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Designing optimal supply chains for anaerobic bio-digestion/energy generation complexes with distributed small farm feedstock sourcing

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A B S T R A C T

Anaerobic bio-digestion/energy generation (ABD/EG) complexes that use animal waste have become increasingly important as renewable energy sources and logistics considerations are essential as animal biomass is of costly transportation due to its high weight per unit of energy generated. To ensure overall economic viability it is necessary to take into account the supply chain network when designing such a complex for at least two main reasons. First, these complexes provide power from energy sources which otherwise would go to waste and a well-designed supply chain network will significantly lower long-term operating costs. Second, because they provide an outlet for farm manure (their feedstock), these complexes allow farmers to expand production capacity whenever environmentally sound animal waste disposal is an active constraint to operations. This paper presents a methodology to design a supply chain which maximizes contribution and minimizes gas loss in the commonly found configuration in which feedstock providers are numerous small farms without on-site bio-digestion units, i.e., a configuration in which *in-natura* biomass is transported from those small farms to supply a nearby ABD/EG complex serving the region. The paper details three layers of analysis for designing optimal animal waste supply for anaerobic bio-digestion, including model formulation and mathematical solution for each stage. The broadest layer in the methodology is the identification of the optimal ABD/EG complex positioning given farm locations and consequent biomass transportation costs. The middle layer is the specification of the optimal logistics and transportation system, including the prioritization of supplying farms. The operational layer includes scheduling optimal biomass collection from each farm to minimize biogas loss.

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1. Introduction

An anaerobic bio-digestion/energy generation (ABD/EG) complex provides several benefits, among them processing biomass, generating energy, and obtaining bio-fertilizers as a by-product. When well designed, the complex can become an integral part of the broader food production system allowing for higher throughput with sustainability. Fig. 1 conceptually depicts such a system with the most important inputs and outputs for each component subsystem. The main subsystems depicted are the set of farms, the transportation/logistics network, a bio-digestion/energy generation complex, and the external environment. In the absence of these ABD/EG complex components, biomass would be disposed of *in natura* resulting in significantly lower volume absorption capacity by the external environment. Such complexes ideally are located in regions with intensive animal farming and consequent substantial amount of animal waste. Indeed, due to its high water content and consequent weight, this type of biomass is costly to transport when compared with the value of the energy it can produce. As a result, the economic feasibility of this kind of energy source will depend on the specific supply network configuration, in particular on the optimization of the logistics system developed to collect and process the biomass feedstock.

From a conceptual point of view there are several possible configuration schemes for biomass collection depending on the locations of the various feedstock sites, the number and location of the bio-digestion units and the location of the energy generation plant. This paper focuses on one particular configuration type: that in which a network of many small animal farms are feedstock providers and do not have bio-digestion units on site. In this configuration, a bio-digestion unit and an energy generation plant are planned side-by-side at the most appropriate site as described

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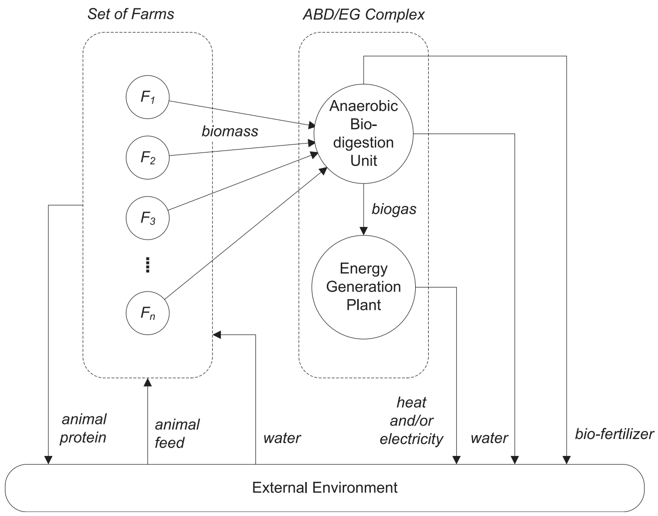

Fig. 1. Bio-digestion unit near the generation plant.

below. Tank-trucks collect waste and transport it to the bio-digestion unit co-located with the energy generation plant.

This paper investigates the importance of logistics systems for energy production from anaerobic decomposition, a process which involves transporting large quantities of biomass and capturing biogas, mostly methane. The problem addressed is that of optimizing the logistics network linking farms with excess biomass to a bio-digestion unit, which generates biogas that will be used by a co-located electricity power plant or another type of energy-producing installation. This situation, in which a large number of small farms are located relatively near potential plant sites, is not uncommon and has the advantage of flexibility in that additional farms may easily supply manure if there is a need or desire to invest in additional generation capacity. The methodology proposed herein provides the least costly way to collect and transport animal waste biomass from a chosen subset of the farms in the region, including determining the optimal location for the ABD/EG complex.

This paper contributes to the literature by providing a conceptual formulation and an analytical solution for this problem including the system-wide solution of three sub-problems. The first, described in section 3, is the determination of the cost-minimizing location of the ABD/EG complex, a decision with long-term impact as it is costly to reverse once construction is underway. The second layer, the more easily alterable identification of the set of farms for which biomass collection is economically advantageous given every potential ABD/EG complex location, is described in section 4. Solving this second sub-problem involves dimensioning of the entire supply logistics system and quantifying biomass loads to feed the anaerobic bio-digestion plant, including determining how far from the plant to collect, given manure gas-loss characteristics, specified equipment (truck) sizes, and labor force structure choices. The third layer, which is to schedule the collection process in a way that minimizes loss of biogas, is described in section 5. These three layers need to be solved sequentially, i.e., the output of each provides input to the other two. Section 6 summarizes a real-world design application and section 7 concludes.

2. Literature review

Several authors have mentioned the importance of logistics costs when analyzing bio-energy projects. In general these involve high costs to transport feedstock and low profitability of energy production, which renders logistics optimization crucial for determining project viability. As such, this paper builds on three literature streams. The first such stream concerns the use of biomass anaerobic decomposition for energy generation purposes. The second involves the role of logistics and reverse logistics in achieving sustainable and efficient energy generation practices. These two streams are addressed in this section. In addition, throughout the paper we make reference to the academic literature on mathematical optimization techniques.

The literature exemplifies the widespread dissemination of and interest in energy generation resulting from anaerobic decomposition of biodegradable matter as academic contributions are plentiful and geographically widespread. There have been many economic assessments of feasibility of biomass use for energy production at the country and regional levels. Some examples are Spain [1], Portugal [2], Italy [3], Germany, France, and other North-West European countries [4], Canada [5], Japan [6], China [7], Malaysia [8], Turkey [9], and Brazil [10]. The academic literature on biomass use for energy purposes is extensive and includes evaluation of biomass types [3,6,7,11–13]; biomass treatment and management [1,4,14]; biogas emission and capture [15,16]; bio-digestion technology advances [17,18]; efficiency analyses [19–22]; and bio-energy decision support methodologies for planning, implementation, and operations, most of which adopt a systemic approach [23–26]. Several studies have focused on best ways to leverage manure and solid waste at the municipal level, including co-digestion and hydro-thermal pretreatment [7,16,27].

Biomass can be converted to different forms of energy, including electricity, heating, and biofuels such as bioethanol and biodiesel. Each such configuration is subject to unique logistics and transportation characteristics depending on conversion technology, biomass feedstock, need for preprocessing or storage, energy or fuel output type, distribution method, and other local and geographic contextual factors. Consequently, this brief literature review would be incomplete without referencing supply chain management and optimization studies for other such configurations. A substantial literature addresses electricity and/or heat generation from agricultural biomass sources [28–31] while another portion of the literature focuses on optimizing supply chains specifically for biofuels, including deterministic [32,33] and stochastic models [34,35]. The literature also includes surveys of forest biomass [36,37], biofuel [38,39], and biomass-for-bioenergy [40] supply chain optimization research as well as strategic issues in the design, planning, and management of biomass supply chain operations [41,42] and multi-source waste biomass supply chain management [43].

Authors have pointed out that energy generation from biomass is relatively expensive partly due to low conversion efficiencies and partly due to logistics costs [44], i.e., logistics variables were found to be an important component of the analysis of biomass as a raw material in both combustion and gasification plants. Simulation and sensitivity analysis techniques have been used to find the break-even distance of feedstock supply for biogas production [45]. Optimization techniques such as mixed-integer programming and evolutionary algorithms have also been used to integrate supply chain structures in the most cost-effective way [46,47]. This academic research has occurred with the backdrop of an increased use of mathematical models to optimize logistics systems with sustainability in mind [48]. Despite this recent interest in the literature, including a top-down description of a systemic approach for designing anaerobic bio-digestion supply networks [49], to our knowledge this is the first analytical treatment in the literature which includes the multilayered analytical solutions of determining optimal plant location, identifying farm animal biomass providers, and scheduling operations.

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