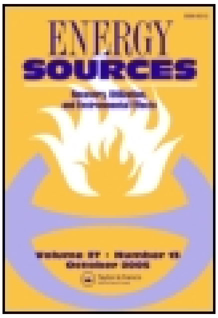

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Biogas as a Renewable Energy Source—A Review

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Abstract *This article reviews the production processes and characterization of biogas as an alternative energy source. Biogas, the gas generated from organic digestion under anaerobic conditions by mixed population of microorganisms, is an alternative energy source, which has been commenced to be utilized both in rural and industrial areas at least since 1958. Biogas technology offers a very attractive route to utilize certain categories of biomass for meeting partial energy needs. Unlike other forms of renewable energy, biogas neither has any geographical limitations and required technology for producing energy and it is neither complex or monopolistic.*

Keywords anaerobic digestion, biogas, feedstock, properties, reaction parameters, yield

Introduction

Energy demand forecasting is one of the most important policy tools used by the decision makers all over the world (Ediger and Akar, 2007). The high energy demand in the industrialized world as well as in the domestic sector, and pollution problems caused due to the widespread use of fossil fuels make it increasingly necessary to develop the renewable energy sources of limitless duration and smaller environmental impact than the traditional one (Meher et al., 2006). Renewables such as solar, wind, hydropower, and biogas are potential candidates to meet global energy requirements in a sustainable way (Muneer et al., 2006; Balat, 2007).

Biogas technology offers a very attractive route to utilize certain categories of biomass for meeting partial energy needs. In fact, proper functioning of biogas systems can provide multiple benefits to the users and the community resulting in resource conservation and environmental protection (Santosh et al., 2004). But what makes biogas distinct from other renewable energies is its importance in controlling and collecting organic waste material and at the same time producing fertilizer and water for use in agricultural irrigation. Unlike other forms of renewable energy, biogas neither has any geographical limitations and required technology for producing energy and it is neither complex or monopolistic (Taleghani and Kia, 2005).

Definition of Biogas

Biogas, a clean and renewable form of energy, could very well be a substitute (especially in the rural sector) for conventional sources of energy (fossil fuels, oil, etc.), which are causing ecological—environmental problems and at the same time depleting at a faster

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Table 1
Composition of biogas

	Typical analysis (% by volume)
Methane (CH_4)	55–65
Carbon dioxide (CO_2)	35–45
Hydrogen sulphide (H_2S)	0–1
Nitrogen (N_2)	0–3
Hydrogen (H_2)	0–1
Oxygen (O_2)	0–2
Ammonia (NH_3)	0–1

rate (Santosh et al., 2004). The most important biogas components are methane (CH_4), carbon dioxide (CO_2), and sulfuric components (H_2S) (Coelho et al., 2006). The gas is generally composed of methane (55–65%), carbon dioxide (35–45%), nitrogen (0–3%), hydrogen (0–1%), and hydrogen sulfide (0–1%) (Anunputtikul and Rodtong, 2004). Composition of biogas is presented in Table 1.

Due to its elevated methane content, resultant of the organic degradation in the absence of molecular oxygen, biogas is an attractive source of energy. The physical, chemical, and biological characteristics of the manure are related to diet composition, which can influence the biogas composition (Mogami et al., 2006). Natural gas is about 90–95% methane, but biogas is about 55–65% methane. So biogas is basically low-grade natural gas (House, 2007). The biogas composition is an essential parameter, because it allows identifying the appropriate purification system, which aims to remove sulfuric gases and decrease the water volume, contributing to improve the combustion fuel conditions (Coelho et al., 2006). Biogas has a heat value of approximately 5.0–7.5 kWh/m^3. Table 2 shows typical combustion properties of biogas.

Sources for Biogas

Biogas production has usually been applied for waste treatment, mainly sewage sludge, agricultural waste (manure), and industrial organic waste streams (Hartmann and Ahring, 2005). Table 3 cites some potential feedstocks in anaerobic digestion processes. The primary source, which delivers the necessary microorganisms for biomass biodegradation and as well one of the largest single sources of biomass from the food/feed industry, is manure from animal production, mainly from cows and pig farms. In the EU-27, more than 1,500 million tons (Mt) is produced every year (Nielsen et al., 2007). Table 4 depicts

Table 2
Typical combustion properties of biogas

Ignition point	700°C
Density (dry basis)	1.2 kg/m^3
Ignition concentration gas content	6–12%
Heat value	5.0–7.5 kWh/m^3

Table 3
Possible feedstock in anaerobic processes

Origins		
Agricultural origin	Industrial origin	Municipal origin
Animal waste	Wastewater	Sewage sludge
Crop waste	Sludge	Municipal solid waste
Dedicated energy crops	By-products	

Source: Buekens, 2005.

Table 4
Estimated amounts of animal manure in EU-27

Country	Cattle (1,000 heads)	Pigs (1,000 heads)	Cattle (1,000 livestock units)	Pigs (1,000 livestock units)	Cattle manure, Mt	Pig manure, Mt	Total manure, Mt
Austria	2,051	3,125	1,310	261	29	6	35
Belgium	2,695	6,332	1,721	529	38	12	49
Bulgaria	672	931	429	78	9	2	11
Cyprus	57	498	36	42	1	1	2
Czech R.	1,397	2,877	892	240	20	5	25
Denmark	1,544	13,466	986	1,124	22	25	46
Estonia	250	340	160	28	4	1	4
Finland	950	1,365	607	114	13	3	16
France	19,383	15,020	12,379	1,254	272	28	300
Germany	13,035	26,858	8,324	2,242	183	49	232
Greece	600	1,000	383	83	8	2	10
Hungary	723	4,059	462	339	10	7	18
Ireland	7,000	1,758	4,470	147	98	3	102
Italy	6,314	9,272	4,032	774	89	17	106
Latvia	371	436	237	36	5	1	6
Lithuania	792	1,073	506	90	11	2	13
Luxembourg	184	85	118	7	3	0	3
Malta	18	73	11	6	0	0	0
Netherlands	3,862	11,153	2,466	931	54	20	75
Poland	5,483	18,112	3,502	1,512	77	33	110
Portugal	1,443	2,348	922	196	20	4	25
Romania	2,812	6,589	1,796	550	40	12	52
Slovakia	580	1,300	370	109	8	2	11
Slovenia	451	534	288	45	6	1	7
Spain	6,700	25,250	4,279	2,107	94	46	140
Sweden	1,619	1,823	1,034	152	23	3	26
U.K.	10,378	4,851	6,628	405	146	9	155
EU-27	91,364	160,530	58,348	13,399	1,284	295	1,578

Source: Nielsen et al., 2007.

Table 5
Energy potential of pig and cattle manure in EU-27

Total manure, Mt	Biogas, Mm^3	Methane, Mm^3	Potential, PJ	Potential, Mtoe
1,578	31,568	20,519	827	18.5

Mt (million tons), Mm^3 (million cubic meter); Mtoe (million tons oil equivalent); 1 Mtoe = 44.8 PJ.

Methane heat of combustion: 40.3 MJ/m^3; Assumed methane content in biogas: 65%.

Source: Nielsen et al., 2007.

the amount of cattle and pig manure produced every year in the European Union. Table 5 shows the biogas and energy potential of pig and cattle manure in the EU-27.

Anaerobic digestion of organic fraction municipal solid waste (OFMSW) has been studied in recent decades, trying to develop a technology that offers waste stabilization with resources recovery (Nguyen et al., 2007). The anaerobic digestion of municipal solid waste (MSW) is a process that has become a major focus of interest in waste management throughout the world. In India, the amounts of MSW generated in urban areas range from 350 to 600 g per capita/day (Elango et al., 2006). MSW stream in Asian cities is composed of high fraction of organic material of more than 50% with high moisture content (Juanga et al., 2005).

Currently, biogas production is mainly based on the anaerobic digestion of single energy crops. Maize, sunflower, grass, and sudan grass are the most commonly used energy crops. In the future, biogas production from energy crops will increase and requires to be based on a wide range of energy crops that are grown in versatile, sustainable crop rotations (Bauer et al., 2007).

A specific source of biogas is landfills. In a typical landfill, the continuous deposition of solid waste results in high densities and the organic content of the solid waste undergoes microbial decomposition (Filipkowska and Agopsowicz, 2004). The production of methane-rich landfill gas from landfill sites makes a significant contribution to atmospheric methane emissions. In many situations the collection of landfill gas and production of electricity by converting this gas in gas engines is profitable and the application of such systems has become widespread. The benefits are obvious: useful energy carriers are produced from gas that would otherwise contribute to a build-up of methane greenhouse gas (GHG) in the atmosphere, which has stronger GHG impact than the CO_2 emitted from the power plant. This makes landfill gas utilization, in general, a very attractive GHG mitigation option that is widely adopted throughout the EU and North America and increasingly deployed in other world regions (Faaij, 2006).

Biogas Production Processes

Biogas, the gas generated from organic digestion under anaerobic conditions by mixed population of microorganisms, is an alternative energy source, which has been commenced to be utilized both in rural and industrial areas at least since 1958 (Anunputtikul and Rodtong, 2004). In the complex process of anaerobic digestion, hydrolysis/acidification and methanogenesis are considered as rate-limiting steps (Juanga et al.,

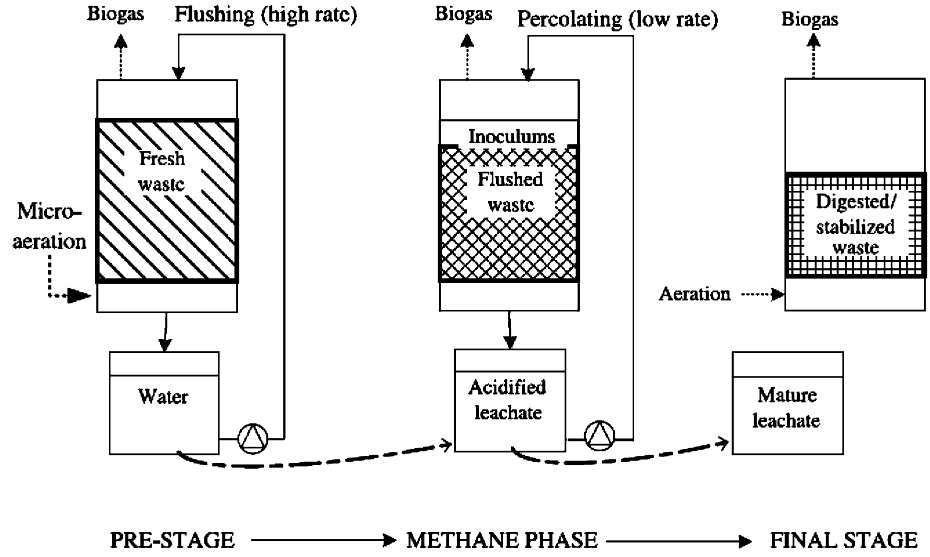

Figure 1. Schematic diagram of the three-stage anaerobic digestion system. *Source*: Nguyen et al., 2007.

2005; Nguyen et al., 2007). Figure 1 illustrates the three stages involved in the combined anaerobic digestion process (Nguyen et al., 2007). Since hydrolytic/acidogenic bacteria and methanogens have different growth requirements, it may not be possible to use a single-phase system, especially in high-solid digestion where substrates are concentrated and volatile fatty acids are produced in high amounts inhibiting the growth of methanogens. Thus, separation of hydrolysis/acidogenesis and methanogenesis would possibly enhance the process. Growth of hydrolytic and acidogenic bacteria can be optimized in the first stage where methanogenesis can be optimized in the second stage. In parallel, the rate of pre-stage reaction can be optimized by applying microaeration (Juanga et al., 2005). Typical reactions during anaerobic digestion are (Ostrem et al., 2004):

$$\underset{\text{(organic compound)}}{C_6H_{12}O_6} \rightarrow \underset{\text{(ethanol)}}{2C_2H_5OH} + \underset{\text{(carbon dioxide)}}{2CO_2} \tag{1}$$

$$\underset{\text{(ethanol)}}{2C_2H_5OH} + \underset{\text{(carbon dioxide)}}{CO_2} \rightarrow \underset{\text{(methane)}}{CH_4} + \underset{\text{(acetic acid)}}{2CH_3COOH} \tag{2}$$

$$\underset{\text{(acetic acid)}}{CH_3COOH} \rightarrow \underset{\text{(methane)}}{CH_4} + \underset{\text{(carbon dioxide)}}{CO_2} \tag{3}$$

$$\underset{\text{(carbon dioxide)}}{CO_2} + \underset{\text{(hydrogen)}}{4H_2} \rightarrow \underset{\text{(methane)}}{CH_4} + \underset{\text{(water)}}{2H_2O} \tag{4}$$

The biogas produced in anaerobic digestors could contain methane concentrations of until 80% in volume, and its quality would depend on its origin (drain, anaerobic digestion of residual waters, or treatment of residuals) (Benito et al., 2007). The end products of anaerobic digestion are biogas and digestate, a moist solid, which is normally dewatered to produce a liquid stream and a drier solid. The components of the biogas depend on the process of digestion, but are predominately methane and CO_2. The solid is a humus-like, stable, organic material, the quality and subsequent use of which is determined by the characteristics of the feedstock to the anaerobic digestion process. The liquid contains soluble materials, including dissolved organic compounds. In a typical anaerobic digestion facility processing OFMSW, the gas mass comprises about 15% of the output stream and the liquid and solid compose approximately equal parts, or 42.5% each (Ostrem, 2004).

Anaerobic digestion offers an effective way to manage dairy manure by addressing the principal problems of odor and environmental control while offering an opportunity to create energy from conversion of biogas with a system of combined heat and power (CHP). The use of biogas as an energy source has numerous applications. However, all of the possible applications require knowledge about the composition and quantity of constituents in the biogas stream (Scott et al., 2006).

The most widely employed systems are granular sludge-based bioreactors, such as the upflow anaerobic sludge blanket (UASB), expanded granular sludge bed, and the anaerobic hybrid reactor, which consists of a granular sludge bed and an upper fixed bed section (Pender et al., 2004). The advantage of the UASB design is the ability to retain high biomass concentrations despite the upflow velocity of the wastewater and the production of biogas. Consequently, the reactor can operate at short hydraulic retention times since the sludge retention time is almost independent of the hydraulic retention time. In UASB reactors, the biomass is retained as granules, formed by the natural self-immobilization of the bacteria (Trnovec and Britz, 1998). Most of the anaerobic reactor types tried have achieved quite satisfactory removals of chemical oxygen demand (COD) (Gelegenisa et al., 2007). Throughout the recent years the performance of biogas reactors has been increased through a better control of the process and improved reactor design based on a better understanding of the process mechanisms and inhibiting factors. On a worldwide basis, the biogas process will still have its singificance as a robust and easily to establish low-cost technology for the treatment of organic waste. Especially in developing countries like China, India, and Africa thousands of simple small-scale reactors are under operation and will still, in the future, have their benefit of waste management combined with decentralized energy production (Hartmann and Ahring, 2005).

Although most full-scale anaerobic treatment plants are operated at mesophilic temperatures (typically 35°C–37°C), many wastewaters are discharged at relatively high temperatures making these effluents potentially attractive for thermophilic anaerobic treatment. In recent years, thermophilic systems have become a more common option for medium- and high-strength wastewaters since they are capable of handling very high organic loading rates while maintaining high treatment efficiency. However, significant drawbacks of thermophilic processes include: (a) they are reported to be more sensitive to environmental perturbations than mesophilic systems and (b) the formation of granular sludge is not straightforward under thermophilic conditions (Pender et al., 2004).

Parameters in Anaerobic Digestion

The performance of biogas plants can be controlled by studying and monitoring the variation in parameters like pH, temperature, carbon/nitrogen ratio, retention time, etc. Any drastic change in these can adversely affect the biogas production. So these parameters should be varied within a desirable range to operate the biogas plant efficiently (Santosh et al., 2004).

pH

pH is a major variable to be monitored and controlled. The range of acceptable pH in digestion is theoretically from 5.5 to 8.5. However, most methanogens function only in a pH range between 6.7 and 7.4 (Buekens, 2005). A falling pH can point toward acid accumulation and digester instability. Gas production is the only parameter that shows digester instability faster than pH (Ostrem, 2004). For an anaerobic fermentation to proceed normally, concentration of volatile fatty acids, acetic acid in particular, should be below 2,000 mg/l (Santosh et al., 2004).

Temperature

Bacteria have a limited range of temperature in which they are active (Elango et al., 2006). Methane production has been documented under a wide range of temperatures, but bacteria are most productive in either mesophilic conditions, at 25°C–40°C, or in the thermophilic range, 50°C–65°C. A mesophilic digester must be maintained between 30°C and 35°C for optimal functioning. A thermophilic digester is maintained near 50°C (Ostrem et al., 2004).

C/N Ratio

It is necessary to maintain proper composition of the feedstock for efficient plant operation so that the C/N ratio in feed remains within a desired range. It is generally found that during anaerobic digestion microorganisms utilize carbon 25–30 times faster than nitrogen. Thus, to meet this requirement, microbes need a 20–30:1 ratio of C to N with the largest percentage of the carbon being readily degradable (Santosh et al., 2004). A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure (Verma, 2002).

Retention Time

In anaerobic digestion technology, two types of reactors are used: the batch process and the continuous process. In the batch process, the substrate is put in the reactor at the beginning of the degradation period and sealed for the duration of digestion. All of the reaction stages occur more or less consecutively and therefore the production of biogas follows a bell curve. Retention time ranges from 30–60 days and only about 1/3 of the tank volume is used for active digestion (Ostrem et al., 2004).

If anaerobic digestion is to compete with other MSW disposal options, the retention time must be lower than the current standard of 20 days. The retention time is determined by the average time it takes for organic material to digest completely, as measured by the chemical and biological oxygen demand (COD and BOD) of exiting effluent. Speeding up the process will make the process more efficient. Microorganisms that consume organic material control the rate of digestion that determines the time for which the substrate must remain in the digestion chamber, and therefore the size and cost of the digester (Ostrem et al., 2004).

Reducing retention time reduces the size of the digester, resulting in cost savings. Therefore, there is incentive to design systems that can achieve complete digestion in shorter times. A shorter retention time will lead to a higher production rate per reactor volume unit, but a lower overall degradation. These two effects have to be balanced in the design of the full-scale reactor. Several practices are generally accepted as aiding in reducing retention time. Two of these are continuous mixing and using low solids (Ostrem, 2004).

Biogas and Methane Yields

Accumulated biogas yields over the retention time were fitted by regression analysis with an exponential form of the Chapman function (Mahnert et al., 2002; Prochnow et al., 2005):

$$y(t) = y_{\max}(1 - e^{-a*t})^{b} \tag{5}$$

where $y(t)$ = biogas yield at time t (lN/kg VS); $y_{\max}$ = maximum biogas yield (lN/kg VS); t = time (d); and a, b = coefficients.

Methane contents in the biogas were also fitted by regression analysis using an empirical equation of the Hill function (Mahnert et al., 2002; Prochnow et al., 2005):

$$p_{CH_4}(t) = p_0 + a\frac{t^b}{c^b + t^b} \tag{6}$$

where p_{CH_4} = methane content at time t (vol%); p_o = minimum content of methane (vol%); a, b, c = coefficients. Accumulated methane yields over the retention time can be calculated by multiplication of Eqs. (5) and (6).

Up to now the preferred cultivated energy crops are maize (*Zea mays*), different cereals like rye (*Secale cereale*) and triticale (*Triticum X Secale*), and to some extent sugar beet (*Beta vulgaris*). In addition to the cereals already in use wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*) are of interest as input material. Viewing on growing conditions, plants like hemp (*Cannabis sativa*) or alfalfa (*Medicago sativa*) are remarkable substrates as well. Experiments have demonstrated that maize and cereals harvested at milk ripeness gain the highest yields in biogas. Under laboratory conditions these crops produce within approx. 28 days 450 to 920 m^3 biogas per ton dry matter (DM) with an average methane content of 50 to 60% (Table 6). These yields of energy crops compare to the biogas yields obtained from animal manure and animal slurry, which ranges from 370 m^3 per ton DM cattle manure to 450 m^3/ton DM pig manure with average methane contents of 60 to 65%. In Table 7 dry matter content and organic dry matter as well as methane or biogas yields are summarized for a whole range of tropical substrates (Plöchl and Heiermann, 2006).

With biogas production, the key factor to be optimized is the methane yield per hectare. This may result in different harvesting strategies when growing energy crops for anaerobic digestion compared to growing them as a forage source for ruminants. Specific harvest and processing technologies and specific genotypes are required when crops are used as a renewable energy source. Table 8 compares energy yields from specialized and integrated crop rotations from arable land in EU-25. The total arable land is 93 million hectares. In the specialized crop rotation, it is assumed that 20% of arable land is used for energy crop production, and that a mean of 234 GJ energy ha^{-1} a^{-1} is produced. This

Table 6
Biogas and/or methane yields from energy crops

Energy crop	DM (% FM)	ODM (% DM)	Biogas yield ($Nm^3\ t^{-1}$ ODM)	Methane yield ($Nm^3\ t^{-1}$ ODM)
Forage mix	10–16	86–91		297–370
Paddock mix	10	88		246
Clover	9–17	88–91		290–390
Alfalfa	14–35	84–88	514–737	283–405
Maize	30–48	96–97		247–375
Barley	25–38	90–93	694–920	382–506
Rye	33–46	91–93	733–734	403–404
Triticale	27–41	93–95	740–807	407–444
Sugar beet	22	90	840	504
Turnip	23	95		400
Hemp	28–36	92–93	452–485	250–267

DM = dry matter; FM = fresh matter; ODM = organic dry matter, Nm^3 = norm cubic meter, i.e., volume is standardized to norm conditions of 0°C, 1,023 mbar air pressure and 0% relative humidity.

Source: Plöchl and Heiermann, 2006.

Table 7
Biogas and/or methane yields from different tropical substrates

Substrate	DM (% FM)	ODM (% DM)	Methane yield ($Nm^3\ t^{-1}$ ODM)	Biogas yield ($Nm^3\ t^{-1}$ ODM)
Bagasse				165
Banana peel		87–94	243–322	
Citrus waste		89–97	433–732	
Coriander waste		80–86	283–325	
Mango peel		89–98	370–523	
Oil palm fibre	37	94	183	
Onion peels		88	400	
Pine apple waste		93–95	355–357	
Pomegranate		87–97	312–430	
Rice				
Straw	87	86	210	
Seed hull	86	84	17–22	
Sapote peels		96	244	
Tomato waste		93–98	211–384	
Water hyazinth	7	81	211–310	

DM = dry matter; FM = fresh matter; ODM = organic dry matter, Nm^3 = norm cubic meter, i.e., volume is standardized to norm conditions of 0°C, 1,023 mbar air pressure and 0% relative humidity.

Source: Plöchl and Heiermann, 2006.

Table 8

Annual energy yields of specialized and integrated crop rotation from arable land in EU-25 (Arable land in EU-25: 93 million ha)

Specialized crop rotation	Integrated crop rotation
Specialized energy crop production on 20% of the arable land 18.6 million ha	Integrated energy crop production on the whole arable land: 93 million ha
Energy yield (methane): 234 GJ ha^{-1} a^{-1}	Energy yield (methane): 20.5 GJ ha^{-1} a^{-1} Energy yield (ethanol): 76.1 (109.1) GJ ha^{-1} a^{-1}
Energy production: 4,352,400 TJ a^{-1} 104 Mtoe a^{-1}	Energy production: 9,727,800 (13,122,300) TJ a^{-1} 232 (313) Mtoe a^{-1}

Total energy demand of road traffic in EU-25: 334 Mtoe a^{-1}.
Source: Bauer et al., 2007.

results in an energy production in EU-25 of 4,352,400 TJ a^{-1}. This amount of energy corresponds to 104 Mtoe a^{-1} (Bauer et al., 2007).

The energy of the biogas comes from the methane. Methane has an energy value of 37.78 MJ/m_n^3. Allowing for 55% methane, then the energy value of biogas is about 21 MJ/m_n^3 (Murphy, 2005).

Categories of Biogas Plants

The biogas plants studied were in one of two categories. The first was farm-based plants (Table 9), and the other was community-based, or co-operative plants (Table 10). The farm-based plants were located on farms, but some were solely operated by the farm owner, while others involved partnerships between two or three farm owners. Others were located at the farm site, but were owned and operated by companies separate from the farm. The community and co-operative sites were large commercial sites collecting manure from as many as 200 farms, digesting it, and then returning it to the farms to be land applied. Two research station plants were also visited (Table 11) (House, 2007).

Uses of Biogas

The produced biogas may be utilized for CHP production or for transport fuel production as CH_4-enriched biogas. When used to produce transport fuel some of the biogas is used in a small CHP unit to meet electricity demand on site. This generates a surplus thermal product (Murphy and McKeogh, 2004).

Traditionally, biogas has been burned in internal combustion engines for the electricity production and heat, but its potential use in fuel cells could increase its electric efficiency, especially in applications at low scale, diminishing the NOx emissions to the atmosphere (Benito et al., 2007).

To use biogas as a transport fuel, the carbon dioxide, impurities and water content of the gas should be removed. This process of cleaning the biogas is known as scrubbing and is carried out to increase the calorific value of the gas. To utilize the gas as a transport fuel, the gas is usually scrubbed to a methane content of more than 97%. Once the biogas is cleaned, it is known as CH_4-enriched biogas. CH4-enriched biogas has an energy value of 36.6 MJ/m_n^3 and replaces 1 liter of petrol (Murphy, 2005).

Table 9
Farm-based biogas plants

Biogas plant	Company	Feedstock	BG production, m^3/day	Methane content, %	Genset, kW	Energy production, kWh/day
Eissen Dairy	PlanET	50% hog manure 50% dairy manure Corn silage		54	2 × 625	20,000
Beeston	Lipp	75% hog manure 25% beef cattle Ground corn	1,680	52	190 250	10,000
Spargelhof Querdl	Bio Energy	Turkey manure Corn silage		52	120 190	
Bioenergie Ahden	Biogas Nord	30% hog manure 70% food waste		65–70	750	
Hohne	Archea	Corn silage Wheat in secondary			500	
RWG Jameln	Biogas Nord	Manure Corn silage	7,000	53	250 300	
Agrarenergie Kaarben	BioConstruct	Dairy manure Corn silage	28,800	51–52	2 × 1,416	
Hegndal	Skaaning	Hog manure Fish waste	3,600		300	11,500
Skovbaekgaard Diary	Skaard	Dairy manure Vegetable fats Glycerine			625	8,000
SNO	PlanET	Dairy manure Hog manure Vegetables	1,600		200	

Source: House, 2007.

Typically 1 m_n^3 of biogas will generate 0.57 m_n^3 of CH_4-enriched biogas and replace 0.57 liters of petrol. In April 2005, 1 liter of petrol cost approximately €1; thus biogas may generate a revenue of €0.47/m_n^3 (excluding VAT at 21%). In terms of electricity production, 1 m_n^3 of biogas will generate 2 kWh of electricity, which will generate a revenue of €0.14 (allowing €0.07/kWh from biogas). A significant revenue advantage (€0.33/m_n^3) is available in utilizing biogas as a transport fuel in Ireland rather than as a raw material for the production of electricity (Murphy, 2005).

Conclusions

Biogas is most commonly produced by using animal manure mixed with water, which is stirred and warned inside an airtight container, known as a digester. The most important biogas components are methane, carbon dioxide, and sulfuric components. The is gas

Table 10
Community and co-operative biogas plants

Biogas plant	Company	Feedstock	BG production, m^3/day	Methane content, %	Genset, kW	Energy production, kWh/day
Bio Energie Haestal	Schmack	Manure Corn silage	10,000	52–55	10 × 80	19,200
Wertle	Krieg & Fischer	60% manure 40% food waste	25,000	60–65	2 × 1,250	10,000
Ribe	Kruger	Manure Food waste	13,150		2 × 1,000	
Juhnde Village	Haas Anlagenbau	Dairy manure Corn silage Ground corn	7,800	50–52	700	

Source: House, 2007.

Table 11
Other biogas plants

Biogas plant	Company	Feedstock	BG production, m^3/day	Methane content, %	Genset, kW	Energy production, kWh/day
Futterkamp Research Station	Envitec	Dairy manure Corn silage			330	
Nij Bosma Zathe	Krieg & Fischer	Dairy manure Silage crops Food wastes		Up to 75%	37	

Source: House, 2007.

generally composed of methane (55–65%), carbon dioxide (35–45%), nitrogen (0–3%), hydrogen (0–1%), and hydrogen sulfide (0–1%).

Anaerobic processes could either occur naturally or in a controlled environment such as a biogas plant. Organic waste such as livestock manure and various types of bacteria are put in an airtight container called digester so the process could occur. In the complex process of anaerobic digestion, hydrolysis/acidification and methanogenesis are considered as rate-limiting steps.

The performance of biogas plants can be controlled by studying and monitoring the variation in parameters like pH, temperature, carbon/nitrogen ratio, retention time, etc. Any drastic change in these can adversely affect the biogas production. So these parameters should be varied within a desirable range to operate the biogas plant efficiently.

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