill site that is receiving a constant stream of waste, landfill gas generation from the site will remain broadly constant, if the volume of waste landfilled at the site declines, or ceases, due to the site closing than landfill gas generation will start to decline. Four cases are therefore considered, two where enough landfill gas is produced to run plant at full capacity for 8 and 13 years respectively, and two cases where the available landfill gas declines to half its original value over these periods.

Capital and operating costs for the plant, and fuel costs assumed for fossil based gaseous fuels are summarised in Appendix 1.

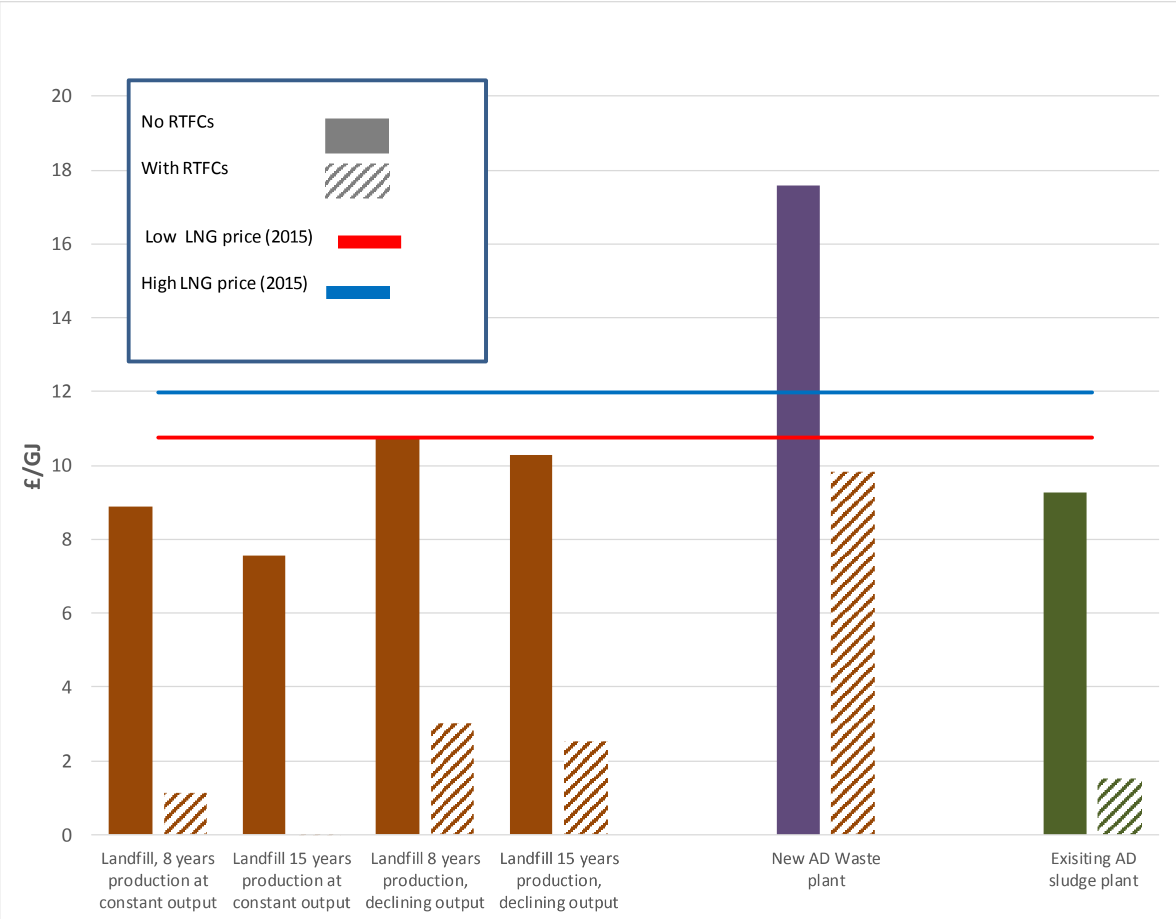
Figure 4.1 shows that the production of LBM at existing landfill sites could be profitable for operators (at a 12% discount rate), even in a 'worst case' of no RTFC payments. The LNG price shown represents a best estimate of the price of LNG as delivered to a dispensing station by road tanker. A range is shown, and is based on a number of sources, including information from stakeholders. With RTFC payments, the production cost is significantly below the lowest LNG price, even in a 'worst case scenario' where LBM production is only viable for 8 years, and throughput declines to 50% of design capacity over that time. For a site where LBM production is possible at the design throughput for 15

[15] These are identical for biomethane and natural gas so can be excluded from the calculation.

years, then RTFC income more than offsets production costs. The production cost of LBM from biogas from anaerobic digestion plant is also lower than the price of delivered LNG.

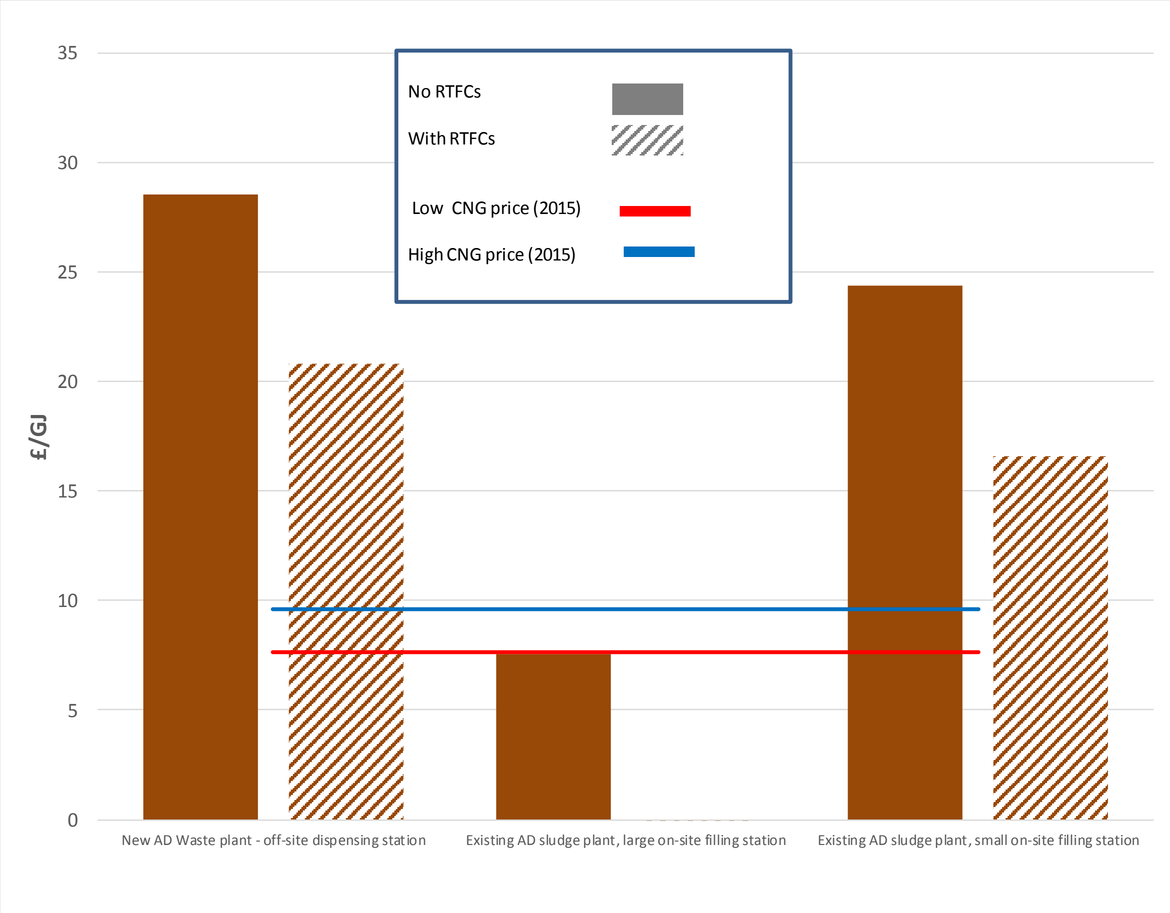
Figure 4.2 shows examples where gas is upgraded to biomethane which is then either dispensed at an on-site filling station, or compressed and delivered by road tanker to an off-site filling station. For a new anaerobic digestion plant, the costs of CBM production, even with RTFC payments, is much higher than the price for the equivalent fossil gaseous fuel – natural gas from the pipeline dispensed at CNG[16]. This is mainly due to the costs of the anaerobic digestion plant, and in the case of an existing AD plant, where the only costs are those of upgrading and compressing the biogas, the production cost is lower than the CNG price.

Figure 4.1 Production cost of LBM (with and without income from RTFCs)



[16] The CNG price is taken as the price of natural gas plus an allowance for the cost of transporting natural gas and dispensing it as CNG

Figure 4.2 Production cost of CBM (with and without income from RTFCs)



In the case of injection of gas to the grid (Figure 4.3), production costs are compared to the cost of natural gas in the grid. For biomethane from upgraded landfill gas, production costs are lower than the natural gas price, at the assumed RTFC price. However, the cost of anaerobic digestion plant means that production of biomethane via this route would not be profitable at current gas prices, even if RTFCs were available for biomethane injected into the grid for transport[17].

RTFCs are traded under a market mechanism, and the price per certificate has varied significantly in the past. A sensitivity analysis was therefore carried out based on the range of prices observed over the last year (of 7 pence to 12 pence per certificate) The results show (Figure 4.4) that for LBM production, production at landfill sites or where there are existing AD plants, could be economic under the full range of RTFC prices considered. Indeed at higher RTFC prices, RTFC income offsets production costs. For new AD plant, if the value of the RTFC fell then production could be uneconomic. In the case of CBM (Figure 4.5), higher RTFC prices are still not sufficient to make production of CBM from a new AD plant viable.

[17] It is assumed that gas for transport would not receive RHI payments and the analysis does not imply that injection of biomethane to the grid which received RHI payments would not be profitable.

Figure 4.3 Production cost of biomethane (with and without income from RTFCs)

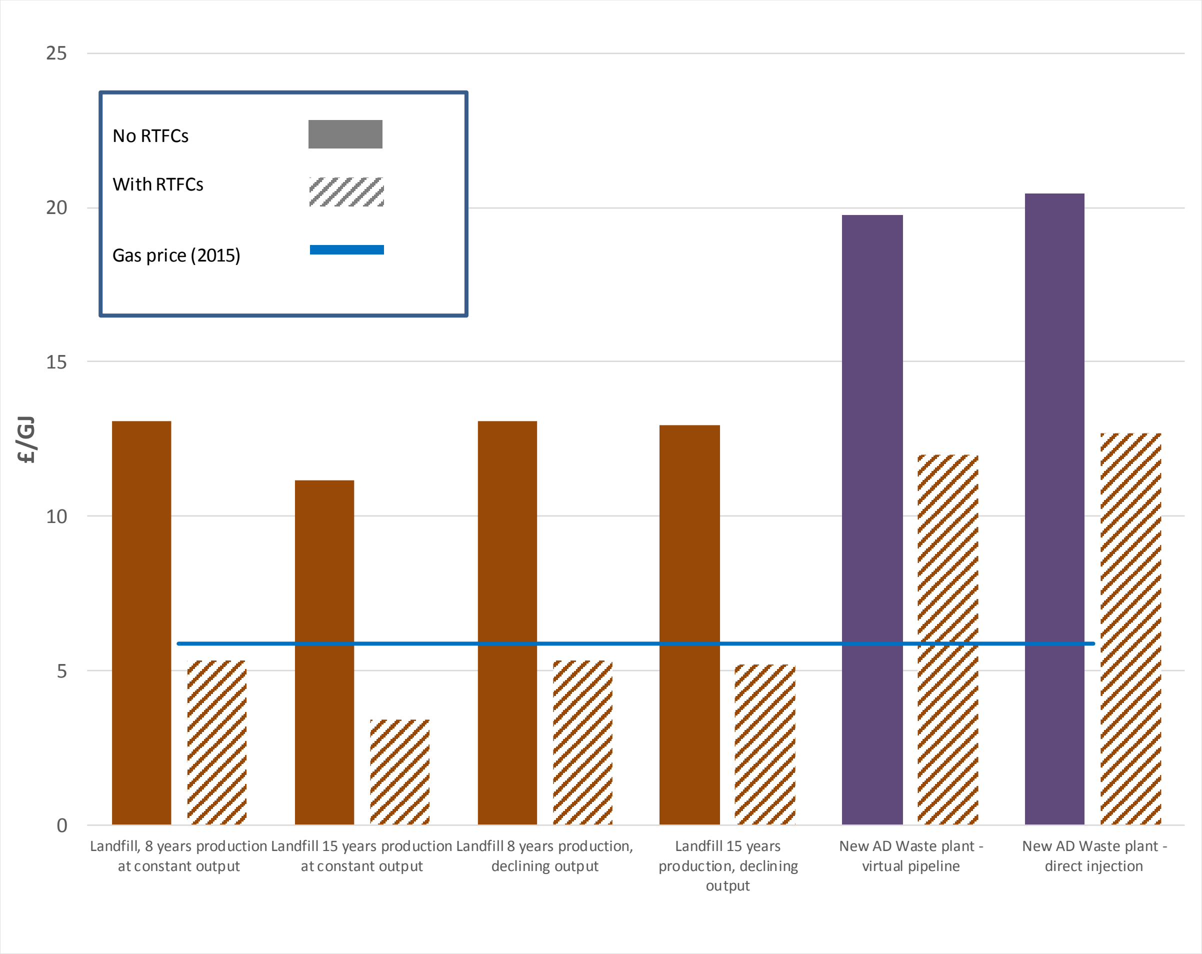


Figure 4.4 Production cost of LBM with income from RTFC (for prices from 7p to 12p per certificate)

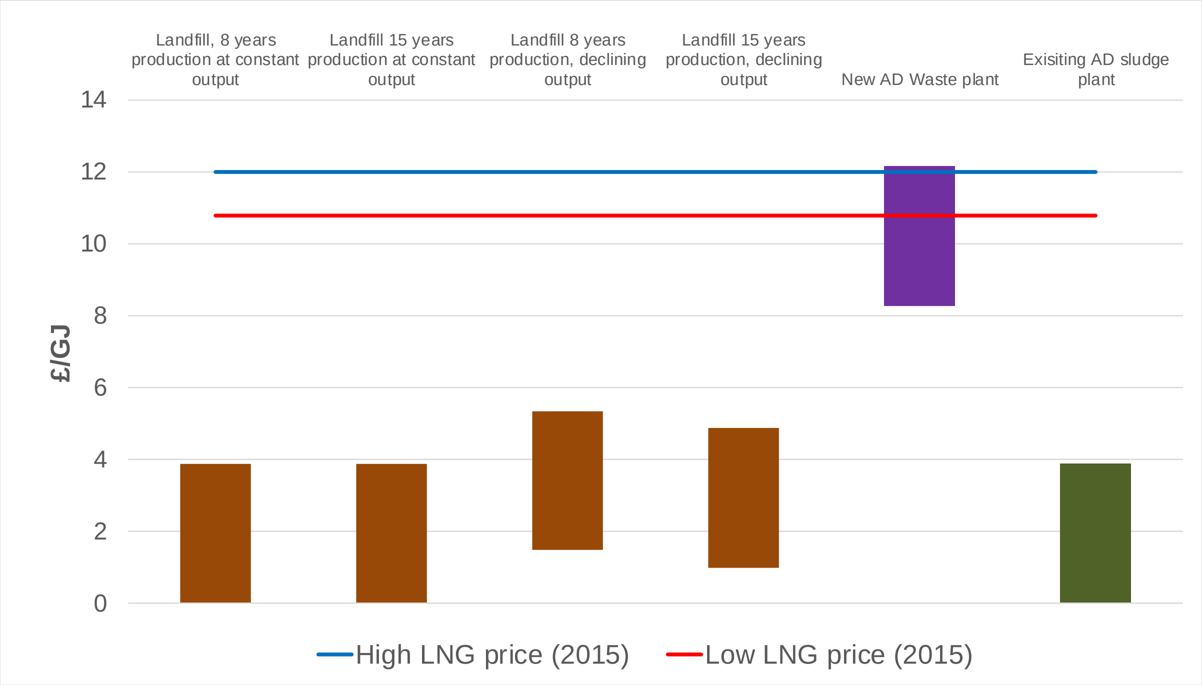


Figure 4.5 Production cost of CBM for range of RTFC prices (7p to 12p per certificate)

Figure 4.6 Production cost of biomethane for range of RTFC prices (7p to 12p per certificate)

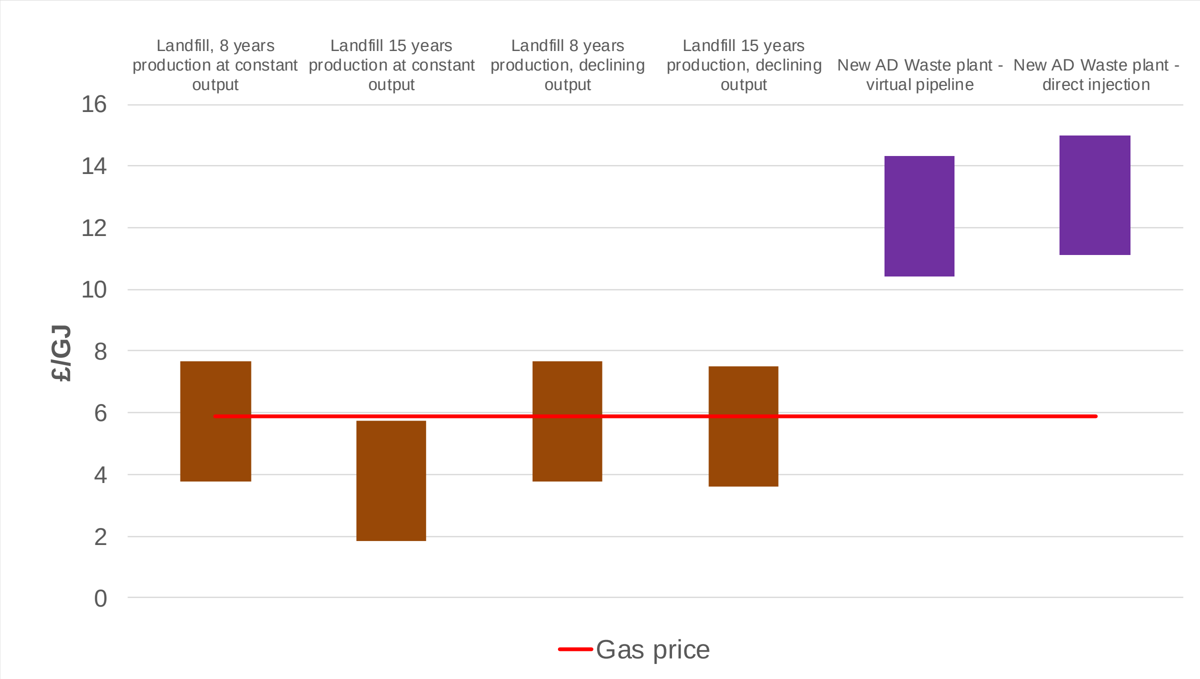


Figure 4.6 indicates that the profitability of injected gas to the grid for transport is sensitive to the RTFC price, and that it could be uneconomic for operators if the RTFC price were to fall. The higher RTFC prices assumed in the sensitivity analysis still do not provide enough income to make biomethane injection from new AD plant economic.

It is possible that operators could be able to sell biomethane at a higher price than the fossil equivalent, in effect receiving a 'green' premium for the gas. Green gas trading and certification schemes have been established to enable this, with certificates trading at a value of about 4 pence/kg. It is also possible that the RTFC price could rise again in the future to levels seen in previous years. A further sensitivity analysis was therefore carried out, assuming that an RTFC price of 18 pence per certificate. At this level of RTFC, all options are profitable, apart from the reduction of biomethane for injection to the grid, or supply as CBM from a new AD plant.

A full set of detailed results is given in Appendix 2.

4.2 Economic viability of producing biomethane for transport

4.2.1 Profitability of transport fuel production options

The profitability of the production of transport fuels from biogas can also be examined by looking at the net present value (NPV) of the operation over its lifetime, with a positive NPV indicating that there will be a return to the investor. The NPV of each of the transport fuel production options examined is given in Table 4.1. It has been calculated assuming that the operator can sell the LNG, CBM and biomethane produced at the price of the equivalent fossil fuel (as discussed above). Future trends in the price of these fossil fuel equivalents are allowed for in the analysis (Details are given in Appendix 1).

Table 4.1 NPV of transport fuel production options (£ '000)

Source	Fuel produced	Details	*RTFC price 10p*	*10p*	*7p*	*7p*	*12p*	*12p*	*18p*
			Fossil fuel price Base	*High*	*Base*	*High*	*Base*	*High*	*High*
Landfill	LBM	8 years production, constant output	**£15,093**	**£16,996**	**£11,477**	**£13,380**	**£17,504**	**£19,407**	**£26,639**
Landfill	LBM	15 years production constant output	**£22,653**	**£25,114**	**£17,977**	**£20,438**	**£25,770**	**£28,231**	**£37,582**
Landfill	LBM	8 years production, declining output	**£10,010**	**£11,575**	**£7,037**	**£8,601**	**£11,992**	**£13,557**	**£19,504**
Landfill	LBM	15 years production declining output	**£12,449**	**£14,247**	**£9,033**	**£10,831**	**£14,726**	**£16,524**	**£23,357**
AD Waste	LBM	New	**£3,079**	**£6,017**	**-£2,503**	**£435**	**£6,801**	**£9,738**	**£20,902**
AD Waste	LBM	New	**£3,079**	**£6,017**	**-£2,503**	**£435**	**£6,801**	**£9,738**	**£20,902**
AD sludge	LBM	Existing	**£21,874**	**£24,721**	**£16,463**	**£19,311**	**£25,481**	**£28,328**	**£39,149**
AD Waste	CBM	New, off-site dispensing station	**-£11,145**	**-£9,185**	**-£13,266**	**-£11,306**	**-£9,731**	**-£7,771**	**-£3,529**
AD sludge	CBM	Existing, large on-site filling station	**£9,011**	**£11,215**	**£6,574**	**£8,778**	**£10,635**	**£12,839**	**£17,712**
AD sludge	CBM	Existing, small on-site filling station	**-£429**	**-£319**	**-£551**	**-£441**	**-£348**	**-£238**	**£6**
Landfill	Biomethane	8 years production, constant output	**£2,580**		**£626**		**£3,883**		**£7,790**
Landfill	Biomethane	15 years production constant output	**£5,004**		**£2,478**		**£6,689**		**£11,742**
Landfill	Biomethane	8 years production, declining output	**£537**		**-£1,070**		**£1,608**		**£4,822**
Landfill	Biomethane	15 years production declining output	**£871**		**-£975**		**£2,102**		**£5,794**
AD Waste	Biomethane	New, injection via 'virtual pipeline'	**-£7,181**		**-£10,078**		**-£5,250**		**£544**
AD Waste	Biomethane	New, direct injection of gas to grid	**-£8,033**		**-£10,930**		**-£6,102**		**-£307**

An examination of the NPVs shows the same picture as derived from comparing production costs to fossil fuel costs[18]:

- Production of **LBM** from **landfill gas** is profitable under all scenarios considered including a worst case scenario of declining gas output, short production lifetime and a low RTFC price (7 pence per certificate).
- Production of **LBM** from a **new anaerobic digestion plant** using waste as a feedstock, is profitable under all scenarios, apart from a worst case scenario of a low RTFC price.
- Production of **LBM** from an **existing sewage sludge digestion plant** (where only the additional costs of liquefaction are considered) is profitable under all scenarios.
- Upgrading biogas and dispensing as **CBM** is profitable for the case of an **existing sewage sludge digestion** plant (where only the additional costs of upgrading and dispensing are considered) when all the biogas is used as at transport fuel. Diverting only a proportion of the biogas to service a small dispensing station is not profitable under any of the main scenarios considered and is marginal even with a very high RTFC price (of 18 pence per certificate).
- Upgrading biogas and dispensing as **CBM** biogas produced from a **new anaerobic digestion plant** is not profitable under any of the scenarios considered
- Upgrading **landfill gas** and injecting into the grid via a virtual pipeline is profitable where landfill gas generation is maintained, but is not profitable with a low RTFC price (7 pence) when landfill gas generation declines
- Upgrading biogas from a **new anaerobic digestion plant** using waste as a feedstock for injection to the grid for use in transport is not profitable under all of the core scenarios, and is still marginal at the very high RTFC price (of 18 pence per certificate).

4.2.2 Commercial attractiveness of transport fuel production options

For production of transport fuels to be attractive to landfill site operators as well as developers and operators of AD plant, it is not enough that the production of the fuel is profitable – it will need to be more commercially attractive to them than using the biogas in other ways, such as electricity generation, use in a combined heat and power (CHP) plant or upgrading and injecting to the gird and receiving payments under the RHI.

For each of the transport fuel production options, the net present value (NPV) of other options available to the plant operator for use of the biogas to produce heat or power was therefore calculated. For landfill gas this was production of electricity; for AD plant, either production of electricity or upgrading and injection to the grid to receive RHI payments. Landfill gas plants and sewage sludge anaerobic digestion plant producing electricity were assumed to receive 1 ROC per MWh[19], and new anaerobic digestion plant using waste feedstocks FITs payments. As for the transport option, the NPV for the heat or power was calculated based on the capital and operating costs of the plant[20], and income received for heat or electricity produced, and assuming a discount rate of 12%. Details of rates assumed for incentives and prices are given in Appendix 1, and the NPV of each of the heat and power options is given in Appendix 2.

For each of the production routes, it is then possible to compare the NPV of using the biogas to produce a transport fuel with the NPV of using biogas to produce heat or power. If the NPV of the transport option is more positive than the NPV of the heat or power option, than production of the transport fuel will be more financially attractive to the operator. If the NPV of transport fuel production is less than the NPV of the heat and power options, then heat or power production will be financially attractive to the

[18] The main difference in using the NPV to evaluate the profitability of the plant, is that any forecast increases in fossil fuel prices are included in the analysis as compared to the analysis comparing production costs for biomethane against the price of fossil fuels, which use only the current price. In using NPV to judge the profitability of the production routes, it is important to remember the uncertainty in cost assumptions and future forecasts of prices, and the conclusions drawn assume that a positive NPV of less than one million pounds indicates that profitability is marginal.
[19] While generation at new landfill sites is no longer eligible for ROCs, as discussed in Section 3.1, it seems probable that most future landfill gas supply will be at existing landfill sites, almost all of which receive 1ROC per MWh. Similarly generation from existing anaerobic digestion of sewage sludge almost all receives 1 ROC per MWh.
[20] For cases where existing plant already producing electricity were considered (landfill gas and sewage sludge AD) only the operating costs of the plant going forward where considered, as the original capital costs of the existing plant were considered as a sunk cost. As the aim is to evaluate whether it is profitable for the operator to switch from existing electricity production to transport fuel production, only future costs and income were considered.

operator. The difference between the NPV of transport fuel production options and heat and power production options for each production route is shown in Table 4.2:

- a positive value in blue, indicates that the NPV of transport fuel production is greater than the NPV of heat or power production. In these cases, producing a transport fuel gives a greater return than producing electricity or injecting to the grid and receiving RHI payments
- a negative value in red indicates that the NPV of transport fuel production is less than the NPV of producing heat or power from the biogas. In these cases producing transport fuel gives a lower rate of return than production heat or power from the biogas.

The comparison of NPVs shows that even though a number of transport fuel production options are profitable, at the current rates of incentives available for biogas in the heat, power and transport sectors, the only option which is potentially more profitable than use of the biogas for heat and power is the production of LBM from landfill gas. Even then, the option is only more profitable under favourable conditions: at a price of 10 pence per RTFC, the results suggest that the liquefaction plant needs to operate at full capacity for at least 10 years, and ideally for longer. Even at a higher RTFC price (of 12 pence per certificate), levels of landfill gas generation need to be maintained for the option to be attractive.

A very high RTFC price of 18 pence per certificate could make production of LBM from biogas from a new AD plant for use as a transport fuel attractive compared to electricity production. However, if a suitable gas grid injection point was available for the plant, then upgrading to biomethane for injection to the gas grid, and receiving RHI payments would be more attractive.

Similarly a very high RTFC price of 18 pence per certificate could make production of CBM from biogas from an existing AD sludge plant attractive compared to electricity production.

Upgrading to biomethane for injection to the grid is not profitable for any of the sources considered compared to electricity production for the typical range of RTFC prices considered (7p to 12p per certificate). At a very high RTFC price, injection of biomethane to the grid is more profitable for a new AD plant, and becomes marginal for a landfill site if landfill gas generation is maintained over a 15 year period. However, any AD plant which is injecting biomethane to the grid could claim RHI payments, which for new plant, will be under the new tariff introduced for biomethane from AD plant in February 2015. The income from these RHI payments would be higher than that from RTFCs (at 3.8 certificates per kg of biomethane, and a price of 12p per certificate). For the size of AD plant considered for grid injection, the RTFC price would need to be approaching 30p per certificate to offer returns similar to those available under the RHI. Some indicative rates which RTFC prices would need to reach for each of the production routes considered to give similar returns to those achievable from using biogas to produce electricity or heat are given in Appendix 3.

It should be noted that the conclusions above are based on the current rates for incentives[21] which support heat and power production from biogas. These could fall in the future, e.g. both FITs and the RHI have digression mechanisms in place, and this could make heat and power production from biogas less financially attractive.

[21] In the case of biomethane injection into the grid, the new tariff rates announced in December 2014 have been used.

Table 4.2 Difference in NPV of transport and heat and power options (£000)

Source	Fuel produced	Details	Heat & power option for comparison	RTFC price: *10p* / Fossil fuel price: *Base*	*10p* / *High*	*7p* / *Base*	*7p* / *High*	*12p* / *Base*	*12p* / *High*	*18p* / *High*
Landfill	LBM	8 years production, constant output	Elec. prod. (1 ROC/MWh)	-£2,028	-£125	-£5,644	-£3,741	£382	£2,285	£9,517
Landfill	LBM	15 years production constant output	Elec. prod. (1 ROC/MWh)	£655	£3,115	-£4,021	-£1,560	£3,772	£6,233	£15,584
Landfill	LBM	8 years production, declining output	Elec. prod. (1 ROC/MWh)	-£4,267	-£2,703	-£7,241	-£5,676	-£2,285	-£720	£5,227
Landfill	LBM	15 years production declining output	Elec. prod. (1 ROC/MWh)	-£3,530	-£1,732	-£6,946	-£5,148	-£1,252	£545	£7,378
AD (waste)	LBM	New	Elec. prod. (FITs)	-£7,772	-£4,835	-£13,354	-£10,417	-£4,051	-£1,113	£10,050
AD (waste)	LBM	New	Grid injection of gas (RHI)	-£23,063	-£20,125	-£28,645	-£25,707	-£19,342	-£16,404	-£5,240
AD (sludge)	LBM	Existing	Elec. prod. (1 ROC/MWh))	-£6,850	-£4,002	-£12,260	-£9,413	-£3,243	-£395	£10,426
AD (waste)	CBM	New, off-site dispensing station	Elec. prod. (FITs)	-£10,529	-£8,569	-£12,650	-£10,690	-£9,115	-£7,156	-£2,914
AD (sludge)	CBM	Existing, large on-site filling station	Elec. prod. (1 ROC/MWh)	-£5,337	-£3,133	-£7,773	-£5,569	-£3,713	-£1,509	£3,364
AD (sludge)	CBM	Existing, small on-site filling station	Elec. prod. (1 ROC/MWh)	-£1,004	-£894	-£1,126	-£1,016	-£923	-£813	-£569

Source	Fuel produced	Details	Heat & power option for comparison	*RTFC price* 10p / *Fossil fuel price* Base	10p / High	7p / Base	7p / High	12p / Base	12p / High	18p / High
Landfill	Biomethane	8 years production, constant output	Elec. prod. (1 ROC/MWh)	**-£5,981**	**-£5,981**	**-£7,935**	**-£7,935**	**-£4,678**	**-£4,678**	**-£770**
Landfill	Biomethane	15 years production constant output	Elec. prod. (1 ROC/MWh)	**-£5,995**	**-£5,995**	**-£8,521**	**-£8,521**	**-£4,310**	**-£4,310**	**£743**
Landfill	Biomethane	8 years production, declining output	Elec. prod. (1 ROC/MWh)	**-£6,602**	**-£6,602**	**-£8,208**	**-£8,208**	**-£5,531**	**-£5,531**	**-£2,317**
Landfill	Biomethane	15 years production declining output	Elec. prod. (1 ROC/MWh)	**-£7,118**	**-£7,118**	**-£8,964**	**-£8,964**	**-£5,888**	**-£5,888**	**-£2,196**
AD (waste)	Biomethane	New, injection to grid off-site ('virtual pipeline')	Elec. prod. (FITs)	**-£6,566**	**-£6,566**	**-£9,463**	**-£9,463**	**-£4,634**	**-£4,634**	**£1,160**
AD (waste)	Biomethane	New, direct injection of gas to grid on site	Elec. prod. (FITs)	**-£7,418**	**-£7,418**	**-£10,315**	**-£10,315**	**-£5,486**	**-£5,486**	**£308**

4.2.3 Other considerations

Technologies for the production of biomethane as a transport fuel have all been demonstrated, and are in use, if not in the UK then in Europe, The technology for upgrading and liquefying biomethane from landfill gas has been demonstrated at the Albury landfill site, and could be easily adapted for use with an AD plant. There is increasing interest worldwide in the development of small scale liquefaction plant. Liquefaction plant requires a high quality of upgraded biogas (97% biomethane), suggesting that upgrading of landfill gas to a quality which could be further conditioned to a quality suitable for injection to the grid is feasible. As discussed in Section 2, there are a number of plants already operating which upgrade biogas from AD plant for injection into the grid as biomethane, and more are planned. As the number of plants increases, more experience will be gained with upgrading. Furthermore, containerised solutions for conditioning and injection are being developed.

Stakeholders did not consider that planning permission or regulatory and permitting requirements would pose particular barriers to the production of transport fuels from biogas, and would not be expected to be any more onerous than those required if using biogas for heat and power options. In the case of landfill gas, operators reported that power purchase agreements for electricity produced at the site were generally not long term agreements, so would not prove a barrier to switching to transport fuel production. However, where production of electricity from landfill gas is contracted out to landfill gas management companies, rather than being managed by the operator of the landfill site, then depending on the nature of the contract, this could present a barrier.

The main potential barrier identified by stakeholders to the production of biomethane for use in transport is the nature of RTFCs. RTFCs can be traded bilaterally between producers and obligated suppliers, or sold via brokers or traders; for example NFPAS trades RTFCs via monthly on-line auctions. While information on the price of RTFCs traded bilaterally is not available, data on certificates traded via NFPAs shows that certificates have traded over a wide price range and that pricing is very volatile. This means that when making investment decisions, and when seeking finance for investments, the income from RTFCs is not considered very 'bankable'. In addition, at present, there is no guaranteed period over which RTFCs will be made available.

To mitigate against the risk of RTFC prices falling, and future income from this source falling, developers may take a very conservative view of the income that RTFCs may deliver and/or require a higher than normal internal rate of return from the project. A sensitivity analysis shows however that even at a higher discount rate (of 15%), those options which are most profitable, i.e. production of LBM from landfill, remain profitable.

While examination of demand for biomethane as a transport fuel was outside the scope of this study, it is possible that the perceived lack of an established market for gaseous fuels in general and biomethane in particular could also be a potential barrier.

4.2.4 Summary

In summary the analysis shows that several transport fuel production options could be profitable at the level of RTFC prices seen in the last year, and there appear to be no technical or regulatory barriers which would particularly hinder their development. However, the only case identified where production of transport fuel could be more profitable than using biogas to produce electricity or upgrading to biomethane and injecting to the grid and receiving RHI payments, is the production of LBM from landfill gas. Even then, the option is only more profitable under favourable conditions: at a price of 10 pence per RTFC, and where the liquefaction plant can operate at full capacity for at least 10 years, and ideally for longer. Even at a higher RTFC price (of 12 pence per certificate), levels of landfill gas generation need to be maintained for the option to be attractive. This suggests that the option might only be considered at sites which will still be receiving waste for several years, and landfill gas generation is high enough now, that even when it declines in the future, there would still be sufficient to run the liquefaction plant at close to full capacity[22]. An additional barrier to the development of such projects is the 'unbankability' of RTFC income, which, as it is not fixed, but traded, has fluctuated widely in the past. Developers or operators might seek to mitigate this risk by requiring a higher rate of return, or

[22] It is assumed that surplus biogas in earlier years could still be used for generation of electricity.

discounting potential RTFC income, which could mean that even projects where high landfill gas generation rates are expected into the future may not look attractive compared to electricity generation.

5 Cost-effectiveness of using biomethane in transport

Biomethane is a limited resource, and it is therefore important to make the best use of it in meeting renewable energy targets and GHG reduction targets.

5.1 Contribution to Renewable Energy Directive targets

The 2009 Renewable Energy Directive set a target for the UK to achieve 15% of its (gross) final energy consumption from renewable sources by 2020, with a specific target for the transport sector of 10%. When biogas from landfill or anaerobic digestion is used to generate electricity in a gas engine, each MWh of biogas produces about 0.36 MWh of 'renewable' electricity which can be counted towards the target. Using the biogas in a combined heat and power unit, and utilising the heat as well as electricity produced from the gas engine, could mean (providing that a heat load was available) that up to 0.75 MWh of renewable heat and electricity could be produced from 1 MWh of biogas. In contrast, upgrading the biogas to produce biomethane for use in the transport sector means that almost all (0.995 MWh) of the biomethane is used to provide renewable transport fuel.[23].

Table 5.1 shows the cost of producing 1 MWh of electricity from biogas compared to the cost of producing LBM or CBM as a transport fuel. The cost of producing 1 MWh of biomethane injected into the gas grid is also shown for comparison. The costs of producing 1 MWh of renewable energy as LBM are lower than producing 1 MWh of renewable energy as electricity in all cases. While the costs associated with converting biogas to electricity are much lower than those of converting biogas to LBM, the energy losses when converting biogas to electricity more than offset this.

If the costs of dispensing the LBM to vehicles are also included then the cost of LBM dispensed is still slightly lower than the cost of electricity production from biogas, in the scenarios where gas production is maintained over the production period. In the scenarios where landfill gas output at a site declines over the period LBM is produced, then the cost per MWh of dispensed LBM is slightly higher (by up to 10%) than the cost of producing electricity. Overall the results suggest that if feasible, utilising biogas as LBM or CBM, or upgrading biogas and injecting as biomethane into the grid, could increase the contribution of biogas to renewable energy targets substantially at no or little increase in cost.

Table 5.1 Cost of producing renewable energy from biogas (£/MWh of renewable energy)

Biogas source	Electricity	Bio-methane in grid	LBM (production cost)	LBM (inc. dispensing costs)	CBM (inc. dispensing costs)
Landfill, 8 years production at constant output	39	39*	32	38	
Landfill, 15 years production at constant output	36	34*	27	33	
Landfill, 8 years production, declining output	41	47*	39	45	
Landfill, 15 years production, declining output	41	47*	37	43	
New AD waste plant (large)	106	46	63	69	
New AD waste plant (medium)	145	71 to 74*			103

* via virtual pipeline

[23] There is small loss (about 0.5%) of biogas during the upgrading process

5.2 Contribution to greenhouse gas targets

The use of biogas, either for electricity production or as a transport fuel, delivers substantial greenhouse gas savings. The carbon savings delivered per GJ of biogas produced were examined in a previous study (Ricardo-AEA, 2014). Table 5.2 shows the saving which are achieved by using biogas in various ways, **compared to the use of natural gas**. In the case of using biogas in a gas engine, the greenhouse gas (GHG) emissions were compared to emissions from producing electricity using natural gas in a CCGT plant. For the transport and heat sectors, emissions were compared to using natural gas, or in the case of LBM, liquefied natural gas (LNG)[24]. Table 5.2 shows that the savings which can be achieved from using biogas for heat, combined heat and power, or transport, are about 60% higher than if it is used to produce electricity in a gas engine. This reflects the fact that the efficiency of electricity generation using gas in a CCGT plant is much higher than the efficiency with which electricity can be generated from biogas in a gas engine.

Table 5.2 CO_2 savings per GJ of biogas produced (compared to use of natural gas)[24]

End use	Carbon Savings (kg CO_2/GJ of biogas)
Gas engine	32
Injection to gas grid (for use as transport fuel or for heat or in CHP)	52
Compressed biomethane used in vehicles	53
Liquefied biomethane used in vehicles	55

+ Saving is for liquefied biomethane from landfill compared to LNG delivered by road tanker

The costs of achieving these greenhouse gas savings can also be compared. In the case of electricity production, the cost and greenhouse gas savings achieved from generation from biogas in a gas engine, and generation from natural gas in the grid in a CCGT are compared. In the case of transport, the cost and greenhouse gas savings of providing a biomethane-based transport fuel, are compared to the cost of producing a fossil based transport fuel. Where costs and emissions associated with dispensing the fuel to vehicles are identical for the 'bio' and 'fossil' gaseous fuel, they are not included in the assessment of the cost of greenhouse gas savings.

Table 5.3 shows the cost-effectiveness of greenhouse gas savings achieved from using biogas in transport and heat. A negative number indicates that overall there is a cost saving from using biogas compared to using natural gas. Table 5.3 shows that in the case of LBM production, that where landfill gas generation remains high enough for LBM plant to operate at full capacity, the cost-effectiveness of greenhouse gas savings achieved from using the LBM are about the same as for biogas production. Where landfill gas generation is not maintained and throughput at the plant is lower, the high capital cost of liquefaction means that using biogas in a gas engine for electricity generation produces more cost-effective carbon savings than using it to produce LBM.

In contrast, in the case of a new AD plant, where the liquefaction plant can operate at full capacity for 20 years, the cost of GHG savings from production and use of LBM is less than for savings achieved from electricity production. In the case of biomethane injection to the grid, the cost of GHG savings from use of biogas from an AD plant are similar, whether biogas is upgraded for injection to the grid or

[24] Savings for the transport sector are calculated assuming that the fuel replaces natural gas rather than petrol or diesel, as it is considered that an infrastructure for using gaseous fuels for transport will not be developed only for biomethane. As savings from the use of biomethane in transport are compared to the use of natural gas or LNG in transport, only the difference in upstream emissions and CO_2 released on combustion need to be considered as fugitive emissions of methane in vehicles whether from boil of methane slip in exhaust gases will be the same for both biomethane and natural gas. If the savings were calculated on the basis of replacing petrol or diesel in a vehicle, then these additional emissions would be included in the comparison. This was done in the previous study (Ricardo-AEA, 2014) which showed that in some cases, use of natural gas gave small or no savings, compared to petrol or diesel use. However the renewable nature of biomethane meant that savings were always achieved.

used for electricity production[25]. If the biogas comes from a landfill site, then use for electricity production delivers more cost-effective savings.

Table 5.3 Cost of CO_2 savings achieved in the transport and power sector from use of biogas

Source	Notes	Transport fuel (£/t CO_2)	Electricity (£/t CO_2)
Biogas from landfill		Converted to LBM	Biogas used in gas engine
	8 years production, constant output	-£38	-£51
	15 years production constant output	-£59	-£56
	8 years production, declining output	-£9	-£45
	15 years production declining output	-£17	-£46
Biogas from AD of waste	New large sized plant (20 tonnes/day of biomethane)	£112	£156
		Injected to grid* then dispensed as CBM	Biogas used in gas engine
Biomethane in grid from landfill via ‘virtual pipeline’	8 years production, constant output	£82	-£51
	15 years production constant output	£60	-£56
	8 years production, declining output	£121	-£45
	15 years production declining output	£118	-£46
Biomethane from AD (waste)	New medium sized plant (10 tonnes/day of biomethane)	£266	£285

*via virtual pipeline

[25] The cost of savings is lower for electricity production at the large AD plant due to economies of scale for the AD plant.

6 Potential supply of biomethane for transport

As discussed in Section 4, while production of biomethane for transport is profitable for several production routes, at the current level of RTFC prices, financial returns for operators are generally better from power generation, or for injection to the grid under the Renewable Heat Incentive. Coupled with the question of the bankability of the RFTO, this suggests that any additional supply of biomethane to transport by 2020 or 2030 is unlikely.

The only production route which is commercially attractive under some 'optimistic' scenarios (i.e. a higher RTFC price of 12 pence/certificate and a higher price received for LBM) is the production of LBM from landfill sites. Even under these 'optimistic' conditions, conversion would only be viable at very large landfills, where even if gas production falls due to declining quantities of biodegradable waste landfilled, there is still sufficient gas production for LBM plant to run at close to capacity for a reasonable length of time.

As discussed in Section 3, volumes of waste landfilled are declining rapidly, and the overall supply of landfill gas will decline into the future. However, without a detailed site-by-site assessment (which is outside the scope of this study), it is not possible to identify which individual sites might continue to have sufficient gas generation into the future to support LBM plant. However from the data on landfill gas flared and combusted in 2013, there were 33 sites which currently have enough landfill gas output to support such plant. Of these, 11 currently have landfill gas generation which is double or more that needed to support a liquefaction plant. For these sites, even if landfill gas generation were to decline by 50% over a 10 year period, there would still be enough biogas to run an LBM plant. Of these it is considered an 'optimistic' scenario that perhaps two could convert to LBM production with any excess biogas production still utilised for electricity production. The physical conversion from electricity production to liquefaction could be completed fairly quickly (in six months to a year) although a two year lead-in time, in order to allow for project development, is more realistic. This suggests that conversion to LBM could be possible by 2018 to 2019. This would give an additional 0.6 PJ of LBM for transport by 2020. This is 2% of the feasible total supply of landfill in 2020. Supply in 2030 is likely to be lower than this.

7 Conclusions

In 2013, about 85 PJ of biogas were produced in the UK, and used predominantly for electricity generation, with only 0.1 PJ being used for transport. About two-thirds (61PJ) of biogas supply came from landfill sites, and the remainder (24 PJ) from anaerobic digestion. By 2020, the available landfill gas resource is likely to decline significantly. Whilst biogas production from anaerobic digestion is forecast to increase, there is considerable uncertainty about the magnitude of the increase. Total potential biogas supply could be up to 30% higher in 2020 than 2013 (at 106 PJ or 2.2 Mt biomethane) but more pessimistic forecasts of the development of AD suggest it could be up to 30% lower (at 60 PJ or 1.3 Mt of biomethane).

Economic analysis suggests however that very little of this resource will be used to produce additional biomethane for transport. Production of transport fuels could be profitable for operators, assuming RTFC prices remain at levels seen recently of 7 to 12 pence per certificate. However, with the current levels of payments available under from ROCs, FITs, and the RHI, operators can currently achieve better rates of return by using biogas to generate electricity or upgrading to biomethane and injecting gas into the grid.

The only option which is potentially more profitable than use of the biogas for heat and power is the production of LBM from landfill gas. Even then, the option is only more profitable under favourable conditions - a higher RTFC price (of 12p per certificate), and sustained levels of landfill gas generation. An additional barrier to the development of such projects is the ‘unbankability’ of RTFC income which, as it is traded rather than being fixed, has fluctuated considerably in the past.

Overall it is therefore considered unlikely that, at under current levels of RTFC prices, and current levels of support available in the heat and power sector (from ROCs, FITS and RHI) that the supply of biomethane into the transport sector will increase by 2020. In a more optimistic scenario, it is considered that perhaps two landfill sites might convert from electricity production to LBM production, delivering an additional 0.6 PJ of LBM (equivalent to 13 kt of LBM) for transport by 2020. This could fuel almost 1,000 dual fuel HGVs running on a mixture of 60% LBM and 40% diesel. Supply in 2030 is likely to be lower than this.

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Appendices

Appendix 1: Assumptions for cost modelling

Appendix 2: Detailed results

Appendix 3: 'Break-even' RTFC prices

Appendix 1 – Assumptions for cost modelling

A1.1 Capital and Operating Costs for Transport Fuel Production

These capital and operating costs for each of the transport fuel production routes were drawn from a variety of sources including the previous study by Ricardo-AEA (2014) for DfT which examined the costs of using gaseous fuels in transport, the recent consultation by DECC on biomethane grid injection RHI tariff review (DECC 2014, 2014b and 2014c), previous work by SKM Enviros (2010) on biogas production, and evidence from stakeholders. The capital and operating costs for each route are summarised in Table A1.1. More detail on the individual data sources used for each element of the costs, and assumptions on technical characteristics are given in Table A2.2.

Capital costs include development costs, civils, clean up of biogas and upgrading to biomethane and as appropriated depending on the transport fuel option, liquefaction plant, and LBM storage and balance of plant, conditioning of gas prior to injection, injection plant, gas grid connection and filling station. For transfer of CBM by road, the capital costs of dedicated trailers, and pressure reduction system.

Opex costs in Table A1.1 include maintenance costs, cost of propane to condition gas where appropriate, transport costs and insurance. Electricity costs are calculated on the consumption shown in Table A1.1 and industrial electricity prices (see below). Labour required is estimated as full time equivalents (FTE), and is costed at £31,000 p.a. per FTE. The income from gate fees for waste for AD plant is based on £15/t as assumed in the review of the RHI tariff (DECC, 2014b)

Table A1.1 Capital and operating costs for transport fuel production routes

	Size (t/day)	Capex (£'0000)	Opex (£'000/yr)	Elec use (MWh/yr)	Labour (FTE)	Income from gate fees (£'000/yr)
Landfill (excluding cost of gas recovery system)						
Liquefaction	**20**	10,188	499	8,629	6	
Virtual pipeline	**10**	5,488	583	1,759	2	
AD waste plant (including cost of new AD plant)						
Liquefaction	**20**	24,965	2,876	10,550	10	1,862
Biomethane to grid	**20**	21,234	3,180	5,075	9	1,862
Biomethane to grid	**10**	14,870	1,753	2,782	8	931
Virtual pipeline	**10**	15,740	1,857	2,964	8	931
Upgrade and transport by road to CNG filling station	**10**	15,624	1,852	2,964	8	931
AD sludge plant (excluding cost of existing AD plant)						
Liquefaction	**20**	9,263	495	12,008	6	
Large on site CNG filling station	**10**	3,975	159	3,473	2	
Slipstream to small filling station	**0.5**	536	39	214		

Table A1.2 Sources of data for capex and opex costs and technical characteristics

#	Category	Item	Description	Reference	Date point for costs
1	AD Plant Capacity	Quantity of food waste	To calculate the quantity of food waste to produce the required quantities of biomethane, a biomethane potential of 400m3 CH4/t ds is used for food waste feedstock, with 25% dry solids.	Typical assumptions for AD plant design	
2	AD Plant Capacity and	Gross capacity of AD plant in MW biomethane	This is the capacity of the plant in MW of biomethane which includes both biomethane to produce biofuel and biomethane diverted to heat the AD processes through a boiler. It is assumed 20% of the gross biomethane produced is required for process heat purposes.	Typical assumption for AD plant design	
3	AD Plant Capacity and	MW biomethane to biofuels	This is the net quantity of biomethane calculated in MW which can be upgraded to biofuel.		
4	Capex	Development costs	Development costs are calculated as 10% of the process capex.	Typical assumption for biogas plant development	
5	Capex	Grid connection import only	Cost of grid connection on conversion options where AD plant parasitic power is imported from the grid.	ARUP [26]	2011
6	Capex	Other infrastructure	Cost of roads and ancillary civil structures.	ARUP [1]	2011
7	Capex	Civil Works	Civil works are calculated as 15% of the process capex.	Derived from DECC post consultation [27] prices for AD gas to grid plant	

[26] ARUP - Review of the generation costs and deployment potential of renewable electricity technologies in the UK, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/66176/Renewables_Obligation_consultation_-_review_of_generation_costs_and_deployment_potential.pdf

[27] Renewable Heat Incentive - Biomethane Tariff Review, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/384203/Biomethane_Tariff_Review_-_Impact_Assessment_-_Annex_G.pdf

#	Category	Item	Description	Reference	Date point for costs
8	Capex	AD plant	The food waste AD plant comprises costs for: • Food waste pre treatment • Anaerobic digester • Boiler • Digestate storage This equipment is sized to the gross capacity of the AD plant in MW biomethane.	DECC post consultation prices	2014
9	Capex	Landfill and sewage sludge plants	Only capex for power generation or biofuels production is considered for these options.		
10	Capex	Upgrading equipment	This equipment is sized to the MW of biomethane to biofuels.	DECC post consultation prices	2014
11	Capex	Upgrading and boiler for sewage sludge options	Capital cost for this equipment. It is assumed for the sewage sludge conversion options a boiler supplies heat to the AD process, fuelled by diverted biogas. All gas engines are sold.	DECC post consultation prices	2014
12	Capex	H_2S/VOC clean-up	Gas clean up equipment.	DECC post consultation prices	2014
10	Capex	Surcharge for landfill gas upgrade	This is an estimate of the extra capital cost of refining landfill gas based on GasRec cost information. A contingency has also been added.	GasRec and feedback from DfT workshop Dec 2014	2013
11	Capex	Liquefaction	Price for liquefaction process equipment.	GasRec costs from Wartsila	2013
12	Capex	LBM storage and BoP	Price for LBM storage and balance of plant.	Included in the above	Jun-14
13	Capex	Injection plant	Injection plant equipment	DECC post consultation prices	2014
14	Capex	Gas grid connection	Gas grid connection equipment	DECC post consultation prices	2014

#	Category	Item	Description	Reference	Date point for costs
15	Capex	Slipstream	Capital cost of 0.5tpd packaged CBM slipstream unit. Container includes upgrading, compression and filling point.	SKM Enviros [28]	2011
16	Capex	Compression 250 bar filling station	Cost of refuelling station with compression and storage.	LowCVP [29]	2011
17	Capex	Pressure reduction - 250bar to gas grid pressure	Price estimate of £100,000 to enable CBM transported by road to be injected to the gas grid at a central point at around 10 bar.	DfT workshop 2014	2014
18	Capex	Transport capex CBM	Capex for tractor unit plus 2 x trailers (as trailer also used for storage). A composite trailer carrying 10t is assumed with 8t being transferred. Cost is £410,000 per trailer.	DfT workshop 2014	2014
19	Capex	Transport capex LBM	The capex of the LBM 26t road tankers needed for transport is included in the LBM opex calculation.	Italian Ministry of Transport	2014
20	Opex	Civils	Annual maintenance opex is calculated as 2.5% capex.	estimate	2014
21	Opex	Biogas upgrading	Annual maintenance opex is calculated as 3.5% capex.	DECC post consultation prices	2014
22	Opex	H_2S/VOC clean-up	Annual maintenance opex is calculated as 3.5% capex.	DECC post consultation prices	2014
23	Opex	Liquefaction	Annual maintenance opex is calculated as 5% capex.	estimate	2014
24	Opex	LNG storage and BoP	Included in liquefaction.		
25	Opex	Compression to 250 bar and filling station	Annual maintenance opex is calculated as 3% capex.	estimate	2014
26	Opex	Pressure reduction - 250bar to gas grid	Annual maintenance opex is calculated as 3% capex.	estimate	2014

[28] ANALYSIS OF CHARACTERISTICS AND GROWTH ASSUMPTIONS REGARDING AD BIOGAS COMBUSTION FOR HEAT, ELECTRICITY AND TRANSPORT AND BIOMETHANE PRODUCTION AND INJECTION TO THE GRID, available at: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48166/2711-SKM-enviros-report-rhi.pdf

[29] Biomethane for Transport - HGV cost modelling Part 1 Report, Prepared for LowCVP by Transport and Travel Research Ltd

#	Category	Item	Description	Reference	Date point for costs
27	Opex	Injection plant	Annual maintenance opex is calculated as 7.5% capex.	DECC post consultation prices	2014
28	Opex	Gas grid connection	Annual maintenance opex is calculated as 1.1% capex.	DECC post consultation prices	2014
29	Opex	Slipstream	SKM Enviros estimated annual slipstream opex of £50,000 of which maintenance is assumed to be £30,000 per annum.	SKM Enviros	2011
30	Opex	Electricity – Sewage sludge and food waste AD plants	Food waste and sewage sludge AD plant parasitic power consumptions in MWh. In the conversions, it is assumed all electrical parasitic power is imported with process heat generated in a boiler using biogas (as SKM Enviros basis).	SKM Enviros	2011
32	Opex	Electricity - liquefaction plant	Wartsila liquefaction plant power consumption of 0.75kWh per kg of LBM produced.	GasRec	
33	Opex	Electricity - upgrade & grid injection	Veissmann (Carbotech) pressure swing adsorption process power consumption 180kW (10tpd BM) model BGAA1000. Veissmann (Carbotech) pressure swing adsorption process power consumption 360kW (20tpd BM) model BGAA2000.	Veissmann (Carbotech)	
34	Opex	Electricity - compression to 250bar & transfer	Power consumption calculation for natural gas compressor from 10bar to 250bar.		
35	Opex	Electricity - slipstream unit	SKM Enviros estimated annual slipstream opex of £50,000 of which electrical power is assumed to be £20,000 per annum.	SKM Enviros	2011
36	Opex	Propane addition	To increase calorific value of biomethane at £54 per MWh	DECC post consultation prices	2014
37	Opex	Transport	Opex for a 100km round trip to the LBM / CBM delivery point including : • tyres	Italian Ministry of Transport	2014

#	Category	Item	Description	Reference	Date point for costs
			• repairs and maintenance • vehicle cost • driver salary • insurance • overhead • fuel LBM calculations include vehicle cost. CBM calculations excludes vehicle cost as this is included in CBM scheme capex.		
38	Opex	Insurance	Annual premium equal to 1% capex	DECC post consultation prices	2014
39	Opex	Landfill costs for contraries	Landfill fees of £22 / tonne, 5% of waste rejected.	DECC post consultation prices	2014
40	Opex	Landfill tax	Landfill tax of £80 / tonne.	DECC post consultation prices	2014
41	Opex	Polyelectrolyte	Not required.	DECC post consultation prices	2014
42	Opex	Digestate disposal	Disposal £10 / tonne Ratio feedstock to digestate 1:1	DECC post consultation figures & prices	2014
	Opex	Gas engines	Running costs for AD food waste gas engines.	SKM Enviros	2011
43	Opex	Gate fees	Gate fee revenue £15 / tonne for food waste.	DECC post consultation prices	2014
44	Opex	Labour	Labour estimate in terms of FTEs Labour cost at £31,300 per FTE	GtG plant as DECC post consultation prices	2014
45	Divert	Biogas diverted to boiler for food waste and	Boiler 85% efficiency, 25% of total biogas output needed to meet process heat requirements.	Typical assumption for AD plant design	

#	Category	Item	Description	Reference	Date point for costs
		sewage sludge AD plant heat requirements			
47	Output	Annual upgrade to biomethane	Upgrade biomethane capture rate 99.5%.	DECC post consultation	
48	Output	Annual output biomethane (actual)	Actual plant capacity adjusted for plant availability. The design point capacity of the plant (10 or 20 tpd) is reduced to allow for equipment downtime.	DECC post consultation and estimates	
49	Capex	Resale value of gas engines for rounded MW	Gas engine resale value for landfill and sewage sludge conversion options is estimated at £200,000 per MW electrical output.	Online resale values	2014
50	Capex	Food waste AD plant grid connection for import and export	Grid connection capacity and cost for export of power at the capacity of the plant for counterfactual.	ARUP	2011
51	Capex	Food waste AD gas engines	Capital cost of gas engines for counterfactual.	SKM Enviros	2011
52	Capex	Power generation equipment only land fill and sewage sludge options	Capital cost of power generation equipment for counterfactual.	ARUP	2011
53	Opex	Land fill and sewage sludge options, power generation only	Opex for power generation equipment for counterfactual.	ARUP	2011
54	Revenue	Sewage sludge options	Net electricity generated (MWh) in counterfactual options once sewage sludge AD plant parasitic load is met		
55	Revenue	Sewage sludge options	Proportion of net electricity (MWh) used on site in a large sewage sludge and waterworks – 80%.	estimate	
56	Revenue	Sewage sludge options	Remainder of net electricity exported to grid with ROCs (MWh)	estimate	

A1.2 Fuel prices

Prices for natural gas and electricity are taken from the reference scenario of DECCs energy and emissions projections (DECC, 2014e). Electricity sold (e.g., in the evaluation of heat and power options) is assumed to receive the wholesale price for electricity. Electricity consumed in transport fuel production (e.g. in liquefaction) is based on the retail price of electricity to industry.

Prices for LNG (as delivered by road tanker to a filling station were derived following a targeted literature review[30] and review of information received from stakeholders. This showed a wide variation in price and therefore tow cases were used in the analysis, a 'base case' reference price and a high price. Future prices were assumed to follow the trend in gas prices.

In the case of CNG, prices were based on the wholesale prices of gas plus an estimate of the costs (including supplier margin) of transporting gas and dispensing as CNG. Estimates were based on information from Ricardo-AEA (2014), Low CVP, 2011 and information from stakeholders. Again a 'base case' reference price and a high price were assumed; these reflect the range in costs and types of stations for CNG. Prices assumed for LNG and CNG are summarised in Table A1.3

Table A1.3 Prices assumed for LNG and CNG

Fuel	Case	2015	2020	2025	2030
LNG	Base case	10.8	10.6	11.7	12.1
	High case	12.0	11.8	12.9	13.3
CBM	Base case	8.3	8.1	9.2	9.6
	High case	10.3	10.1	11.5	12.0

A1.2 Incentives

The rates assumed for tariffs and incentives applicable to heat and power generation options. For transport fuel production options, biomethane is assumed to receive (after double counting) 3.8 RTFCs per kg of biomethane.

[30] Sources reviewed included Citi, 2013, LowCVP. 2011, Danish Maritime Authority, 2012, Ernst and Young, 2013. Information was also received from GasRec and BOC.

Table A1.4 Incentive and tariff rates assumed

Assumption	Reference Value (2015 prices)	Description of methodology, assumptions and sources
FIT rate for AD waste	FIT 8.14p/kWh in 2017 Export tariff is set at wholesale price	FIT rate based on latest published FIT rates for AD with installed capacity greater than 500kW[31]. It is assumed that the baseline degression rate of 5% per annum applied from April 2014 continues to apply to 2017. Generators can either claim export tariffs or the market value payable by the electricity company. For the modelling the latter is assumed, with DECC's UEP wholesale electricity price projection used as a proxy price.
ROC price	£44.56 / ROC in 2015	ROC price is set taking the latest published ROC buy-out price of £43.30 per ROC for 2014-15[32]. The buy-out price is updated each year by RPI. This value is updated to 2015 (and 2015 prices) using an RPI of 2.9% (average of 15 years to 2013, the year for which latest data is available). ROC price then rises in 2027 by 10% to account for DECC's announcement that it will purchase all ROCs from this date at their long-term value[33].
RHI tariff	7.5 p/KWh (<40,000 kWh) 4.4 p/kWh (40 to 80,000 kWh) 3.4 p/kWh (>80,000 kWh)	Tiered tariff as announced in governments response to consultation on biomethane RHI tariff (DECC, 2014 b)

[31] https://www.ofgem.gov.uk/ofgem-publications/89098/fitpaymentratetableforpublication1october2014nonpvtariffs.pdf
[32] https://www.ofgem.gov.uk/publications-and-updates/renewables-obligation-buy-out-price-and-mutualisation-ceiling-2014-15
[33] https://www.gov.uk/government/policies/increasing-the-use-of-low-carbon-technologies/supporting-pages/the-renewables-obligation-ro

Appendix 2 – Detailed Results

Note: In the Tables below, counterfactual refers to use of biogas in the heat and power sector, and conversion/alternative to use of biomethane as a transport fuel.

Scenario 1 - Base prices, RTFCs @ 10p				NPV 2015 ('000s)			£/MWh Overall LCOE		£/MWh LCOE incl. subsidies	
Source	Fuel produced	Details	Heat and power option for comparison	Heat or Power Use Option	Transport Fuel Option	Change in NPV	Heat or Power Use Option	Transport Fuel Option	Heat or Power use option	Transport Fuel Option
Landfill	LBM	Existing landfill site, 8 years production at constant output	Electricity production (1 ROC/MWh)	£17,121	£15,093	-£2,028	38.71	31.58	-4.89	3.67
Landfill	LBM	Existing landfill site, 15 years production at constant output	Electricity production (1 ROC/MWh)	£21,998	£22,653	£655	36.48	26.75	-7.33	- 1.16
Landfill	LBM	Existing landfill site, 8 years production, declining output	Electricity production (1 ROC/MWh)	£14,277	£10,010	-£4,267	40.97	38.29	-2.56	10.37
Landfill	LBM	Existing landfill site, 15 years production, declining output	Electricity production (1 ROC/MWh)	£15,979	£12,449	-£3,530	40.58	36.41	-3.06	8.49
AD Waste	LBM	New AD Waste plant	Electricity production (FITs payment)	£10,852	£3,079	-£7,772	106.22	63.29	24.82	35.37
AD Waste	LBM	New AD Waste plant	Grid injection of gas (RHI payment)	£26,142	£3,079	-£23,063	46.50	63.29	-10.32	35.37
AD sludge	LBM	Exisiting AD sludge plant	Electricity production (FITs payment)	£28,723	£21,874	-£6,850	35.66	33.35	26.91	5.43
Landfill	Biomethane	Existing landfill site, 8 years production at constant output	Electricity production (FITs payment)	£8,561	£2,580	-£5,981	38.71	37.94	-4.89	10.02
Landfill	Biomethane	Existing landfill site, 15 years production at constant output	Electricity production (FITs payment)	£10,999	£5,004	-£5,995	36.48	33.19	-7.33	5.27
Landfill	Biomethane	Existing landfill site, 8 years production, declining output	Electricity production (FITs payment)	£7,139	£537	-£6,602	40.97	46.14	-2.56	18.22
Landfill	Biomethane	Existing landfill site, 15 years production, declining output	Electricity production (FITs payment)	£7,989	£871	-£7,118	40.58	45.43	-3.06	17.51
AD Waste	Biomethane	New plant - injection to grid off-site ('virtual pipleine')	Electricity production (FITs payment)	-£615	-£7,181	-£6,566	145.21	71.07	63.81	43.15
AD Waste	Biomethane	New plant - direct injection of gas to grid on site	Electricity production (FITs payment)	-£615	-£8,033	-£7,418	145.21	73.53	63.81	45.61
AD Waste	CBM	New AD Waste plant - off-site dispensing station	Electricity production (FITs payment)	-£615	-£11,145	-£10,529	145.21	102.89	63.81	74.97
AD sludge	CBM	Existing AD sludge plant, large on-site filling station	Electricity production (FITs payment)	£14,348	£9,011	-£5,337	35.92	27.25	27.17	- 0.67
AD sludge	CBM	Existing AD sludge plant, small on-site filling station	Electricity production (FITs payment)	£575	-£429	-£1,004	14.73	87.72	-29.01	59.81

Scenario 2 - High prices, RTFCs @ 10p				NPV 2015 ('000s)			£/MWh Overall LCOE		£/MWh LCOE incl subsidies	
Source	Fuel produced	Details	Heat and power option for comparison	Counterfactual	Conversion	Net Result	Counterfactual	Conversion/Alternative	Counterfactual	Conversion
Landfill	LBM	Existing landfill site, 8 years production at constant output	Electricity production (1 ROC/MWh)	£17,121	£16,996	-£125	38.71	31.58	-4.89	3.67
Landfill	LBM	Existing landfill site, 15 years production at constant output	Electricity production (1 ROC/MWh)	£21,998	£25,114	£3,115	36.48	26.75	-7.33	- 1.16
Landfill	LBM	Existing landfill site, 8 years production, declining output	Electricity production (1 ROC/MWh)	£14,277	£11,575	-£2,703	40.97	38.29	-2.56	10.37
Landfill	LBM	Existing landfill site, 15 years production, declining output	Electricity production (1 ROC/MWh)	£15,979	£14,247	-£1,732	40.58	36.41	-3.06	8.49
AD Waste	LBM	New AD Waste plant	Electricity production (FITs payment)	£10,852	£6,017	-£4,835	106.22	63.29	24.82	35.37
AD Waste	LBM	New AD Waste plant	Grid injection of gas (RHI payment)	£26,142	£6,017	-£20,125	46.50	63.29	-10.32	35.37
AD sludge	LBM	Exisiting AD sludge plant	Electricity production (FITs payment)	£28,723	£24,721	-£4,002	35.66	33.35	26.91	5.43
Landfill	Biomethane	Existing landfill site, 8 years production at constant output	Electricity production (FITs payment)	£8,561	£2,580	-£5,981	38.71	37.94	-4.89	10.02
Landfill	Biomethane	Existing landfill site, 15 years production at constant output	Electricity production (FITs payment)	£10,999	£5,004	-£5,995	36.48	33.19	-7.33	5.27
Landfill	Biomethane	Existing landfill site, 8 years production, declining output	Electricity production (FITs payment)	£7,139	£537	-£6,602	40.97	46.14	-2.56	18.22
Landfill	Biomethane	Existing landfill site, 15 years production, declining output	Electricity production (FITs payment)	£7,989	£871	-£7,118	40.58	45.43	-3.06	17.51
AD Waste	Biomethane	New plant - injection to grid off-site ('virtual pipleine')	Electricity production (FITs payment)	-£615	-£7,181	-£6,566	145.21	71.07	63.81	43.15
AD Waste	Biomethane	New plant - direct injection of gas to grid on site	Electricity production (FITs payment)	-£615	-£8,033	-£7,418	145.21	73.53	63.81	45.61
AD Waste	CBM	New AD Waste plant - off-site dispensing station	Electricity production (FITs payment)	-£615	-£9,185	-£8,569	145.21	102.89	63.81	74.97
AD sludge	CBM	Existing AD sludge plant, large on-site filling station	Electricity production (FITs payment)	£14,348	£11,215	-£3,133	35.92	27.25	27.17	- 0.67
AD sludge	CBM	Existing AD sludge plant, small on-site filling station	Electricity production (FITs payment)	£575	-£319	-£894	14.73	87.72	-29.01	59.81

Scenario 3 - Base prices, RTFCs @ 7p				NPV 2015 ('000s)			£/MWh Overall LCOE		£/MWh LCOE incl subsidies	
Source	Fuel produced	Details	Heat and power option for comparison	Counterfactual	Conversion	Net Result	Counterfactual	Conversion/Alternative	Counterfactual	Conversion
Landfill	LBM	Existing landfill site, 8 years production at constant output	Electricity production (1 ROC/MWh)	£17,121	£11,477	**-£5,644**	38.71	31.58	-4.89	12.04
Landfill	LBM	Existing landfill site, 15 years production at constant output	Electricity production (1 ROC/MWh)	£21,998	£17,977	**-£4,021**	36.48	26.75	-7.33	7.21
Landfill	LBM	Existing landfill site, 8 years production, declining output	Electricity production (1 ROC/MWh)	£14,277	£7,037	**-£7,241**	40.97	38.29	-2.56	18.74
Landfill	LBM	Existing landfill site, 15 years production, declining output	Electricity production (1 ROC/MWh)	£15,979	£9,033	**-£6,946**	40.58	36.41	-3.06	16.87
AD Waste	LBM	New AD Waste plant	Electricity production (FITs payment)	£10,852	-£2,503	**-£13,354**	106.22	63.29	24.82	43.74
AD Waste	LBM	New AD Waste plant	Grid injection of gas (RHI payment)	£26,142	-£2,503	**-£28,645**	46.50	63.29	-10.32	43.74
AD sludge	LBM	Exisiting AD sludge plant	Electricity production (FITs payment)	£28,723	£16,463	**-£12,260**	35.66	33.35	26.91	13.80
Landfill	Biomethane	Existing landfill site, 8 years production at constant output	Electricity production (FITs payment)	£8,561	£626	**-£7,935**	38.71	37.94	-4.89	18.40
Landfill	Biomethane	Existing landfill site, 15 years production at constant output	Electricity production (FITs payment)	£10,999	£2,478	**-£8,521**	36.48	33.19	-7.33	13.65
Landfill	Biomethane	Existing landfill site, 8 years production, declining output	Electricity production (FITs payment)	£7,139	-£1,070	**-£8,208**	40.97	46.14	-2.56	26.60
Landfill	Biomethane	Existing landfill site, 15 years production, declining output	Electricity production (FITs payment)	£7,989	-£975	**-£8,964**	40.58	45.43	-3.06	25.89
AD Waste	Biomethane	New plant - injection to grid off-site ('virtual pipleine')	Electricity production (FITs payment)	-£615	-£10,078	**-£9,463**	145.21	71.07	63.81	51.52
AD Waste	Biomethane	New plant - direct injection of gas to grid on site	Electricity production (FITs payment)	-£615	-£10,930	**-£10,315**	145.21	73.53	63.81	53.99
AD Waste	CBM	New AD Waste plant - off-site dispensing station	Electricity production (FITs payment)	-£615	-£13,266	**-£12,650**	145.21	102.89	63.81	83.35
AD sludge	CBM	Existing AD sludge plant, large on-site filling station	Electricity production (FITs payment)	£14,348	£6,574	**-£7,773**	35.92	27.25	27.17	7.71
AD sludge	CBM	Existing AD sludge plant, small on-site filling station	Electricity production (FITs payment)	£575	-£551	**-£1,126**	14.73	87.72	-29.01	68.18

Scenario 4 - High prices, RTFCs @ 7p				NPV 2015 ('000s)			£/MWh Overall LCOE		£/MWh LCOE incl subsidies	
Source	**Fuel produced**	**Details**	**Heat and power option for comparison**	**Counterfactual**	**Conversion**	**Net Result**	**Counterfactual**	**Conversion/Alternative**	**Counterfactual**	**Conversion**
Landfill	LBM	Existing landfill site, 8 years production at constant output	Electricity production (1 ROC/MWh)	£17,121	£13,380	**-£3,741**	38.71	31.58	-4.89	12.04
Landfill	LBM	Existing landfill site, 15 years production at constant output	Electricity production (1 ROC/MWh)	£21,998	£20,438	**-£1,560**	36.48	26.75	-7.33	7.21
Landfill	LBM	Existing landfill site, 8 years production, declining output	Electricity production (1 ROC/MWh)	£14,277	£8,601	**-£5,676**	40.97	38.29	-2.56	18.74
Landfill	LBM	Existing landfill site, 15 years production, declining output	Electricity production (1 ROC/MWh)	£15,979	£10,831	**-£5,148**	40.58	36.41	-3.06	16.87
AD Waste	LBM	New AD Waste plant	Electricity production (FITs payment)	£10,852	£435	**-£10,417**	106.22	63.29	24.82	43.74
AD Waste	LBM	New AD Waste plant	Grid injection of gas (RHI payment)	£26,142	£435	**-£25,707**	46.50	63.29	-10.32	43.74
AD sludge	LBM	Exisiting AD sludge plant	Electricity production (FITs payment)	£28,723	£19,311	**-£9,413**	35.66	33.35	26.91	13.80
Landfill	Biomethane	Existing landfill site, 8 years production at constant output	Electricity production (FITs payment)	£8,561	£626	**-£7,935**	38.71	37.94	-4.89	18.40
Landfill	Biomethane	Existing landfill site, 15 years production at constant output	Electricity production (FITs payment)	£10,999	£2,478	**-£8,521**	36.48	33.19	-7.33	13.65
Landfill	Biomethane	Existing landfill site, 8 years production, declining output	Electricity production (FITs payment)	£7,139	-£1,070	**-£8,208**	40.97	46.14	-2.56	26.60
Landfill	Biomethane	Existing landfill site, 15 years production, declining output	Electricity production (FITs payment)	£7,989	-£975	**-£8,964**	40.58	45.43	-3.06	25.89
AD Waste	Biomethane	New plant - injection to grid off-site ('virtual pipleine')	Electricity production (FITs payment)	-£615	-£10,078	**-£9,463**	145.21	71.07	63.81	51.52
AD Waste	Biomethane	New plant - direct injection of gas to grid on site	Electricity production (FITs payment)	-£615	-£10,930	**-£10,315**	145.21	73.53	63.81	53.99
AD Waste	CBM	New AD Waste plant - off-site dispensing station	Electricity production (FITs payment)	-£615	-£11,306	**-£10,690**	145.21	102.89	63.81	83.35
AD sludge	CBM	Existing AD sludge plant, large on-site filling station	Electricity production (FITs payment)	£14,348	£8,778	**-£5,569**	35.92	27.25	27.17	7.71
AD sludge	CBM	Existing AD sludge plant, small on-site filling station	Electricity production (FITs payment)	£575	-£441	**-£1,016**	14.73	87.72	-29.01	68.18

Scenario 5 - Base prices, RTFCs @ 12p				NPV 2015 ('000s)			£/MWh Overall LCOE		£/MWh LCOE incl subsidies	
Source	**Fuel produced**	**Details**	**Heat and power option for comparison**	**Counterfactual**	**Conversion**	**Net Result**	**Counterfactual**	**Conversion/Alternative**	**Counterfactual**	**Conversion**
Landfill	LBM	Existing landfill site, 8 years production at constant output	Electricity production (1 ROC/MWh)	£17,121	£17,504	**£382**	38.71	31.58	-4.89	- 1.92
Landfill	LBM	Existing landfill site, 15 years production at constant output	Electricity production (1 ROC/MWh)	£21,998	£25,770	**£3,772**	36.48	26.75	-7.33	- 6.75
Landfill	LBM	Existing landfill site, 8 years production, declining output	Electricity production (1 ROC/MWh)	£14,277	£11,992	**-£2,285**	40.97	38.29	-2.56	4.79
Landfill	LBM	Existing landfill site, 15 years production, declining output	Electricity production (1 ROC/MWh)	£15,979	£14,726	**-£1,252**	40.58	36.41	-3.06	2.91
AD Waste	LBM	New AD Waste plant	Electricity production (FITs payment)	£10,852	£6,801	**-£4,051**	106.22	63.29	24.82	29.78
AD Waste	LBM	New AD Waste plant	Grid injection of gas (RHI payment)	£26,142	£6,801	**-£19,342**	46.50	63.29	-10.32	29.78
AD sludge	LBM	Exisiting AD sludge plant	Electricity production (FITs payment)	£28,723	£25,481	**-£3,243**	35.66	33.35	26.91	- 0.16
Landfill	Biomethane	Existing landfill site, 8 years production at constant output	Electricity production (FITs payment)	£8,561	£3,883	**-£4,678**	38.71	37.94	-4.89	4.44
Landfill	Biomethane	Existing landfill site, 15 years production at constant output	Electricity production (FITs payment)	£10,999	£6,689	**-£4,310**	36.48	33.19	-7.33	- 0.31
Landfill	Biomethane	Existing landfill site, 8 years production, declining output	Electricity production (FITs payment)	£7,139	£1,608	**-£5,531**	40.97	46.14	-2.56	12.64
Landfill	Biomethane	Existing landfill site, 15 years production, declining output	Electricity production (FITs payment)	£7,989	£2,102	**-£5,888**	40.58	45.43	-3.06	11.93
AD Waste	Biomethane	New plant - injection to grid off-site ('virtual pipleine')	Electricity production (FITs payment)	-£615	-£5,250	**-£4,634**	145.21	71.07	63.81	37.56
AD Waste	Biomethane	New plant - direct injection of gas to grid on site	Electricity production (FITs payment)	-£615	-£6,102	**-£5,486**	145.21	73.53	63.81	40.03
AD Waste	CBM	New AD Waste plant - off-site dispensing station	Electricity production (FITs payment)	-£615	-£9,731	**-£9,115**	145.21	102.89	63.81	69.39
AD sludge	CBM	Existing AD sludge plant, large on-site filling station	Electricity production (FITs payment)	£14,348	£10,635	**-£3,713**	35.92	27.25	27.17	- 6.25
AD sludge	CBM	Existing AD sludge plant, small on-site filling station	Electricity production (FITs payment)	£575	-£348	**-£923**	14.73	87.72	-29.01	54.22

Scenario 6 - High prices, RTFCs @ 12p				NPV 2015 ('000s)			£/MWh Overall LCOE		£/MWh LCOE incl subsidies	
Source	**Fuel produced**	**Details**	**Heat and power option for comparison**	**Counterfactual**	**Conversion**	**Net Result**	**Counterfactual**	**Conversion/Alternative**	**Counterfactual**	**Conversion**
Landfill	LBM	Existing landfill site, 8 years production at constant output	Electricity production (1 ROC/MWh)	£17,121	£19,407	**£2,285**	38.71	31.58	-4.89	- 1.92
Landfill	LBM	Existing landfill site, 15 years production at constant output	Electricity production (1 ROC/MWh)	£21,998	£28,231	**£6,233**	36.48	26.75	-7.33	- 6.75
Landfill	LBM	Existing landfill site, 8 years production, declining output	Electricity production (1 ROC/MWh)	£14,277	£13,557	**-£720**	40.97	38.29	-2.56	4.79
Landfill	LBM	Existing landfill site, 15 years production, declining output	Electricity production (1 ROC/MWh)	£15,979	£16,524	**£545**	40.58	36.41	-3.06	2.91
AD Waste	LBM	New AD Waste plant	Electricity production (FITs payment)	£10,852	£9,738	**-£1,113**	106.22	63.29	24.82	29.78
AD Waste	LBM	New AD Waste plant	Grid injection of gas (RHI payment)	£26,142	£9,738	**-£16,404**	46.50	63.29	-10.32	29.78
AD sludge	LBM	Exisiting AD sludge plant	Electricity production (FITs payment)	£28,723	£28,328	**-£395**	35.66	33.35	26.91	- 0.16
Landfill	Biomethane	Existing landfill site, 8 years production at constant output	Electricity production (FITs payment)	£8,561	£3,883	**-£4,678**	38.71	37.94	-4.89	4.44
Landfill	Biomethane	Existing landfill site, 15 years production at constant output	Electricity production (FITs payment)	£10,999	£6,689	**-£4,310**	36.48	33.19	-7.33	- 0.31
Landfill	Biomethane	Existing landfill site, 8 years production, declining output	Electricity production (FITs payment)	£7,139	£1,608	**-£5,531**	40.97	46.14	-2.56	12.64
Landfill	Biomethane	Existing landfill site, 15 years production, declining output	Electricity production (FITs payment)	£7,989	£2,102	**-£5,888**	40.58	45.43	-3.06	11.93
AD Waste	Biomethane	New plant - injection to grid off-site ('virtual pipleine')	Electricity production (FITs payment)	-£615	-£5,250	**-£4,634**	145.21	71.07	63.81	37.56
AD Waste	Biomethane	New plant - direct injection of gas to grid on site	Electricity production (FITs payment)	-£615	-£6,102	**-£5,486**	145.21	73.53	63.81	40.03
AD Waste	CBM	New AD Waste plant - off-site dispensing station	Electricity production (FITs payment)	-£615	-£7,771	**-£7,156**	145.21	102.89	63.81	69.39
AD sludge	CBM	Existing AD sludge plant, large on-site filling station	Electricity production (FITs payment)	£14,348	£12,839	**-£1,509**	35.92	27.25	27.17	- 6.25
AD sludge	CBM	Existing AD sludge plant, small on-site filling station	Electricity production (FITs payment)	£575	-£238	**-£813**	14.73	87.72	-29.01	54.22

Appendix 3 – ‘Break-even points for RTFCs

Table A3.1 shows the approximate price that RTFCs would need to be for each of the production routes evaluated to give as good an NPV (at a discount rate of 12%) from the production of transport fuel, as the heat and power option that they have been evaluated against, given the assumptions made in the modelling. These are specified in Appendix 1 and include the assumptions that subsidies available under the RO, RHI and FITS remain at current rates as specified in Appendix 1. Changes in these rates (e.g. through the degression mechanism would alter the RTFC price at which transport fuel production would become as attractive as heat and power production. As discussed in the main report, the ‘unbankability’ of RTFCs may also mean that a higher discount rate is used by developers when assessing transport fuel production options, in order to offset the potential fluctuations in RTFCs values; this would then require a higher RTFC price that shown in the Table for the transport fuel production to be as profitable as the alternative heat or power production shown. Values in the Table should therefore be taken as indicative only.

Table A3.1 Indicative value of RTFC certificate necessary for transport fuel production to be as profitable as heat or power production

Source	Fuel produced	Details	Heat & power option for comparison	Required value of RTFC (pence per certificate)
Landfill	LBM	8 years production, constant output	Electricity production (1 ROC/MWh)	12
Landfill	LBM	15 years production constant output	Electricity production(1 ROC/MWh)	10
Landfill	LBM	8 years production, declining output	Electricity production(1 ROC/MWh)	15
Landfill	LBM	15 years production declining output	Electricity production (1 ROC/MWh)	14
AD (waste)	LBM	New	Electricity production (FITs)	15
AD (waste)	LBM	New	Grid injection of gas (RHI)	23
AD (sludge)	LBM	Existing	Electricity production(1 ROC/MWh))	14
AD (waste)	CBM	New, off-site dispensing station	Electricity production (FITs)	20
AD (sludge)	CBM	Existing, large on-site filling station	Electricity production(1 ROC/MWh)	18
AD (sludge)	CBM	Existing, small on-site filling station	Electricity production(1 ROC/MWh)	23
Landfill	Biomethane	8 years production, constant output	Electricity production(1 ROC/MWh)	22
Landfill	Biomethane	15 years production constant output	Electricity production(1 ROC/MWh)	17
Landfill	Biomethane	8 years production, declining output	Electricity production(1 ROC/MWh)	18
Landfill	Biomethane	15 years production declining output	Electricity production(1 ROC/MWh)	25
AD (waste)	Biomethane	New, injection to grid off-site ('virtual pipeline')	Electricity production (FITs)	17
AD (waste)	Biomethane	New, direct injection of gas to grid on site	Electricity production (FITs)	35

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