Applied Energy 158 (2015) 597–608

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Sustainable energy from biomass: Biomethane manufacturing plant location and distribution problem

Bingqing Wu [a], Bhaba R. Sarker [a,*], Krishna P. Paudel [b]

[a] Department of Mechanical and Industrial Engineering, Louisiana State University, Baton Rouge, LA 70803, USA
[b] Department of Agricultural Economics and Agribusiness, Louisiana State University (LSU) and LSU AgCenter, Baton Rouge, LA 70803, USA

HIGHLIGHTS

- Optimal strategy to locate biogas reactor and allocating feedstock.
- Nonlinear mixed integer programming problem structure.
- Real world supply chain of biogas production system.
- Considers construction cost, transportation and labor costs.
- Novel heuristic improves efficiency to obtain optimal solution.

ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form 31 July 2015
Accepted 17 August 2015

Keywords:
Biogas generation
Multi-material
Heterogeneous transportation cost

ABSTRACT

As an environment-friendly and renewable energy source, biomethane plays a significant role in the supply of sustainable energy. To facilitate the decision-making process of where to build a *biomethane production system* (BMPS) and how to allocate the resources for the BMPS, this paper develops an analytical method to find the solutions to location and allocation problems by minimizing the supply chain cost of the BMPS. The BMPS consists of the local farms for providing feedstock, the hubs for collecting and storing feedstock from farms, and the reactors for producing biomethane from feedstock. A mixed integer nonlinear programming (MINLP) is introduced to model the supply chain by considering building, transportation, and labor costs. An alternative heuristic is proposed to obtain an optimal/sub-optimal solution from the MINLP. The validity of the proposed heuristic is proven by numerical examples that are abstracted from practical scenarios.

1. Introduction

Fossil fuels such as coal, petroleum, and natural gas are nonrenewable resources that are likely to be exhausted in an economic sense at some time in the future [1]. Zittel and Schindler [2] predicted that the "peak coal" era (i.e., the moment when the global coal production rate is at a maximum, and then enters the terminal stage) will occur by 2025 and that natural gas reserves will sustain humans for another 60 years, if we assume that production is kept at the same level as in 2011 [3]. It is now common knowledge that the depletion of nonrenewable resources, particularly fossil fuels, is inevitable.

Realizing the inevitable shortage of fossil fuels, scientists across various disciplines are exploring alternative energy. Methane has drawn attention because of its large ratio of the heat of combustion to molecular mass. It serves as an alternative fuel in automobiles after liquefaction, and it is the major component in natural gas. Burning methane produces less carbon dioxide compared to other hydrocarbon fuels per unit of heat [3]. It is extensively used as a substitute for conventional sources of energy in most parts of the world [4].

There are many ways to produce methane. An effective way is to utilize a biological process, that is, a series of reactions (collectively referred to as the "anaerobic digestion process") conducted in a reactor using feedstock such as forest residues or animal manure. The product gained from this process is called *biogas*, which is composed mainly of 55–70% methane and 30–45% carbon dioxide [5]. Due to its low percentage of methane, the use of biogas is limited and cannot substitute for natural gas. However, through a so-called "biogas upgrading" process, purified methane can be extracted from the biogas. The methane obtained from the upgrading process is called *biomethane*, which has the same uses as natural gas.

* Corresponding author. Tel.: +1 (225)578 5370; fax: +1 (225)578 5924.
E-mail address: bsarker@lsu.edu (B.R. Sarker).

http://dx.doi.org/10.1016/j.apenergy.2015.08.080
0306-2619/

The benefit of biomethane is self-evident. Not only can it be a supplement to natural gas, it is also a renewable energy source that can be obtained from biological waste. In addition, the existence of biogas plants all over the world implies that there is plenty of infrastructure to be utilized for building biomethane production systems (BMPS). As of 2014, there were 2000 sites producing biogas in the U.S. [6] and, with proper government support, there could be as many as 11,000 additional biogas facilities constructed in the future. Biogas production in Europe increased drastically within the last few years. Germany had built 7850 biogas plants as of 2013 [7], and the UK is reported to own approximately 130 non-sewage biogas plants as of 2013 [8].

To build a BMPS, cost control has become a significant issue, because a sustainable profit model attracts investors and ensures healthy development of the biomethane industry. Optimization of the supply chain and logistics is an effective way of minimizing the total cost in building the BMPS. This paper proposes an analytical methodology for decision-makers to determine an optimal location of BMPS and resource allocation of raw material supply. A mixed integer nonlinear programing (MINLP) model is constructed to compute the total supply chain cost of building the BMPS. The solutions for the MINLP provide the optimized location of the BMPS and the optimized allocation of feedstock. An alternative search based heuristic is proposed to obtain the solutions to such problems.

With increasing complexity for obtaining the optimal solution, the prevailing models for a supply chain for bio-fuel production systems can be generalized into three types: a linear or nonlinear programming (LP or NLP) model, a mixed-integer linear programming (MILP) model, and a mixed integer nonlinear programming (MINLP) model. This research develops an MINLP model to describe the supply chain of the BMPS. Other models such as LP, NLP and MILP have been used as well. For example, Illukpitiya et al. [9] developed an LP model to maximize the biofuel production profit given that land availability in Hawaii was limited. Lim et al. [10] provided a methodology based on a NLP model to determine the optimal capacity and distribution of biomass power plants in Sabah, Malaysia to minimize the cost of electricity generation. Balaman and Selim [11] developed a MILP model to describe the supply chain network of producing biogas in Turkey. Cucek et al. [12] addressed an MILP approach for a bioenergy supply network with multi-periods. Lin et al. [13] presented a supply chain optimization model to minimize the production cost for a large-scale biogas plant. Liu et al. [14] provided a life cycle assessment based on a multi-objective biogas supply chain framework that obtained a balance among economy, energy, and the environment. Shabani and Sowlati [15] gave a dynamic model for an electricity generation system using forest biomass to improve its competitiveness and maximize the supply chain's overall value. Smith and Hobbs [16] proposed a supply policy based on solving an MINLP for a power generation system with biomass sources, and combined the output from existing agricultural optimization models. Chen and Önal [17] addressed an MINLP model to simulate a price-endogenous, biofuel feedstock, supply chain system.

This research addresses a location-allocation problem in the bio-fuel supply chain system, which focuses on the determination of an optimal location for reactors/bio-refineries and design of an optimal transportation network for collecting raw material. Vera et al. [18] determined the optimal location of the biomass power plant by introducing a new heuristic called "Binary Honey Bee Foraging (BHBF)". Zhang et al. [19] proposed a two-stage methodology to optimize the biofuel plant's location by minimizing the transportation cost. Zhang and Hu [20] designed an operational planning model for a biofuel plant to investigate facility location and operational levels. Li and Hu [21] optimized locations for a biofuel plant that uses fast pyrolysis to maximize the net present value of total profit. Höhn et al. [22] conducted a case study on optimizing the locations of the biomethane plants for south Finland. Most recently, Franco et al. [23] applied the Fuzzy Weighted Overlap Dominance Procedure to solve a multi-criterion model established for identifying the most suitable locations for the biogas plants.

Generalized studies on the location-allocation problem have a long history dating from the beginning of the 20th century. Early work in solving such problems can be found in Weiszfeld [24], Miehle [25], and Cooper [26]. Because the model for location-allocation problems usually contains multiple local minima, solving for a satisfactory optimum requires careful design of a heuristic. To achieve this goal, various methodologies were designed to efficiently solve the generalized location-allocation problem. Recently, Torgnes et al. [27] provided a Dantzig–Wolfe algorithm for a petroleum plant allocation system. Ghoniem et al. [28] proposed two heuristics for a vehicle routing and demand allocation problem for a food bank. Hajipour et al. [29] developed a new meta-heuristic algorithm to solve the facilities location problem with capacity and budget limitations. Vidyarthi and Jayaswal [30] considered a location-allocation problem with stochastic demand and provided an efficient heuristic to solve the model.

This paper is organized as follow. In Section 2, a biomethane production problem scenario was set up as to the location of manufacturing plant and the distribution of gas. In Section 3, the model for locating plant and the distribution of biogas is formulated. Section 4 provides several multi-stage heuristics capable of solving a large scale MINLP in a reasonable amount of time that can provide an optimal/sub-optimal solution. Some computational test results for large problem instances are given in Section 5 and finally the results were summarized and concluded in Section 6.

2. Biomethane production problem

The supply chain model of the BMPS formulated here is based on a feasibility study conducted by Krich et al. [5] on building BMPS in California. A typical configuration of a regional BMPS consists of farms, hubs, and a single biomethane reactor. The biomethane reactor is built to serve a given area, which often consists of several counties (in the U.S., a county is a geographical region within a state and is used for administrative purposes). The biomethane feedstock are crop residues, forest residues and livestock manure collected from county. The terms residues, biomass and feedstock are interchangeably used throughout the paper to denote input in biomethane gas production. It is assumed that there is one hub in each county and its location is predetermined by a Geographic Information System (GIS). Each hub only collects and stores feedstock from farms in the county within which the hub is located.

The supply chain costs of a BMPS include the feedstock, building, transportation, and labor costs. The feedstock cost is the purchasing cost of raw material from the hubs. The building cost can be estimated from the average construction cost in each county. The transportation cost incurs when residues are delivered from the hubs to the reactor using transportation by road. The labor cost is the wage rates for hiring workers to load and unload residues from trucks. A schematic diagram is helpful for illustrating the locations of farms, hubs, reactor, and different transportation routes (Fig. 1).

The objective of this research is to determine the optimal *location* of the reactor and allocate the *quantity of feedstock* from each hub to it (the reactor) to minimize the total cost in supplying raw materials (forest residues, livestock manure and grass) and building of a BMPS. The amount of residue available at each hub, feedstock costs, building costs of the reactors, labor availability in the region, and transportation costs are considered in this paper.