June 2017

Biogas:
A significant contribution to decarbonising gas markets?

Introduction

With a current focus on the need to decarbonise the energy system, and increasing interest in decarbonising the gas industry[1], this short paper provides an overview of the current status and considers the potential for further growth in the production and use of biogas and biomethane. It focuses on key countries in Europe, which have been leading the way in commercial scale production, and touches briefly on the potential in the rest of the world.

The paper includes:

- a short overview of the feedstocks and technologies involved;
- an assessment of the potential supply growth;
- a review of the economics and comparison with alternative approaches towards decarbonising the energy system;
- a consideration of the impact of government policy on the rate of growth of the industry.

Background

Between 2009 and 2015 the number of biogas plants in Europe increased significantly from around 6,000 to nearly 17,000[2]. Total European Union biogas primary energy production in 2014 was estimated at 14.9 Mtoe, up by 6.6 per cent from the previous year. 57TWh of EU electricity was produced from biogas in 2014, up 9 per cent from 2013[3]. These growth rates are impressive, but with total EU electricity generation of 3,032 TWh[4], biogas still only produces 1.9 per cent of the total. Nevertheless, significant growth is expected in the next 10-15 years: in a recent presentation in Brussels, the European Biogas Association suggested that by 2030, European biogas production could reach 50Bcm/year, or around 10 per cent of the EU's current natural gas consumption. [5]

The United States has been slower to develop biogas plants, with around 2200 in operation, of which the majority are in waste water treatment facilities. The US Department of Energy estimates that there

[1] Stern 2017: The Future of Gas in Decarbonising European Energy Markets
[2] EBA 2016 statistical report
[3] EurObserv'ER: The State or Renewable Energy in Europe 2015.
[4] Eurostat website (Electricity production, consumption and market overview)
[5] EBA Workshop: Contribution of biogas towards European renewable energy policy beyond 2020, 8 February 2017

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is potential for this to grow to over 13,000 plants, producing over 40TWh of electricity.[6] Biogas is also starting to attract attention from major energy companies, as seen by BP's recent US$155m investment in the US acquiring Clean Energy Partners' upstream business.[7]

Biogas, a mixture of predominantly methane and CO_2, can be used for a combination of heat production and power generation near the point of production[8]. In an additional processing step (and hence additional cost), biogas upgrading plants can remove the CO_2 to produce biomethane, potentially for injection into the natural gas grid where it is co-mingled with fossil-derived natural gas.

Whether or not any biomass-derived energy source (including biomass) is "carbon neutral" continues to divide opinion[9], and depends on a complex and detailed life cycle analysis of each supply chain. However, as discussed further in the section on Greenhouse Gas Emissions Impact below, there is general agreement that the use of biogas can result in significant greenhouse gas (GHG) emission savings compared with the fossil-derived alternatives.[10]

Technical Overview

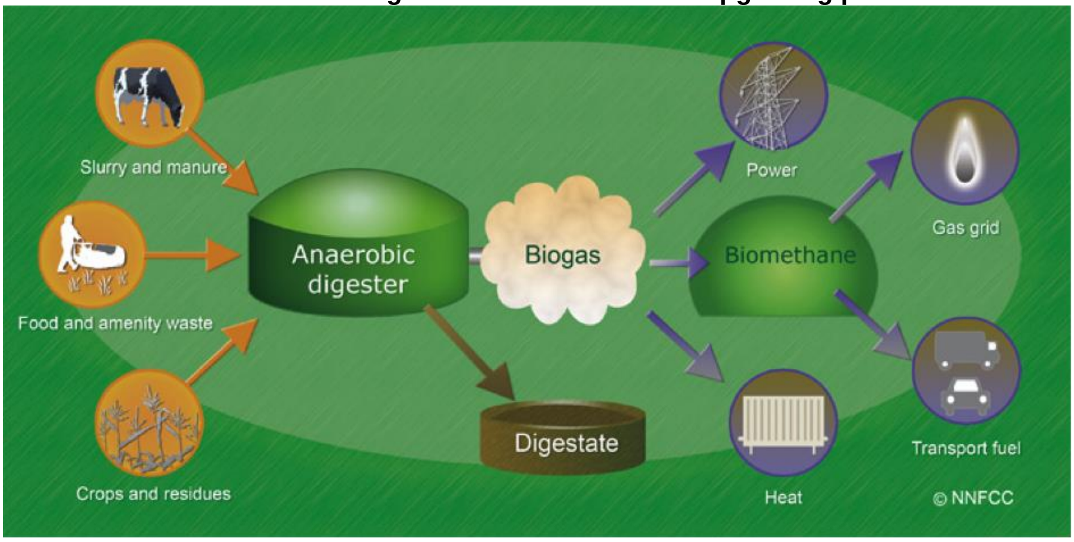
Currently, the primary method of biogas production is the biological breakdown of organic material in the absence of oxygen, known as Anaerobic Digestion (AD). AD plants operate at relatively low temperatures[11], allowing micro-organisms to digest the feedstock in a controlled reactor in the absence of oxygen to produce biogas that is about 50-65 per cent methane. A similar process happens in landfill sites when organic waste decomposes and produces what is known as landfill gas which is about 45 per cent methane.[12] Landfill gas was previously vented to the atmosphere, thereby adding to greenhouse gas emissions, but in the last fifteen years it has increasingly been captured as a source of energy. Apart from methane, biogas contains up to 50 per cent CO_2, and, depending on the feedstock, a small amount of other gases and contaminants (see Table 1).

Table 1: Properties of natural gas and raw biogas[13]

Substance	Biogas from anaerobic fermentation	Natural Gas
Methane	50-85%	83-98%
Carbon dioxide	15-50%	0-1.4%
Nitrogen	0-1%	0.6-2.7%
Oxygen	0.01-1%	-
Hydrogen	traces	-
Hydrogen sulphide	Up to 4,000 ppmv	-
Ammonia	traces	-
Ethane	-	Up to 11%
Propane	-	Up to 3%
Siloxane	0-5 mg/m3	-
Wobbe Index	4.6-9.1	11.3-15.4

[6] US DOE (2014): Biogas Opportunities Roadmap: https://energy.gov/downloads/biogas-opportunities-roadmap
[7] https://www.cleanenergyfuels.com/press-room/bp-clean-energy-partner-expand-u-s-renewable-natural-gas-transportation-fueling-capabilities-bp-acquire-clean-energys-upstream-rng-business-sign-long-term-rng-supply-agreeme/
[8] http://www.biogas-info.co.uk/about/biogas/
[9] https://www.edie.net/news/10/Biomass--carbon-neutrality--debate-continues-to-divide-opinions/
[10] University of Florida: http://biogas.ifas.ufl.edu/FAQ.asp
[11] Either mesophilic (35-45˚C) or thermophilic (50-60˚C) – see https://www.clarke-energy.com/biogas/
[12] Bionett: Biomethane fact sheet
[13] IEA Biomethane – status and factors affecting market development and trade (Sept 2014) p.18

Figure 1: Overview of Anaerobic Digestion and Biomethane upgrading process[14]



Biogas from AD can be upgraded to biomethane by a variety of methods (absorption, adsorption, membrane filtration, cryogenic separation).[15] All of these technologies can result in >95 per cent methane in the product gas, and the resulting biomethane is then sufficiently close to the properties of fossil-derived natural gas (including the key Wobbe index) that it can be injected into the natural gas grid, and can be used interchangeably with natural gas. Figure 1 provides a schematic of the feedstock to end-use process via the AD route.

An alternative route to biogas production is via the thermo-chemical route. Unlike AD, gasification takes place at high temperatures (700-1500˚C) and heat or small amounts of oxygen are added to supply the energy needed for the gasification process.[16] The steps in the process are:

a) biomass pre-treatment
b) gasification
c) gas cleaning and conditioning.

To distinguish from AD-derived biogas, the product of the thermo-chemical route is generally referred to as Bio SNG (or, in the US, Renewable Natural Gas, (RNG)). Commercialization of the technology is still at an early stage, with a limited number of demonstration plants built (for example Güssing, Austria (2002), Gothenburg, Sweden (started methane supply to natural gas grid in December 2014) and Swindon, UK (pilot plant completed 2016)[17].

Figure 2 shows a schematic of the gasification route.

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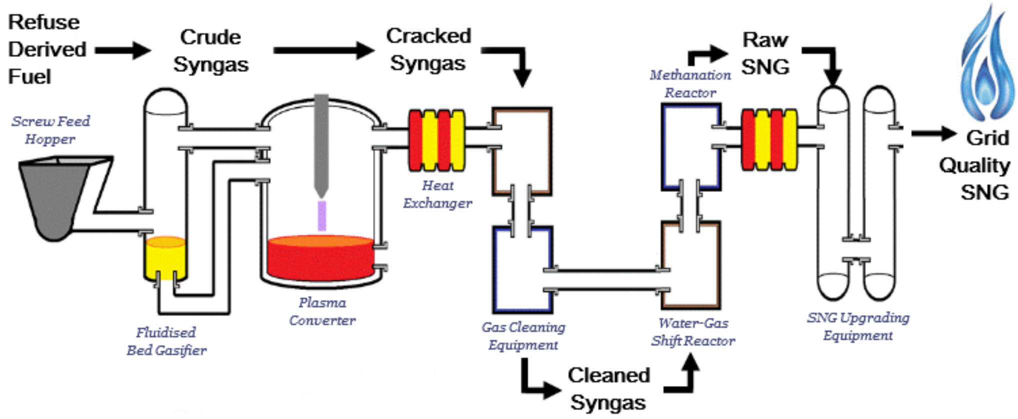
[14] UK Anaerobic Digestion Portal (www.biogas-info.co.uk)
[15] Further details on the relevant technology can be found elsewhere – a good reference (summarised in this section) can be found in: IEA Biomethane – status and factors affecting market development and trade (Sept 2014) p. 19
[16] IEA What is Gasification (http://www.ieatask33.org/download.php?file=files/file/publications/Fact_sheets/IEA_What_is_gasification.pdf)
[17] European Biofuels Technology Platform (http://biofuelstp.eu/bio-sng.html)

Figure 2: Schematic of Thermo-chemical route to Bio-SNG[18]



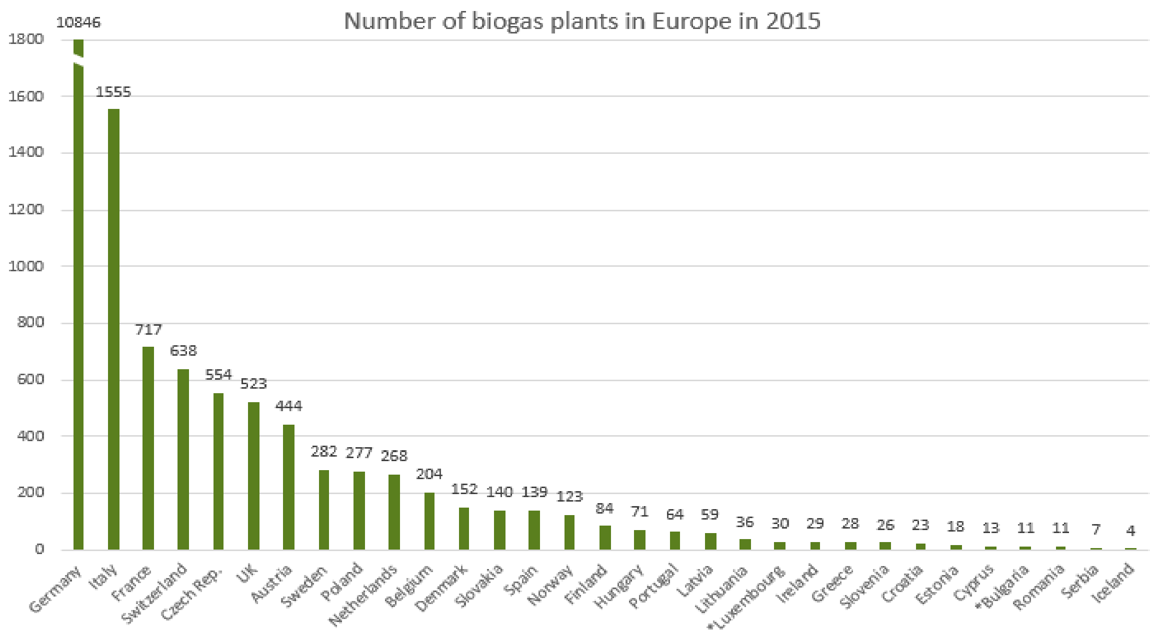
The main feedstocks used commercially in the AD process are[19]:

- Sewage waste
- Agricultural manures
- Food waste from domestic or commercial premises
- Garden or horticultural waste
- Energy crops.

Biogas Production Growth

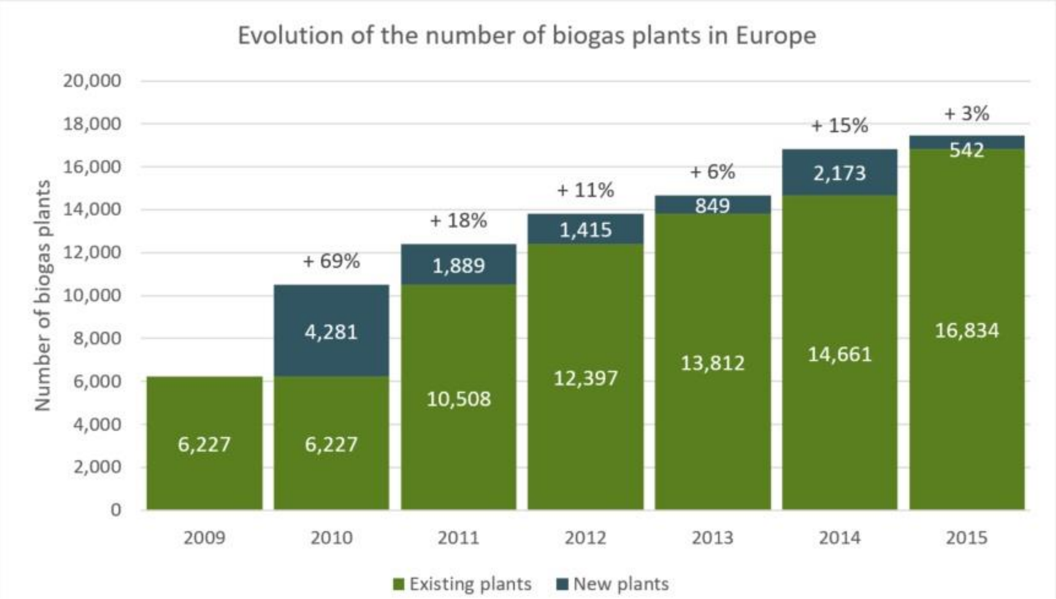
Rates of growth in biogas production have varied significantly between countries and over time, largely driven by government policy.

Figure 3: Number of biogas plants in Europe 2015[20]



[18] UK National Grid: http://www2.nationalgrid.com/UK/Our-company/Innovation/Gas-distribution-innovation/NIC-Projects/BioSNG-Process-Diagram/
[19] Bionett: Biomethane fact sheet
[20] Statistical report of European Biomass Association 2016

Figure 4: Growth of number of biogas plants in Europe



Source: Statistical report of European Biomass Association 2016

As can be seen from Figure 3, Germany has, by a large margin, been the leading proponent of biogas in Europe: its development of biogas plants started in the 1990s and grew rapidly between 2006 and 2013. However, a new renewable energy law in Germany effective from 1 August 2014 aimed to reduce the use of energy crops and refocus the industry on waste-derived feedstocks. This has markedly slowed the rate of growth.[21] While around 1000 new plants per year were added in Germany between 2009 and 2011, this had dropped to only 150 in 2014.[22] (For further details see the Germany case study text box later in this paper).

Italy, with the second highest number of biogas plants in Europe also introduced changes to its incentive scheme in 2013, similarly aiming to reduce incentives for the use of energy crops and promoting smaller scale plants using bio-waste as a feedstock, resulting in a similar slowing of the rate of growth of new capacity.[23]

Taking Europe as a whole, however, as illustrated in Figure 4[24] the number of biogas plants has grown from around 6,000 in 2009 to nearly 17,000 by 2015.

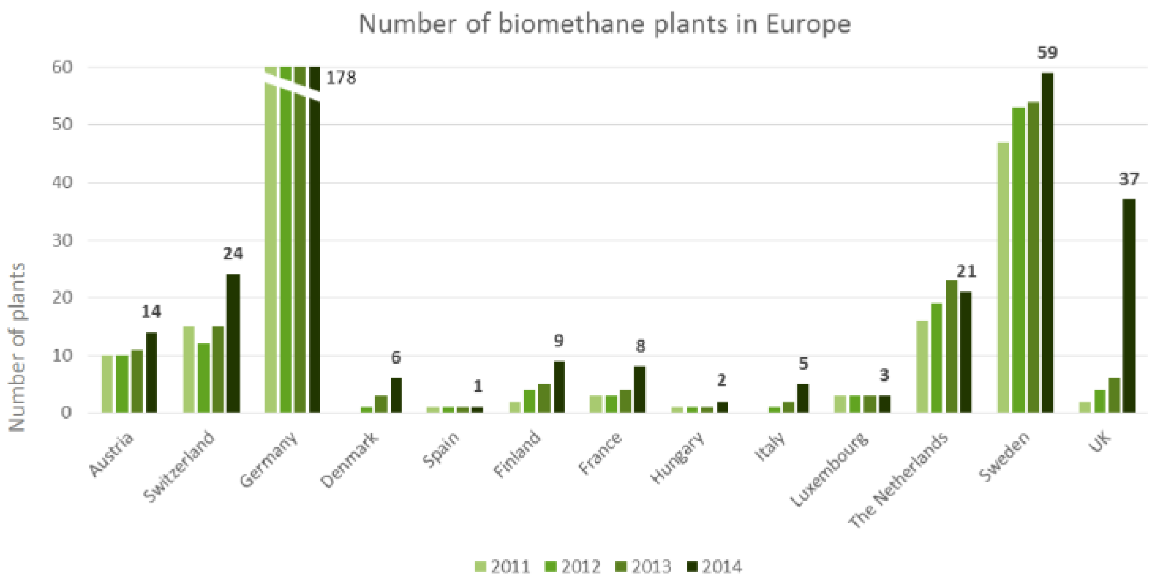
Since there are a large number of widely-distributed AD plants, many of which produce electricity and heat (in differing proportions) for local use, reliable and consistent data for total energy production from biogas is not readily available. According to data collected by the IEA in 2015, annual electricity production from around 900 plants in the UK totalled 7600 GWh/year (2.3 per cent of total UK electricity production) and from around 10000 plants in Germany totalled 28,000 GWh/yr (4.7 per cent of total Germany electricity production)[25]. Heat production was 700 and 12000 GWh respectively. These numbers appear consistent with estimates of total EU-28 production of electricity from biogas in 2014 of 57TWh and total primary energy from biogas of 14.8 mtoe (172TWh or 16Bcm natural gas equivalent)[26]. By comparison, total EU-28 primary energy consumption in 2014 was 1500 mtoe, of

[21] EurObserv'ER Biogas Barometer 2014
[22] IEA Bioenergy Task 37: Germany Country report, October 2015
[23] Torrijos: State of Development of Biogas production in Europe 2015
[24] Statistical report of European Biomass Association 2016
[25] IEA Task 37 Country Reports, 2015
[26] EurObserv'ER Annual Review 2015.

which 330 mtoe was consumed as gas[27], and total electricity production was 3,032 TWh.[28] Thus biogas produced around 1 per cent of EU primary energy, and 1.9 per cent of electricity. At a global level, total electricity generation from biogas in 2014 is estimated at 80TWh (comprising Europe 59, USA 14, RoW 7)[29], showing that to date biogas development has been predominantly concentrated in Europe.

Compared to the amount of raw biogas production, there has been only a relatively small amount of upgrading to biomethane. In 2014, there were estimated to be 367 biomethane upgrading plants in Europe, 70 per cent of which injected gas into the grid, producing a total of approximately 1.4Bcm of gas[30]. Representing just 0.3 per cent of total European gas consumption, this is not yet significant. Like raw biogas production, however, the extent of biomethane upgrading has also varied significantly by country, and can grow rapidly depending on government policy. As can be seen in Figure 5, Germany and Sweden have taken the lead in biomethane production. It is also noticeable that there is no correlation between the number of plants producing raw biogas and those upgrading to biomethane: while Italy is second in terms of raw biogas, it has very little upgrading capacity, whereas in Sweden some 57 per cent of raw biogas production is upgraded to biomethane, primarily for road transport.

Figure 5: Biomethane plants by country and year[31]



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The UK provides a good example of how government policy can stimulate rapid growth in biomethane upgrading. In 2011, there was just one biomethane plant in the country. The introduction of Carbon Price Support from 2013, as well as a Feed-In Tariff per kWh of biomethane injected into the grid under the Renewable Heat Incentive, resulted in 20-30 new plants per year coming onstream between 2014 and 2016, and it is estimated that around 100 new plants could be in operation before 2018.[32] The UK Renewable Energy Association points out that there is a need for clarity on policy beyond 2020/21 if major new projects are to be planned.[33]

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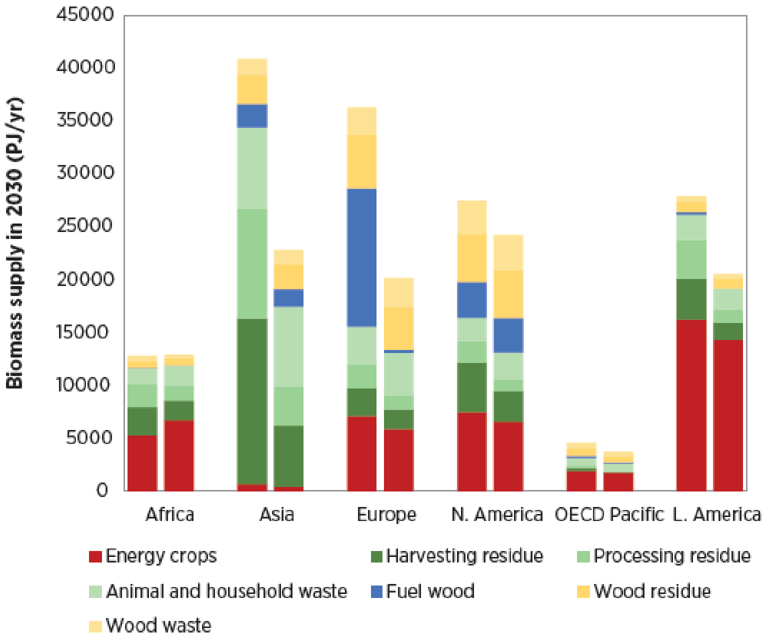
[27] European Environment Agency http://www.eea.europa.eu/data-and-maps/indicators/primary-energy-consumption-by-fuel-6/assessment-1
[28] Eurostat website (Electricity production, consumption and market overview)
[29] IRENA, Renewable Energy Statistics 2016.
[30] Proceedings of BioSurf workshop, Berlin, 17/6/16
[31] EBA: Biomethane Day, Birmingham, April 2016
[32] UK REA presentation to BioSurf, Paris, November 2016 (http://www.biosurf.eu/wordpress/wp-content/uploads/2015/06/BIOSURF_Roadmap-for-UK_REA-RM-additions-GH.pdf)
[33] http://www.r-e-a.net/news/budget-oil-gas-get-more-help-future-low-carbon-technologies-starved-of-support

Feedstock potential

While the rate of growth will be influenced by government policy, ultimate potential growth in biogas production may be limited by the availability of sustainable affordable feedstock.[34] While biogas produced locally from readily available waste (for example sewage, manure, forest residues) is generally seen as environmentally beneficial and sustainable, biogas can be more controversial where arable land is taken up with large scale production of energy crops or where feedstock has to be transported over a long-distance to reach a production facility. For example, the rapid growth in biogas production in Germany until 2013 resulted in 75 per cent of production using energy crops (principally maize) as feedstock.[35] The new renewable energy law which came into force in Germany in August 2014 changed the incentive structure to encourage the use of organic and farming waste and to discourage the use of energy crops. One of the key concerns relating to energy crops has been the environmental impact of Indirect Land Use Change (ILUC).[36] Assessment of this impact is still being studied. Further consideration of this complex topic and the pros and cons of energy crops is beyond the scope of this paper.

In assessing the total feedstock available for biogas production, this clearly cannot be considered in isolation from other applications of biomass (such as direct burning of biomass for power generation).

Figure 6: Breakdown of biomass supply by regions, 2030



Source: IRENA: Global Bioenergy Supply and Demand Projections for the Year 2030 (published Sept 2014)

It has been estimated that global biomass use was around 50EJ (14000TWh) in 2010 and could more than double to around 100 to 150EJ by 2030[37], of which 20-35EJ will be in Europe (see Figure 6). The same study concludes that, even with constraints on the use of energy crops, there will be sufficient biomass resources to meet the expected demand. Given that there is likely to be sufficient feedstock available, the further growth in biogas and upgrading to biomethane is likely to be influenced by the extent to which government policy recognises their ability to decarbonise the energy system and their production costs relative to alternatives. These are considered in the following sections.

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[34] IRENA: Global Bioenergy Supply and Demand Projections for the Year2030 (published Sept 2014)
[35] EurObservER Biogas Barometer 2014
[36] http://biofuelstp.eu/iluc.html
[37] IRENA: Global Bioenergy Supply and Demand Projections for the Year2030 (published Sept 2014)

The Green Gas Grids project, which ran from 2012 to 2014, funded by the Intelligent Energy Europe programme of the EU, forecast a maximum technical biogas production (whether used as biogas or upgraded to biomethane) in the EU-28 in the range (in natural gas equivalent terms) of 150 to 250 Bcm/year, comprising around 100 Bcm from residues, and 50-150 Bcm/year energy crops[38]. The report also postulated that around 33 per cent of the technical potential, or around 50 Bcm/year could be realised by 2030. This is based on reaching around 25 Bcm/year by 2020, based on achievement of the National Renewable Energy Action Plans[39], and (perhaps somewhat more arbitrarily) assuming a further doubling by 2030. While this is only around 10 per cent of forecast European gas demand in 2030, it is over half of the forecast indigenous European natural gas production (excluding Russia and Norway)[40], and in that context is not insignificant.

Uses of Biogas

Raw biogas (typically with CO_2 content > 40 per cent) has generally been burned near the point of production for a combination of electricity generation and heat production. The electricity produced is then consumed locally or, depending on the regulatory regime, exported to the grid. It is expected that, even in an optimistic forecast of biomethane upgrading, by 2030 60 per cent of biogas will still be consumed in this way.[41]

Where upgraded to biomethane, it is generally injected into the natural gas grid (or in the case of Sweden, often transported by road), not least since the additional cost of upgrading is hard to justify if the resulting product is still to be consumed locally to the point of production.

In some countries, most notably in Sweden and more recently in the UK, biomethane is promoted as a vehicle fuel. For example, in 2014, 57 per cent of Swedish biogas production was used as automotive fuel[42]. The focus on vehicle fuel is somewhat misleading, since, when injected into a grid, biomethane is comingled with fossil-derived natural gas in the gas system, since the molecules are essentially indistinguishable. On the other hand, users have been willing to pay a premium to run vehicles on “green gas” (where their offtake of gas molecules is balanced by biomethane injection elsewhere on the grid), in order to promote a “green” image for their products.[43]

Biogas Production Costs

As noted previously, the thermo-chemical route to the production of biogas is still in the research and development phase, so this section considers the production costs of the more widely-used anaerobic digestion route to biogas and its subsequent upgrading to grid-quality biomethane.

The total production cost is influenced by many factors, notably a wide range of feedstock and associated transport costs, which can be negligible for readily available local waste, and substantial where energy crops are grown and transported over some distance.

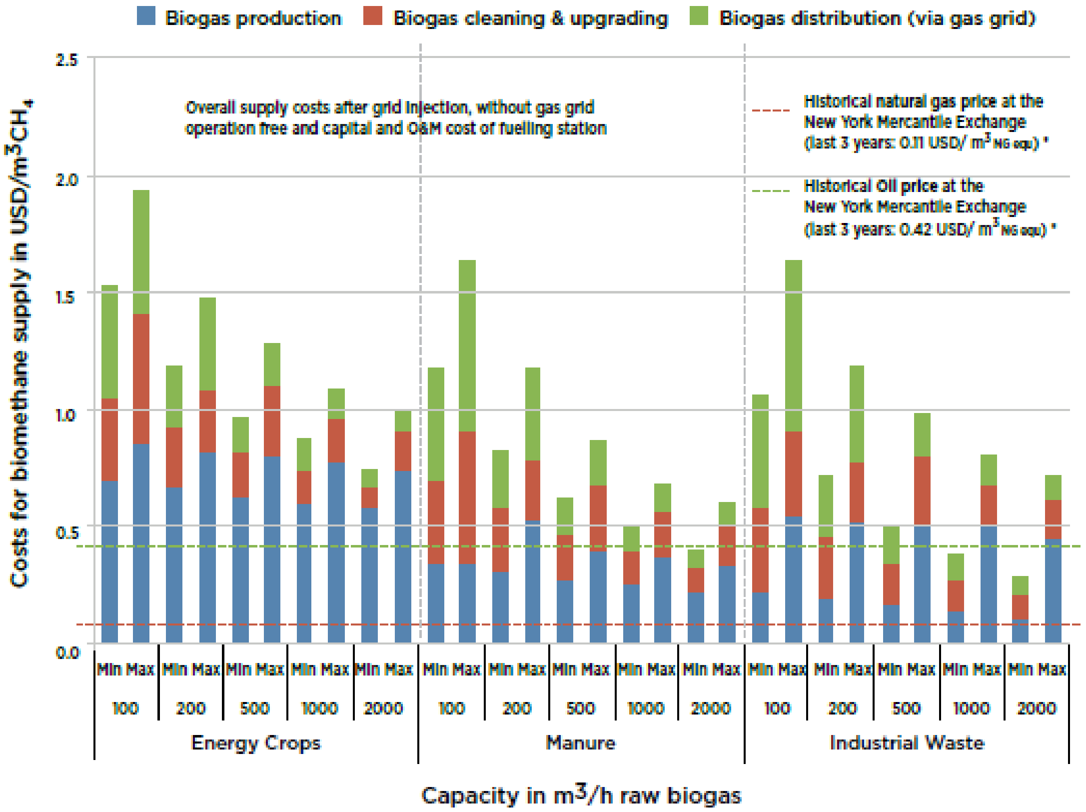
For raw biogas, the main outcome of interest is the levelised cost of electricity (LCOE) of the resulting power generation. The International Renewable Energy Agency (IRENA) has estimated that the LCOE using biogas from a digester can range from 6-14 USc/kWh[44]. The range is principally driven by feedstock costs – the low end being where manure or sewage is available free, and the high end where up to US$40/tonne is paid for energy crops. At the lower end of this range, the LCOE is

[38] Green Gas Grids, Proposal for a European Biomethane Roadmap, Dec 2013, p31
[39] Green Gas Grids, Proposal for a European Biomethane Roadmap, Dec 2013, p33
[40] Total demand and supply forecasts from Shell LNG Outlook, Feb 2017.
[41] Green Gas Grids, Proposal for a European Biomethane Roadmap, Dec 2013, p35
[42] IEA Task 37: Sweden Country report 2015
[43] See, for example: http://www.coca-cola.co.uk/stories/a-greener-fleet or http://www.gasvehiclehub.org/case-studies/10-case-studies/93-john-lewis-partnership-with-biomethane
[44] IRENA (2012): Renewable Energy Technologies Cost Analysis: Biomass for Power Generation (Fig 6.2)

comparable with the latest benchmark for onshore wind at 6.8 USc/kWh, and the higher end of the range is a little higher than the offshore wind benchmark of 12.6 USc/kWh[45].

For biomethane, on the other hand, the resulting cost of gas after upgrading and distribution to the end consumer is of primary interest. A recent study by IRENA, drawing together much of the previous work in the area, illustrates the resulting range in estimated biomethane costs (including upgrading of raw biogas and distribution via the existing gas grid), as shown in Figure 7: Total production costs for biomethane by feedstock and size.

Figure 7: Total production costs for biomethane by feedstock and size[46]



As can be seen, the estimated costs of biomethane range from as low as 0.5 US$/m³ (equivalent to 4.7USc/kWh or 14 US$/MMBtu) to more than 1.5 US$/m³ (equivalent to 15USc/kWh or 42US$/MMBtu). With natural gas prices to industrial customers in Europe typically around 4 EURc/kWh[47] (4.3 USc/kWh) biomethane at the lowest end of the cost curve is nearly competitive, but the higher costs are clearly uncompetitive in the absence of significant government subsidies.

The rapid decline in the cost of renewable energy from wind and solar in recent years has been well documented elsewhere[48]. There is not yet a clear pathway to significant cost reduction in biogas production, but the chart in Figure 7 suggests that at a large enough scale and with the right technology, some further cost reduction may be possible. The need for further research into potential cost reductions has already been recognised.[49]

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[45] BNEF, Nov 2016 (https://about.bnef.com/blog/h2-2016-lcoe-giant-fall-generating-costs-offshore-wind/)
[46] IRENA (2017): Biogas for Road vehicles, Technology Brief.
[47] Eurostat website: http://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics
[48] For example, BNEF, Nov 2016, op. cit.
[49] US DOE: 2014: Biogas Opportunities Roadmap

Greenhouse Gas Emissions impact

The assessment of greenhouse gas emissions is an extremely complex topic, and is dependent on a variety of factors, including the choice of feedstock, its transportation and handling, the specific production processes used, the amount of any methane leakage along the supply chain, and the end use of the product, as well as the overall calculation methodology. As noted earlier, biogas is mainly comprised a mixture of both methane and CO_2, both significant greenhouse gases.

Methane is assessed to have 28-36 times the global warming potential of CO_2 over a comparison period of 100 years - since CH_4 lasts for around a decade, whereas the impact of CO_2 lasts for thousands of years.[50] The extent to which biogas captures methane from organic waste which otherwise would have been emitted to atmosphere is beneficial, but it is important to minimise any methane releases along the entire supply chain.

Between 2010 and 2012, the European Union project "Biograce" aimed to harmonise calculations of Biofuel Greenhouse Gas Emissions.[51] This project was designed to address discrepancies in earlier calculations under the Renewable Energy Directive and the Fuel Quality Directive. The calculations are based on use in road vehicles compared with gasoline as the fossil fuel alternative. The results show three cases for the life cycle emissions of CNG derived from a variety of biogas sources, as summarised in Table 2.

Table 2: GHG emissions from CNG biomethane by feedstock

Feedstock	gCO_{2eq}/MJ	% reduction from gasoline
Biogas from organic waste	21.4	74%
Biogas from wet manure	14.4	83%
Biogas from dry manure	12.9	85%

Source: https://ec.europa.eu/energy/intelligent/projects/en/projects/biograce

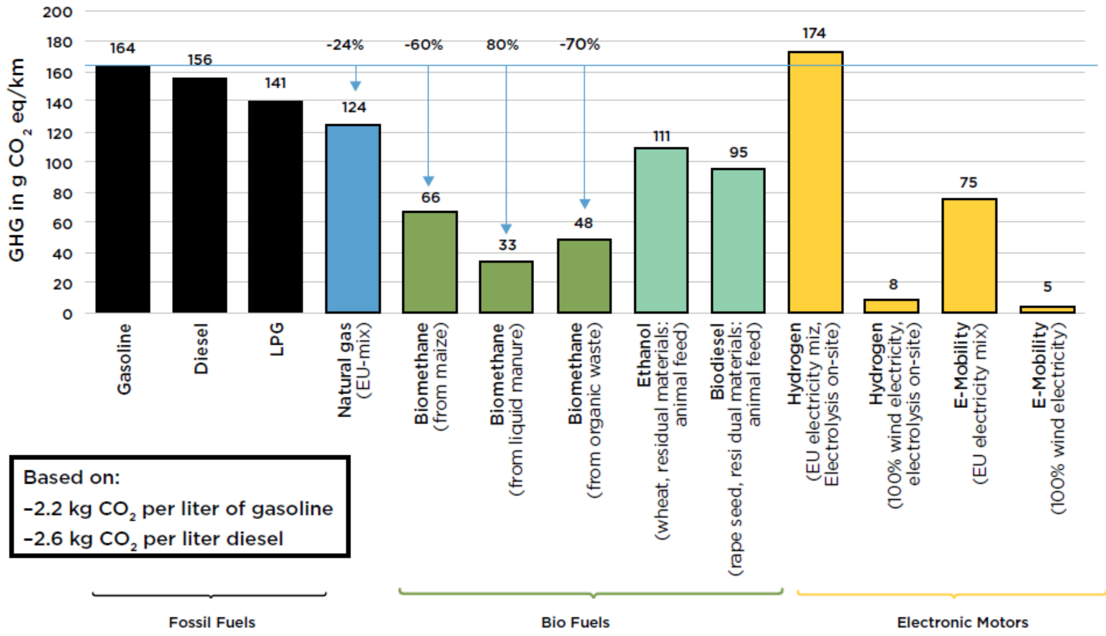
Figure 8 illustrates similar data and scale of reductions of GHG emissions from passenger cars when compared with fossil fuel alternatives.[52] While biomethane derived from energy crops (maize) has lower GHG saving than that from waste, the saving is still significant compared even to fossil-derived natural gas, which itself has the lowest GHG emissions among fossil fuels.

These values do not take account of emissions avoided by the productive use of waste which would otherwise have emitted significant quantities of methane and CO_2. According to McKinsey[53], the waste sector emitted three percent of global emissions in 2005, and it estimated an average cost of abatement of waste emissions (predominantly landfill gas) at *minus* EUR 14 per tCO_{2eq}, due to the avoidance of significant cost through the use of recycled goods in manufacturing processes.

A study of CO_2 abatement costs of different biogas conversion pathways[54] indicates that, for a variety of biowaste feedstocks, the lowest cost of abatement (at around *minus* 100 EUR/tCO_{2eq}) comes from a combined heat and power system based on raw biogas, while a system including upgrading to biomethane for injection into the natural gas grid could have a cost of abatement in excess of 100 EUR/tCO_{2eq}.

[50] US EPA: https://www.epa.gov/ghgemissions/understanding-global-warming-potentials
[51] https://ec.europa.eu/energy/intelligent/projects/en/projects/biograce
[52] IRENA (2017) Biogas for road vehicles, technology brief
[53] McKinsey (2009): Pathways to a low carbon economy, sec 8.8 p. 111
[54] Rehl/Müller (2012): CO2 abatement cost of GHG mitigation by different biogas conversion pathways

Figure 8: Comparative GHG emissions from passenger cars using different fuels



Source: IRENA (2017) Biogas for road vehicles, technology brief

Thus it is reasonable to conclude that production of biogas from waste from all sources (agricultural, forestry, industrial and municipal) for the production of combined heat and power is a very effective GHG mitigation measure. The use of energy crops, and the upgrading to biomethane for injection into the natural gas grid, can still reduce GHG emissions, but the specific circumstances will need to be considered in each case to explore potential lower cost of abatement solutions.

As noted in Jonathan Stern's earlier paper [55], there are essentially three elements to the decarbonisation of gas:

- Carbon capture and storage;
- Power to gas (renewable electricity producing hydrogen via electrolysis), and
- Biogas and biomethane.

Of these three alternatives, further work is needed to assess the likely marginal cost of abatement which could be achieved in the medium term, as a result of further technology improvements and increasing production scale, but biogas and biomethane look well positioned relative to the alternatives.

Impact of Government Policy

It is clear from the discussion under "Biogas Production Costs" that in the absence of a dramatic rise in the price of fossil-derived natural gas, the further development of biogas investments will continue to be driven by government support and incentives. It is also clear from the discussion under "Greenhouse Gas Emissions" that with an urgent need to decarbonise the energy system, biogas can and should have a role to play, particularly where it also reduces GHG emissions from waste.

As indicated earlier, Germany, by a large margin, has led the development of biogas, supported by a feed-in tariff system, and other legislation strongly supporting its development.[56] Italy has followed a

[55] Stern 2017: The Future of Gas in Decarbonising European Energy Markets

similar model[57], while the US has supported biogas production via Production Tax Credits and Investment Tax Credits[58]. Sweden has also strongly supported biogas, but with a particular focus on upgrading to biomethane for use in the transport sector.[59] Similarly, the UK Carbon Price Floor and Renewable Heat Incentive provides a feed-in tariff structure supporting both biogas production and upgrading to biomethane for grid injection.[60] All of these measures have provided sufficient incentives for rapid growth in investment in the relevant infrastructure.

The difficulty with such forms of government support, in an industry where technology is continuing to evolve, and where government resources and priorities evolve over time, is that they do not form a stable basis for making long term investment decisions and for the sustainable development of an industry. As can be seen from the example of Germany after 2014, following the recognition of the potential downside of over-reliance on energy crops, and resulting changes to legislation, this can result in a dramatic slow-down in investment, with associated impacts on profitability, jobs and rural communities. [61]

It is clear that biogas can continue to play a role in decarbonising the energy system, but there is a need to develop a more consistent and widely applied system of incentives in order to drive a more stable, long-term growth of the industry, rather than the localised, variable and uncertain policies which have prevailed to date.

Case Study: Biogas in Germany

To illustrate the various factors influencing the development of biogas, it is instructive to consider the case of Germany from the mid-1990s to the present.

From small beginnings …

Since 1990 (the first year after re-unification of the country), primary energy consumption has been gradually declining (from around 14.5 EJ pa in 1990 to around 13.5EJ in 2016), driven mainly by a rise in energy efficiency.

The first legislation to promote renewable energy was the Stromeinspeisungsgesetz (StrEG - Electricity Feed-in Act) of 1991. This granted electricity generation from all renewable energy sources (biomass, wind, solar) priority dispatch and a guaranteed feed-in tariff for twenty years. Under this legislation, the number of biogas plants grew from around 100 in 1990 to around 1000 by 2000, although over 75 per cent of these plants were very small, with a capacity <70 MW electricity. (IEA Task 40 2015 country report Germany).

… a change in legislation drives rapid growth…

In 2000, the StrEG was replaced by the Erneuerbare Energien Gesetz (EEG – Renewable Energy Act), which was then further modified in 2004 and 2009. This guaranteed a feed-in tariff for renewable electricity (albeit reducing by 1- 1.5 per cent per year to reflect expected improvements in technology), and in addition provided a "biomass bonus" for generation derived from any biomass source. A further incentive was given for use of residual heat in order to promote efficient combined heat and power (CHP) facilities. As a result the average plant now receives a price of around 22 ct/ kWh, while the wholesale spot electricity price is currently around 5c/kWh and the price to large industrial customers is around 15 c/kWh.

[56] IEA Task 37: Germany country report 2015.
[57] Torrijos, State of Development of Biogas Production in Europe 2015, Sec 4.0
[58] US EIA: https://energy.gov/sites/prod/files/2014/03/f10/june2012_biogas_workshop_serfass.pdf p16
[59] IEA Task 37: Sweden country report 2015
[60] IEA Task 37: United Kingdom country report 2015
[61] IEA Task 37: Germany country report 2015

By 2012, this had resulted in the construction of over 7000 biogas plants with an electricity generation capacity of around 3.5 GW, an average capacity of around 500MW per plant – significantly larger than previously.

...but then a further change substantially slows growth.

This rapid growth was largely driven by the use of energy crops, principally corn (maize), which provided around 75 per cent of the feedstock for biogas plants. This resulted in around one million hectares, or 8 per cent of German arable land, being used to grow maize as feedstock for biogas plants. There continues to be debate over whether or not this should be a concern (the producers' trade association, Fachverband Biogas, argues that this can be managed as part of normal crop rotation), but changes to the EEG in 2012 and 2014 removed incentives for use of energy crops.

The impact was dramatic: whereas around 1000 new biogas plants were added in each year from 2009 to 2011, this had dropped to less than 100 new plants per year by 2015. Nevertheless, with electricity generation from biogas at around 30 TWh / year, it still produces around 5 per cent of the total power demand of 600TWh, and an additional 12 TWh/ year is supplied as heat to local premises.

Biomethane for grid injection remains relatively small

Despite around 10,000 plants producing raw biogas in Germany, by end 2016 there were only around 200 plants producing upgraded biomethane for injection to the natural gas grid, with total energy injected around 8.5 TWh/year, or less than 1 per cent of total natural gas consumption.

BioEnergy Villages – a German model for others to follow?

Several rural communities in Germany (for example Jühnde in Lower Saxony in the North and Freiamt in Baden-Würtetemberg in the South) have been developed as "BioEnergy Villages". Perhaps more accurately termed renewable energy villages, these employ a combination of wind and solar electricity generation, together with biogas-fuelled combined heat and power to meet all of the heat and power needs of the local community as well as being able to export surplus electricity to the grid. Such villages have clearly benefited from the generous subsidies available under earlier renewable energy legislation, and the economics of future installations will be very location-dependent, but it does provide a model of biogas providing a valuable contribution to a feasible low-carbon energy solution.

A possible role for biogas in decarbonising the energy system

In considering the decarbonisation of the energy system, it is important to consider the overall system holistically, rather than considering individual technologies independently. There appear to be potential synergies for biogas and other renewable energy sources (notably intermittent wind and solar) to complement each other, particularly with the development of Smart Energy Grids.[62] The intermittency of solar and wind has been well documented – there is limited generation when the sun does not shine and/or the wind does not blow. Batteries, which continue to decline in cost, are clearly part of the solution, at least for managing intermittency hour by hour. There is a recognised need for other solutions for day by day, and month by month variations. Biogas could make a significant contribution to this.

The trend towards more decentralised energy systems has also been observed. The previous model, which had survived for over a century, of a relatively small number of large power plants feeding a distribution grid to spread the electricity to the end consumers, is being replaced with a much larger number of small power generators (for example, rooftop solar and local wind turbines) which then feed into the grid in many more locations.

As noted earlier, one of the key drivers to lower cost and lower carbon intensity for biomass-derived energy is to avoid transporting feedstock over long distances. With over 10,000 biogas plants in

[62] IEA (2014): Role of Biogas in Smart Grids.

Germany, it is clear that, like wind and solar, biogas production also leads to a distributed energy system. Unlike wind and solar, however, biogas has the advantage of allowing greater control over the timing of generation. This could be done by a combination of (a) varying the rate of feedstock supply to the digester, and so varying the amount of biogas production, and (b) relatively uniform production of biogas, with storage of the resulting biogas until electricity generation is required to balance the grid.[63] As this would require productive capacity to be idle some of the time and/or would incur costs of storage, these are likely to be higher cost alternatives than continuous, unconstrained production of electricity from biogas, and will require economic analysis for each case. However, wind, solar, and biogas could be an effective combination on the path towards a low carbon, decentralised energy system. As noted in the case study on Germany above, the combination is already being demonstrated in practice in the BioEnergy Villages[64].

The ability to upgrade biomethane to grid quality, although introducing additional cost, does allow for injection into the natural gas grid. The ability to store energy in existing infrastructure, and the ability to transport gas to be used for generation elsewhere adds further flexibility to the energy system. The relative merits of (a) upgrading to biomethane for injection into the gas grid, compared with (b) electricity generation from biogas with surplus power being exported to the electricity grid will need to be compared for individual cases.

The emerging technology of "Power to Gas" (P2G - the use of surplus renewable electricity to produce hydrogen or methane) may also be able to play a role: at this stage it is difficult to determine whether there will be a structural long-term cost advantage for biomethane over P2G.

Conclusions

- Europe has led the world in applying biogas technology. There has been more limited development in the United States, and for the rest of the world there remains a considerable opportunity to apply the technology, drawing on the lessons learned in Europe.
- Production of biogas from waste, which otherwise would have decomposed and released both methane and CO_2 to the atmosphere, appears an uncontroversial, low cost route to reduce carbon emissions. Selected governments, particularly in Europe, have already recognised this potential, but there is scope for the approach to be adopted more widely.
- Production of biogas from energy crops can also be beneficial, particularly where feeding a limited quantity of energy crops together with waste can enhance the production process. Care needs to be taken, and further research is required, to ensure that the land-use change implications are well understood and the growth of energy crops is not detrimental to other uses of the land or associated water resources, particularly for food production.
- The most cost-effective option is to use biogas near the point of production to meet local requirements for heat and/or power. Where there is insufficient local demand, upgrading to biomethane for injection into the gas grid can be a useful alternative.
- The scale of production will not replace the current level of fossil-derived natural gas consumption, but use of biogas (potentially combined with P2G) will enable continued utilisation of the existing natural gas infrastructure as the energy system decarbonises. In Europe, for example, biogas production could reach the equivalent of 50 Bcm, which is over half of the forecast indigenous natural gas production at that time.
- Biogas, with the ability to control timing of generation, will provide a useful low carbon complement to intermittent renewable power generation from wind and solar.

[63] IEA (2014): Role of Biogas in Smart Grids

[64] See for example: http://www.economist.com/news/briefing/21717365-wind-and-solar-energy-are-disrupting-century-old-model-providing-electricity-what-will and http://snapshotsfromberlin.com/2014/04/10/germanys-bioenergy-villages/

Glossary

Anaerobic Digestion ("AD")	A series of biological processes in which micro-organisms break down organic matter in the absence of oxygen to produce biogas as well as co-products (typically used as fertiliser in agriculture).
Biogas	The product of anaerobic digestion, typically comprising around 50-65 per cent methane, 30-50 per cent CO_2 and small quantities of other gases and impurities, depending on feedstock.
Biomethane	The product of biogas upgrading to remove most of the CO_2 and impurities resulting in a product, typically over 90 per cent methane which meets the quality standards for injection into a natural gas grid.
Bio-SNG or Renewable Natural Gas	The product of a thermo-chemical gasification process using biomass as a feedstock. Technically this product can have similar properties to biomethane but is still at the research and development stage.
CNG	Compressed Natural Gas: a way of increasing the density of natural gas (or biomethane) by storing it at high pressure either for transportation or for use as a transport fuel.
IEA	International Energy Agency
ILUC	Indirect Land Use Change: the impact of biofuel production on arable land resulting in agricultural production being displaced to land which was previously not used for agriculture (for example grasslands or forests).
IRENA	International Renewable Energy Agency
LCOE	Levelised Cost of Electricity: a methodology to compare various forms of electricity generation on a consistent basis by considering all lifetime costs and total lifetime production of electricity.
P2G	Power to Gas: the use of surplus renewable electricity to produce hydrogen or methane, as a potential mitigant for intermittency of wind and solar generation.
Wobbe Index	A function of heating value and specific gravity of gas: used to ensure that all gas injected into a particular network is sufficiently similar to be used interchangeably.