Applied Energy 130 (2014) 289–304

Contents lists available at ScienceDirect

Applied Energy

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

A network design model for biomass to energy supply chains with anaerobic digestion systems

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HIGHLIGHTS

- A MILP model is developed to design and operate bioenergy supply chains.
- Anaerobic digestion is considered as biomass to energy conversion process.
- A real-world application is performed with real data in İzmir, Turkey.
- A reasonable level of profit can be made by the biomass to energy investment in İzmir.
- An acceptable payback period of 4.98 years is obtained for the investment.

ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form 21 April 2014
Accepted 7 May 2014

Keywords:
Biomass to energy conversion systems
Biofuel supply chain
Anaerobic digestion systems
Biogas
Mixed integer linear programming

ABSTRACT

Development and implementation of renewable energy systems, as a part of the solution to the worldwide increasing energy consumption, have been considered as emerging areas to offer an alternative to the traditional energy systems with limited fossil fuel resources and to challenge environmental problems caused by them. Biomass is one of the alternative energy resources and agricultural, animal and industrial organic wastes can be treated as biomass feedstock in biomass to energy conversion systems. This study aims to develop an effective supply chain network design model for the production of biogas through anaerobic digestion of biomass. In this regard, a mixed integer linear programming model is developed to determine the most appropriate locations for the biogas plants and biomass storages. Besides the strategic decisions such as determining the numbers, capacities and locations of biogas plants and biomass storages, the biomass supply and product distribution decisions can also be made by this model. Mainly, waste biomass is considered as feedstock to be digested in anaerobic digestion facilities. To explore the viability of the proposed model, computational experiments are performed on a real-world problem. Additionally, a sensitivity analysis is performed to account for the uncertainties in the input data to the decision problem.

1. Introduction

Decision making for design, operation and management of bioenergy supply chains are increasingly gaining importance in recent years parallel with the rising interest in renewable energy sources. Strategic, tactical and operational level decisions about the locations and capacities of conversion plants and storages, logistics issues and transportation network, feedstock procurement, handling and distribution of process residue, and tactical operation schedules should be made efficiently to obtain robust and cost effective supply chain configurations. Many decisions in such a supply chain involve tradeoffs. For instance, locating the facilities close to demand points of the products will reduce the transportation cost of these products, but might increase the biomass transportation cost if the facilities are far away from the biomass supply regions. Due to the complex tradeoffs involved, various competing supply chain network design decisions cannot be made independently. Therefore, comprehensive management and optimization of all of the individual components along the entire supply chain is essential to facilitate the economical, environmental and social benefits of bioenergy systems.

Decision making in bioenergy supply chain problems requires getting a sound grasp of the supply chain structure and selection of the suitable methodologies as in many complex planning problems. Before the use or development of the methods, it is important to investigate the current literature in the field to prevent research overlaps. Gold and Seuring [1] presented a literature

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http://dx.doi.org/10.1016/j.apenergy.2014.05.043
0306-2619/

Nomenclature

Indices
- p plant location sites
- d storage location sites
- r supply regions
- f feedstock types
- c plant capacity levels

Parameters
- $PCAP_{pc}$ biomass processing capacity limit for the plant at location p with capacity level c (t)
- $PELCAP_{pc}$ electricity production capacity limit for the plant at location p with capacity level c (kW_{el})
- $MaxDCAP$ maximum biomass capacity of a storage (t)
- g_f biomass to fertilizer conversion rate of biomass f (%)
- e_f biomass to biogas conversion efficiency of biomass f (m^3/t)
- υ_{be} biogas to electricity conversion rate (kW/m^3)
- c_{be} biogas to electricity conversion efficiency of cogeneration unit (%)
- TS_f total solid content of biomass f (%)
- Aav_{rf} available amount of biomass f at supply region r (t)
- $MinTS$ minimum total solid content of biomass slurry (%)
- $MaxTS$ maximum total solid content of biomass slurry (%)
- $ICOST_{pc}$ investment cost of the plant at location p with capacity level c (€)
- $OCOST_{pc}$ annual operational cost of the plant at location p with capacity level c (€)
- $TCOST_{dpf}$ unit transportation cost of biomass f from storage d to the plant at location p (€/t)
- $COST_{rdf}$ unit transportation cost of biomass f from supply region r to storage d (€/t)
- $TCOSTF_{pr}$ unit transportation cost of fertilizer from plant p to supply region r (€/t)
- ULC_d unit land cost of location site d (€)
- UCL unit construction cost of liquid storage (€/t)
- UCS unit construction cost of solid storage (€/t)
- $FERPOT_r$ fertilizer requirement of location r (t)
- EP price of electricity (€/kW)
- FP price of fertilizer (€/m^3)
- WP price of water (€/m^3)
- PC_f purchase cost of biomass f (€)
- i discount rate
- N_1 time period for discounting investment costs
- N_2 time period for discounting annual operational costs
- CRF_1 capital recovery factor for the investment costs
- CRF_2 capital recovery factor for the operational costs

Decision variables
- Y_{pc} number of biogas plants with biomass capacity level c to be constructed in location p
- X_d number of biomass storages to be constructed in location d
- A_{dpf} amount of biomass f transported to the plant at location p from the storage at region d (t)
- B_{rdf} amount of biomass f transported to the storage at location d from the supply region r (t)
- FER_{pr} amount of fertilizer transported to the supply region r from the plant at location p (t)
- $Outbio_p$ amount of biogas output of plant at location p (m^3)
- $Outelc_p$ amount of electricity output of plant at location p (kW)
- $DLCAP_d$ liquid biomass capacity of the storage at location d (t)
- $DSCAP_d$ solid biomass capacity of the storage at location d (t)
- W_p water usage amount of plants at location p (t)
- Rem_{rf} unused amount of biomass in region r
- $Remfrac_{rf}$ fraction of unused amount of biomass f to biomass f potential in region r
- $Tremfrac$ fraction of total unused biomass amount to total biomass potential in the whole regions

review of papers from 2000 to 2009 which deal with bioenergy production, logistics and supply chain management, and sustainability issues. An et al. [2] provided a literature review of researches on decision making in biofuel supply chains. They categorized the surveyed studies according to the decision level they include as well as level in the supply chain. Iakovou et al. [3] proposed a critical synthesis of the state of the art literature about design and management of waste biomass supply chains. They mentioned components, activities and characteristics of the supply chain as well as types of biomass to energy conversion technologies.

The state of the art analysis also provides a better comprehension of the technical details of conversion processes and characteristics of biomass sources as well as the supply chain structure. Anaerobic digestion is a well-known and efficient process that converts organic feedstock into biogas by biologic reactions in the absence of oxygen. Donoso-Bravo et al. [4] presented an overview of the modeling procedures for anaerobic digestion processes focusing on mathematical modelling, methods for parameter estimation and optimization, and model validation. Ariunbaatar et al. [5] reviewed mechanical, thermal, chemical and biological pretreatment methods for anaerobic digestion of organic solid waste as well as combination of various pretreatment methods. They compared the methods and evaluated the feasibility of application. Srirangan et al. [6] focused on clean energy production from biomass resources. After defining the first, second and third generation biomass feedstocks, they mentioned biomass to energy conversion routes and various types of biofuels as clean energy carriers. Browne and Murphy [7] proposed a study to assess the resource for biomethane production with a focus on food waste. They dwelt on the technical issues in conversion process such as preparation of food waste and experimental setup as well as biomethane potential of the food waste. Prajapati et al. [8] proposed a study that discusses and compiles main issues about procurement and anaerobic digestion of algal biomass such as growth requirements for algae cultivation, harvesting and cultivation methods, digestibility and biogas potential analyses, limitations of the process. They especially focused on wastewater utilization as the nutrient and waste gases as the CO_2 source for algal biomass production.

Considerable research has been conducted on developing mathematical models to optimize the design and operation of various configurations of biomass to energy supply chains. Among the mathematical modeling approaches, mixed integer linear programming (MILP) has been widely utilized to design and operate bioenergy supply chains. It is a powerful tool for such problems because of its modeling capability and the availability of efficient solvers. One of the advantages of MILP approach is that it provides a general framework for modeling a large variety of problems. However, the major difficulty lies in the computational expenses that may be involved in solving large scale problems, which is due to the computational complexity of MILP problems.

Papapostolou et al. [9] developed a mathematical model to identify the best solutions for the optimal design and operation of biofuel supply chains that takes into account both technical and economic parameters affecting the performance of the supply