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A systemic approach for dimensioning and designing anaerobic bio-digestion/energy generation biomass supply networks

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ABSTRACT

Anaerobic bio-digestion/energy generation complexes using animal waste raw materials represent an important component of renewable energy initiatives and policies worldwide, and are significant contributors to broaden sustainability efforts. In such projects bio-power feasibility depends heavily on generation complex access to biomass which is of costly transportation. As a result, an important component of renewable energy planning is the optimization of a logistics system to guarantee low-cost access to animal waste. This access is a function of local characteristics including number and geographic location of organic waste sources, operating and maintenance costs of the generation facility, energy prices, and marginal contribution of biomass collected and delivered to the anaerobic bio-digestion unit. Because biomass exhibits high transportation costs per unit of energy ultimately generated, and because different types of biomass have different biogas-generating properties, design of the supply logistics system can be the determinant factor towards economic viability of energy generation from an anaerobic bio-digestion plant. Indeed, to address this problem it is helpful to consider the farms, the logistics system, the anaerobic bio-digestion plant, and the generation plant as subsystems in an integrated system. Additionally, the existence of an outlet for manure may allow farmers to significantly raise boundaries of one constraint they face, namely disposing of animal waste, therefore permitting increases in farm production capacity. This paper suggests and outlines a systematic methodology to address the design of such systems.

1. Introduction

Anaerobic bio-digestion with output to bio-energy generation has become a renewable energy option in recent decades as efforts to find fossil-fuel substitutes have intensified, as environmental effects of excessive animal waste have become apparent, and as the technology for both bio-digestion and generation has evolved. Various studies have identified the need for careful analysis of the economics of such anaerobic bio-digestion/energy generation (ABD/EG) complexes. On one hand electricity prices are somewhat mutable – although most regulatory environments provide stabilizing mechanisms, oscillations in fossil fuel prices affect power generation rates. On the other hand transportation of manure and other animal waste from farms to the anaerobic bio-digestion unit tends to be costly relative to the energy obtained at the end of the process mostly because of the high water content in animal waste biomass. Herein we suggest explicitly including the biomass supply chain in the cost-benefit analysis of anaerobic bio-digestion/energy generation complexes in order to allow for complete understanding of the tradeoffs involved.

Fig. 1 provides a very simplified schematic representation of the physical flows of a generic bio-energy generation system (without loss of generality financial flows are not included). This representation specifically calls attention to four subsystems identifying their main inputs and outputs, and separates two environments external to the broader system: the external natural environment and markets (both for energy and for products). The first subsystem is the set of farms whose main inputs are animal feed and water and whose main outputs are protein products to markets and manure for biogas production (this discussion is limited to animal-related farm activities). The second subsystem is the logistics and transportation system that transfers the manure (biomass) to the bio-digestion unit with some loss of methane. These two first subsystems jointly comprise biomass supply. The third subsystem is the anaerobic bio-digestion unit with biomass as a main input and biogas and bio-fertilizer as main outputs and water as a by-product.

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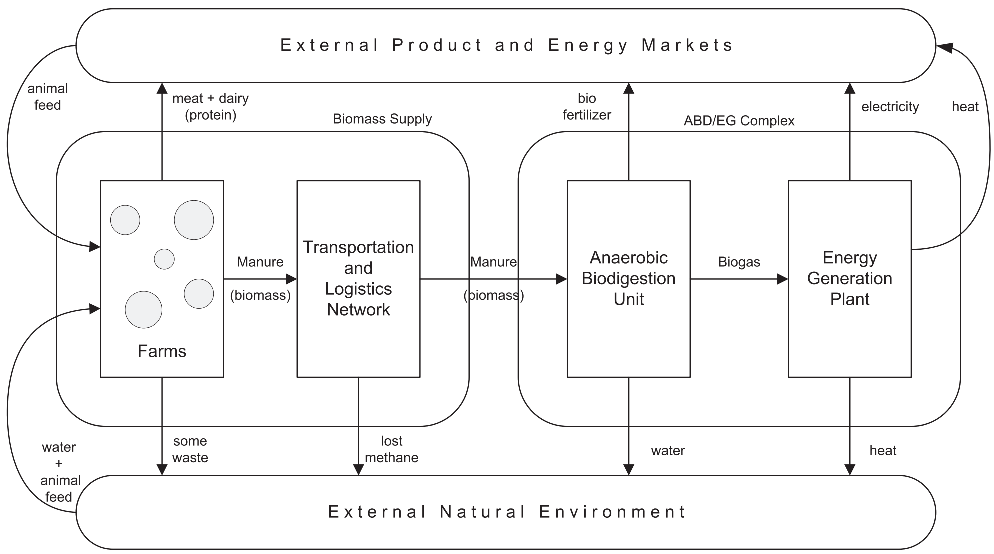

Fig. 1. Schematic representation of a generic biomass disposal/biogas capture/bio-energy generation system.

The energy generation subsystem converts biogas into electricity, and in some climates heat, while dissipating excess heat which also can be captured and put to use. These two subsystems comprise the ABD/EG complex. The aggregate system's environmental feasibility is achieved when the natural environment is not degraded by system outputs. The aggregate system's economic feasibility is achieved when each subsystem (and each respective component therein, especially when operated by distinct economic agents) is profitable and/or cost-effective.

Each of these four subsystems has very different properties and characteristics. The broad system's economic potential can be enhanced without compromising the natural environment if opportunities to benefit from the various interrelationships among subsystems are understood and maximized. Herein we specifically examine two such opportunities. The first is the development of a logistics network to transport biomass to the bio-digestion unit minimizing both cost and loss of methane. The second (and technically less complicated) is to consider potential increases in farm production given the guarantee that manure will be collected periodically which would lead farmers to be willing to pay for this service, therefore increasing their productivity and that of the broader system.

As documented in the literature, rates and quality of biogas production are highly dependent on the type of biomass used [1–3]. Section 2 estimates methane loss from biomass, a necessity for examining the logistics of transport to the ABD/EG complex and for understanding the value of animal waste disposal to farmers. The third section outlines a methodology to minimize methane loss and related costs when transporting biomass to the bio-digestion unit, i.e., it describes the necessary steps in optimizing the transportation and logistics network, which is the second subsystem in Fig. 1. The literature provides examples of systemic approaches to understanding the relevance of biomass supply for the design of bio-digestion units: in gasification plants as well as in combustion plants biomass transportation and logistics costs have been found to be relevant, a fact that is attributed to low biomass-to-energy conversion efficiencies [4,5]. Furthermore, breakeven distances from farm to plant have been found to be helpful in plant design processes [6] and mathematical techniques of optimization including mixed-integer programming and genetic algorithms have been used to identify cost-minimizing supply chain networks [7–9]. The fourth section briefly describes the tradeoffs faced by farmers when animal waste (manure) disposal is the limiting factor in their main economic activity (protein provision). These tradeoffs may lead to synergies with the ABD/EG operator as under certain conditions both parties will have an incentive to increase animal waste biomass supply. The fifth section concludes.

2. Biogas loss

From an energy-generating perspective the two main objectives in the aggregate system described above and depicted in Fig. 1 are to minimize manure supply costs and to minimize biogas loss as there always will be at least some “wait-time” before manure is collected. This section estimates this loss of biogas, an important input to the processes described in the remainder of the paper.

2.1. Biogas energy generation curve

Although in general the academic literature on anaerobic digestion models biogas generation over time as linear [3,10,11], the rate of biogas production depends on the animal source of biomass, with cumulative production generally following an “S” curve when plotted against time. Biomass from non-ruminant animals has low gas emission levels during the initial period of a few days, mostly CO_2. This contrasts with ruminant animals which start producing methane almost immediately. This characteristic has logistics implications as the system should prioritize immediate transportation of ruminant animal waste whereas allowing non-ruminant waste to “sit” for a few days does not have significant negative impact on energy generation.

Chen & Hashimoto [12,13] proposed a modification of Contois' kinetic equation of growth and applied it to anaerobic treatment of organic waste to estimate the production rate of methane from a fermentation process γ_v (m^3 of CH_4/m^3 of animal waste per day):

$$\gamma_v = \frac{B_0\, S_0}{\mathrm{TRH}}\left(1 - \frac{K}{\mathrm{TRH}\,\mu_m - 1 + K}\right) \tag{1}$$

where B_0 is the maximum rate of methane production (m^3 of CH_4 per kg of volatile solids); S_0 is the concentration of volatile solids in the raw effluent material (kg/m^3); TRH is the hydraulic retention