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Renewable methane from anaerobic digestion of biomass

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Abstract

Production of methane via anaerobic digestion of energy crops and organic wastes would benefit society by providing a clean fuel from renewable feedstocks. This would replace fossil fuel-derived energy and reduce environmental impacts including global warming and acid rain. Although biomass energy is more costly than fossil fuel-derived energy, trends to limit carbon dioxide and other emissions through emission regulations, carbon taxes, and subsidies of biomass energy would make it cost competitive. Methane derived from anaerobic digestion is competitive in efficiencies and costs to other biomass energy forms including heat, synthesis gases, and ethanol. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Why renewable energy?

In the 1970s, the US and other developed countries experienced an energy crisis. We were told by government officials and energy companies that fossil fuels were soon to be depleted and that we must reduce energy consumption and very rapidly move to alternative energy supplies with emphasis on renewable sources

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such as solar and biomass. Then as fast as this crisis appeared, it disappeared in the late 1980s. Gas prices plummeted, numerous renewable energy businesses folded, and funding for renewable energy disappeared. Did the basis for the energy crisis go away? It was definitely delayed for the distant future. Conservation practices and new discoveries of fossil fuels relieved the near-term immediacy of the problem and special interest groups encouraged revival of the fossil fuel addiction.

A revived interest in renewable energy and related conversion technologies is emerging again. Although the eventual depletion of fossil fuels lurks in the background as a long-term incentive for development of sustainable energy forms, more urgent incentives to re-emphasize renewable energy are related to global environmental quality. The first concern to emerge was release of toxic compounds and oxides of nitrogen and sulfur resulting from combustion of fossil fuels. These air pollutants contribute globally to health and environmental problems the most common of which is referred to as acid rain. The greatest concern, however, is the threat of global warming related to increasing concentrations of carbon dioxide and other upper atmospheric pollutants resulting from anthropogenic activities. Use of renewable biomass (including energy crops and organic wastes) as an energy resource is not only "greener" with respect to most pollutants, but its use represents a closed balanced carbon cycle with respect to atmospheric carbon dioxide. It also could mitigate atmospheric carbon dioxide levels through replacement of fossil fuels. A third concern is the recognized need for effective methods for treatment and disposal of large quantities of municipal, industrial, and agricultural organic wastes. These wastes may not only represent a threat to environmental quality, but also represent a significant renewable energy resource.

2. Why methane?

Biomass may be converted to a variety of energy forms including heat (via burning), steam, electricity, hydrogen, ethanol, methanol, and methane. Selection of a product for conversion is dependent upon a number of factors, including need for direct heat or steam, conversion efficiencies, energy transport, conversion and use hardware, economies of scale, and environmental impact of conversion process waste streams and product use. Under most circumstances methane is an ideal fuel. Currently it represents about 20% of the US energy supply. Related to this, an extensive pipeline distribution system and a variety of hardware are in place for its domestic, municipal, and industrial use. Compared to other fossil fuels, methane produces few atmospheric pollutants and generates less carbon dioxide per unit energy. Because methane is comparatively a clean fuel, the trend is toward its increased use for appliances, vehicles, industrial applications, and power generation. Although some applications require high purity methane, it can be used in a variety of stages of purity and efficiencies of transport and energy conversion are good compared to electricity. Other fuels such as methanol and hydrogen are not well developed commercially for production and use and are more difficult to produce from biomass. Ethanol is becoming a popular biomass-derived fuel. Although it has the advantage of easy storage and transport, the fermentation process for its production requires extensive feedstock pretreatment and pure culture maintenance, and energy requirements associated with feed processing and product separation result in overall low process efficiencies. These problems are not characteristic of processes for biological conversion of biomass to methane.

3. Conversion processes

Methane can be produced from biomass by either thermal gasification or biological gasification (commonly referred to as anaerobic digestion). Economic application of thermal processes is limited to feeds with either a low water content ($<50\%$) or those having the potential to be mechanically dewatered inexpensively. This limitation is linked to energy needed for evaporation of water in order to achieve high temperatures required for the process. Feedstocks containing 15% total solids require all of the feed energy for water removal. Thermal processes for methane production also are only economic at large scales and generate a mixture of gaseous products (e.g. hydrogen and carbon monoxide) that must be upgraded to methane. This paper emphasizes biological gasification which is a low-temperature process that can convert wet or dry (with added water) feeds economically at a variety of scales. The product gas is composed primarily of methane and carbon dioxide with traces of hydrogen sulfide and water vapor. The major limitation of biological gasification is that conversion is usually incomplete, often leaving as much as 50% of the organic matter unconverted. However, land application of these compost residues is compatible with topsoil maintenance and related sustainable use of the land for growth of biomass. Process rates are significantly lower than those of thermal processes and the bacteria involved require a balanced diet of nutrients that may not be available in some feedstocks.

4. Principles of anaerobic digestion

Anaerobic digestion is an application of biological methanogenesis which is an anaerobic process responsible for degradation of much of the carbonaceous matter in natural environments where organic accumulation results in depletion of oxygen for aerobic metabolism. This process, which is carried out by a consortium of several different microorganisms, is found in numerous environments, including sediments, flooded soils, animal intestines, and landfills. Anthropogenic (man-caused) stimulation of methane formation and release into the atmosphere is of recent concern because, like carbon dioxide, it is also a significant greenhouse gas. The major sources of concern are flooded soil crops, domestic animals with rumens, landfills, and animal waste handling facilities.

In a generalized scheme for anaerobic digestion, feedstock is harvested or collected, coarsely shredded, and placed into a reactor which has an active inoculum of microorganisms required for the methane fermentation. A conventional reactor is mixed, fed once or more per day, heated to a temperature of 35°C, and operated at a hydraulic retention time of 20–30 days and loading rate of 1.7 kg VS (organic matter as ash-free dry weight) m^3 d^{-1} (0.1 lb VS $ft^{-3}day^{-1}$). Under these conditions, about 60% reduction in organic matter is achieved corresponding to a methane yield of 0.24 m^3 per kg (4.0 ft^3 per lb) VS added. The biogas composition is typically 60% methane and 40% carbon dioxide with traces of hydrogen sulfide and water vapor. Solid residues may be settled and/or dewatered by other means and used as a compost. The product gas can be used directly or processed to remove carbon dioxide and hydrogen sulfide.

This conventional design is being replaced by more innovative designs influenced primarily by feed suspended solids content. The objectives of most of these advanced designs are to increase solids and microorganism retention, decrease reactor size, and reduce process energy requirements. For dilute low solids (<1%) wastes such as food processing wastes, attached-film reactors are employed. Attachment of organisms on to inert media permits low retention times (<1 day) without washout. In designs for feeds with intermediate solids (5–10%) content (e.g. sewage sludges or aquatic plants), solids and organisms are recycled following settling within the digester or in a separate secondary digester. For high solids feedstocks (>10%) high-solids stirred digesters or leachbed batch systems are being used. These improved designs have increased possible loading rates 20-fold, reduced residence times, and improved process stability. Study of the biochemical methane potential of numerous biomass feedstocks (Table 1) has shown that many exceed the 50% usually associated with anaerobic digestion; for example biodegradability of some sorghum varieties exceeds 90% with corresponding methane yields of 0.39 m^3 per kg VS.

Table 1
Range of biochemical methane potential data for biomass or waste feedstocks of which several samples were analyzed [4]

Sample	B_o lg^{-1} VS	k d^{-1}
Kelp (*Macrocystis*)	0.39–0.41	
Sorghum	0.26–0.39	
Sargassum	0.26–0.38	
Napiergrass	0.19–0.34	0.05–0.16
Poplar	0.23–0.32	
Water hyacinth	0.19–0.32	0.09–0.11
Sugarcane	0.23–0.30	0.05–0.16
Willow	0.13–0.30	0.01–0.04
Laminaria	0.26–0.28	
Municipal solid waste	0.20–0.22	0.13–0.16
Avicel Cellulose	0.37	0.14

5. Renewable methane from biomass

Several research programs investigated energy crops (aquatic and marine plants, grasses, and woods) coupled with anaerobic digestion for generation of renewable substitute natural gas. These programs integrated research on crop production and harvesting, conversion to methane by anaerobic digestion, and systems analysis. Resource potential estimates for these feedstocks (Table 2) have been reported at 7 EJ (one exajoule = 1 quad = 10^{15} Btu) for wastes and 22 EJ for terrestrial biomass (grasses and woods). Estimates in Table 2 indicate that the potential from land-based biomass is about 22 EJ. The potential for marine biomass is huge at greater than 100 EJ per year. All of the US energy needs could be supplied by marine macroalgae grown on about 243 million hectares (one million square miles) of ocean. However, this optimistic estimate has many uncertainties related primarily to design of offshore farms. Table 3 shows that the cost of methane from these renewable energy systems was significantly higher (2–10 times) than fossil-derived energy and interest in their continued funding dwindled with continuation of energy gluts and depressed prices in the 1980s.

Tables 4 and 5 summarize the assumptions and economics for a typical biomass energy plant processing about 1000 dry tons per day of Napiergrass and generating a net energy of 10^{13} Joules per day. The system would require about 7700 hectares of land and thirty 8500 m^3 digesters. The costs of methane from this system is about $6.70 (1986) per GJ. Costs can be reduced by increase in feed biodegradability, increase in feed energy content, and use of the biogas without cleanup.

Because biomethanogenesis decomposes organic matter with production of a useful energy product, anaerobic digestion of organic wastes is receiving increased attention. With increased levels of waste production, limited area for landfilling or application, and increased awareness of environmental impact, alternative

Table 2
Energy potential of biomass and wastes in the United States [3,6]

Resource	EJ/yr
Municipal solid waste	1.5
Sewage sludge and sludge-grown biomass	0.8
Biodegradable industrial wastes	0.4
Crop residues	4.1
Logging residues	0.3
Animal wastes	0.4
Energy crops 1	
a. land-based	22.0
—payment-in-kind land (32 million hectares)	
—32 million additional hectares	
b. marine	> 100.0
Total (excluding marine)	29.5

Table 3
Cost estimates for production of biomethane from energy crops

Energy crop	Methane cost US \$ per GJ[a]
Grass (sorghum)[b]	6–8
Wood (poplar)[c]	3–7
Seaweed (kelp)[d]	6–14

[a] 1990 gas cost ~\$2.50 per GJ.
[b] Legrand [5].
[c] Legrand [5].
[d] Bird and Benson [1].

methods for treatment of solid and agricultural wastes are being sought. Currently these wastes release undesired methane into the atmosphere due to anaerobic conversion in landfills, lagoons, or stock piles. Treatment and recovery of this gas in reactors would reduce this source of atmospheric methane. An attractive option for treatment of the organic fraction of these wastes is to separately treat the organic fraction by composting and applying the stabilized residues on land as a soil amendment. The residues would reduce water needs and prevent erosion. The compost from treatment of wastes from a population of 100,000 could be applied on a sustained basis on less than 810 hectares of land. This scheme, however, requires effective separation of undesired components such as metals, glass, plastics, and toxic compounds which affect the quality of residues more than the conversion process. In European countries, which lead in this field, the most effective method of separation is source separation, resulting in compost with sufficiently low levels of contaminants for land disposal. Although aerobic composting continues to be a more popular process for stabilization of these wastes, anaerobic digestion has the advantages of methane production and lack of need for aeration or mixing. Several full-scale anaerobic composting plants are in operation in France, Belgium, and Denmark.

The major incentive for reconsideration of energy crops for conversion to methane is the environmental impact of fossil fuel use. The severity of this impact has led to international discussions of imposing a carbon tax in the range of 50–100 dollars per ton of carbon released as carbon dioxide. The impact of such a tax is illustrated in Fig. 1. Considering this tax and the cost of its removal during combustion, biomass will readily become a viable option [7]. Furthermore, the

Table 4
Base case for production of methane from grasses: assumptions [5]

Feedstock	Conversion	Energy production
Napiergrass: 54 dry tons ha per yr	1000 dry tons per day	10^{13} J/day
Growth area: 7600 ha	Thirty 8500 m^3 digesters, 55°C, HRT 35 days	3×10^{15} J/year
Storage: ensiled, in 49 silos	Organic conversion: 75%	

Table 5
Base case for production of methane from grasses: ecomonics ([5] and Legrand, unpublished data)

Operation	$/GJ	% of total cost
Crop production	1.74	26.1
Harvest and storage	1.29	19.4
Transportation	0.48	7.3
Conversion	2.10	31.5
Residue recycle	0.11	1.6
Gas cleanup	0.94	14.1
Total	6.66	100

long term depletion of fossil fuel resources and reduced dependency on foreign imports provide strong additional incentives for rapid development of renewable energy resources.

6. Conclusion

As population increases and technology development begin to result in significant resource depletion and environmental deterioration, we must take a global view on the ground rules for sustaining our species in a manner that is compatible with preservation of the biosphere. This will require production of feed, food, and energy by technologies that are indefinitely sustainable and which have minimal environmental impacts. This will involve a major shift to renewable resources for energy; sustainable agricultural practices for production of food, feed, and energy; recycle of all non-renewable resources, e.g. minerals, metals, etc.; and elimination of discharge of anthropogenic materials and compounds into the

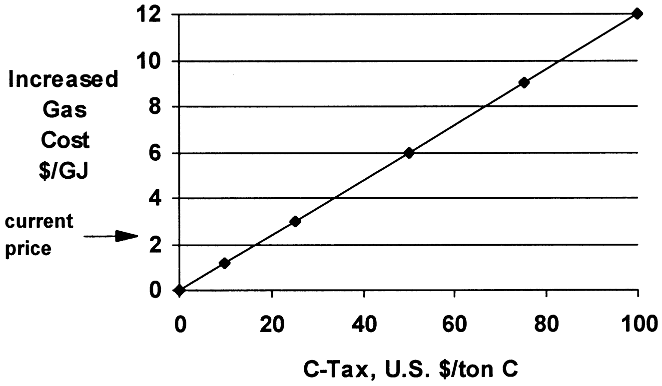

Fig. 1. Effect of carbon tax on US gas prices [2].

environment, e.g. plastics and toxic chemicals. Derivation of methane from energy crops and organic wastes could play a major role toward this objective.

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