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A stochastic, two-level optimization model for compressed natural gas infrastructure investments in wastewater management

Chalida U-tapao [a], Seksun Moryadee [b,*], Steven A. Gabriel [c], Christopher Peot [d], Mark Ramirez [d]

[a] King Mongkut's Institute of Technology, Ladkrabang, Thailand
[b] Ordnance Engineering Department, Chulachomklao Royal Military Academy, Nakhon Nayok, Thailand
[c] University of Maryland, MD, USA
[d] District of Columbia Water and Sewer Authority, 5000 Overlook Avenue, SW, Washington, DC, USA

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A B S T R A C T

In this paper, we present a stochastic two-level optimization model whose upper-level problem depicts a wastewater treatment plant deciding on the size of compressed natural gas (CNG) filling stations and their locations. These upper-level decisions are integrated with operational decisions for the plant as well as downstream markets including agriculture, CNG transportation, residential natural gas, and electricity markets at the lower level. The two-level problem, expressed as a stochastic mathematical program with equilibrium constraints (SMPEC), is reformulated as mixed-integer linear program (MILP) using SOS1 transformations and linearizations. As a case study, the SMPEC is used to evaluate the options for CNG investment for a wastewater treatment plant located in the Washington, DC metro area. Our results indicate that the CNG produced from the wastewater treatment plant could meet approximately 20% of the expected total transportation demand in Washington, DC. In addition, CNG produced from the wastewater treatment plant could reduce CO_2 emissions by a significant amount. The CNG benefits are traded off with less on-site wastewater-derived power production.

1. Introduction

Compressed natural gas (CNG) is natural gas compressed to 200 bas which remains clear, odorless, and non-corrosive (California Energy Commission, 2014). CNG is composed of 83–99 percent methane and has the highest energy/carbon ratio of any fuel. CNG is widely used as a transportation fuel in various parts of the world. Typically, most vehicles use CNG that has been compressed between 3000 and 3600 psi (Alternative Fuel Systems Inc, 2014). The CNG-capable vehicles range from taxis and delivery vans to city buses. The primary goal of using CNG over gasoline or diesel is the potential savings in fuel economies (Whyatt, 2010). According to the U.S. Energy Information Administration (EIA) (DOE, 2014a), CNG costs $2.15/gallon of gasoline equivalent (GGE) compared with gasoline $3.65/GGE and diesel $3.56/GGE as of April 2014. The prices of CNG ($/GGE) differ by state across the U.S. In addition, another advantage of CNG is that the emissions from burning CNG are relatively cleaner than from diesel or gasoline. According to the California Energy Commission, natural gas vehicles emit ozone-forming emissions approximately 80 percent less than those using gasoline (California Energy Commission, 2014).

Generally, CNG is produced from natural gas that can be extracted from three different types of sources: gas-and-condensate wells, coal bed methane wells, and oil wells. In addition to these sources, natural gas can also be generated from anaerobic digestion processes. Anaerobic digestion takes place in the absence of free oxygen. Places like landfills, wastewater treatment plants, or livestock manure lagoons are very common sites where biogas can be captured. Methane and carbon dioxide are the primary elements in biogas (methane about 40%). The important factors that control the anaerobic digestion process are temperature, moisture level, and nitrogen-to-carbon ratio. Natural gas from organic wastes can be converted to renewable natural gas (RNG);

* Corresponding author. The Ordnance Engineering Department, Chulachomklao Royal Military Academy, Nakhon Nayok, Thailand.
E-mail address: seksun.mor@gmail.com (S. Moryadee).

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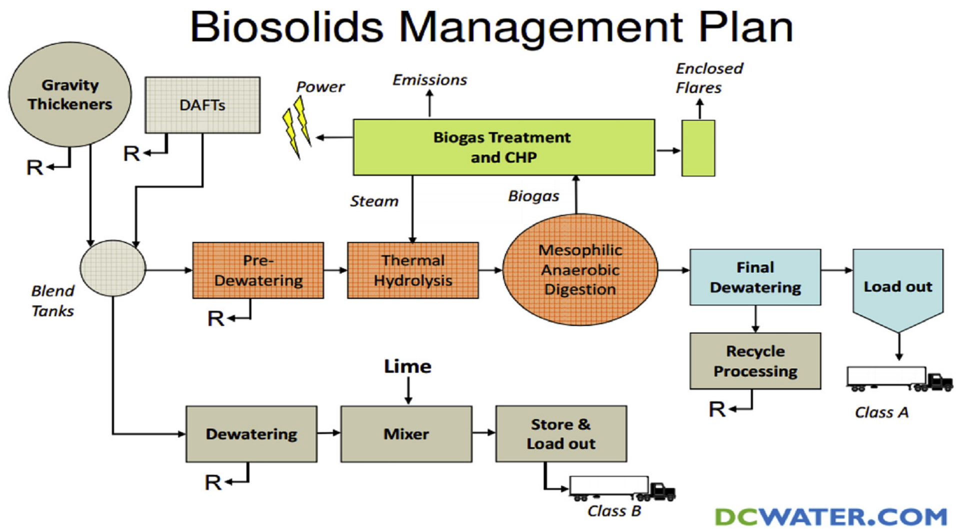

Fig. 1. Biosolid management plan at Blue Plains (The United States Environmental Protection Agency (EPA) eGRID 2006 Version 2.1, 2004).

RNG is also called biomethane (Vision et al., 2014). Organic waste from urban and rural areas include household trash, institutional food waste, animal by-products, etc. These organic wastes could be feedstock for biomethane production.

According to Vision et al. (2014), there are more than 17,000 wastewater treatment plants in the U.S., but only approximately 1300 plants have digesters to manage biosolids and manure. Energy produced from wastewater treatment plants is a significant renewable energy source for household usage (Mamut and Badea, 2015). Although most of the wastewater treatment plants have operating anaerobic digesters, they are primarily used for controlling odor and killing pathogens not for generating biomass. However, the Blue Plains wastewater facility run by the District of Columbia Water and Sewer Authority (DC Water), one of the largest advanced wastewater treatment facilities in the world, is installing a combined-heat-and-power (CHP) facility as well as digesters to produce methane. The products gained from processing wastewater at DC Water include class B, class A biosolids,[1] as well as methane from the digesters, see Fig. 1. This methane can then be used in a variety of ways such as: producing electricity on site, converting it to compressed natural gas and sold in the local transportation market (i.e., for District of Columbia buses), sold to the natural gas end-use sectors, or sold as high-end fertilizer. These options have been explored in a series of papers using both one- and two-level optimization models as well as considering both deterministic and stochastic versions of the model (Gabriel et al., 2013a; U-tapao Chalida, 2013; U-tapao et al., 2014).

The new system at Blue Plains will include three Solar Mercury 50 low nitrogen oxide gas turbines, heat recovery steam generators, duct burners, a backup boiler, electrical equipment needed to operate in parallel with the utility grid and ancillary systems, and digester gas cleaning and compression equipment. The digesters are some of the largest in the world at 14 million liters (3.8 million gallons) each and can handle up to 450 dry tons of solids. The anaerobic digestion for the new system at Blue Plains will generate about 10 MW of power, enough to supply one-third of its demand. In addition, the maximum capacity of digester at Blue Plains can generate CNG up to 2.55 million cubic feet (MMcf) per day while total daily consumption in District of Columbia is 1.98 MMcf and there is just a fueling station that is exclusively for private access called Trillium CNG of Washington Metropolitan Area Transit Authority (WMATA).

Since the CNG production capacity at Blue Palins exceeds the total demand in District of Columbia, bioCNG from wastewater could provide options if demand for CNG increases in the future. However, in order to enter to CNG market, a significant investment in infrastructure cost is required and considering the various options. This is the primary motivation for the current paper.

The main contributions of the research reported in this paper are two-fold. First, we develop a novel SMPEC to analyze investments and operations aspects for advanced wastewater treatment plants considering a number of uncertainties such as fuel prices and biosolids inflow. This model is generalizable and can be applied to other wastewater treatment plants using a variety of scenario trees to represent uncertain data. Second, the SMPEC determines and optimal investment plan using the Blue Plains advanced wastewater treatment plant as a case study to validate the approach.

The remainder of the paper is as follows. Section 2 describes the methodology. The complete formulation of the SMPEC is presented in Section 3. Section 4 and describe the case study and results. Lastly, Section 6 presents the main conclusions.

2. Methodology

Since an advanced wastewater treatment plant can have a strategic advantage relative to the CNG market as discussed earlier, the AWTP can be characterized as a dominant (i.e., Stackelberg) leader for that market. This is precisely the role it has in the model described below with a two-level Stackelberg to model the interaction between the AWTP and the relevant downstream markets. In this setting, the AWTP is the upper-level player (Stackelberg leader) and the independent suppliers associated with each market act as lower-level followers expressed as a stochastic MPEC. The general form of the SMPEC is as follows:

[1] Class A biosolids have the total amount of pathogens below a detectable level and must meet the limitations of metal contaminants related to regulation 503, which is standard for the use or disposal of sewage sludge, (Energy information Administration (EIA)U.S. Department of Energy (2013)). Class B biosolids are less stringent in terms of pathogens but still require farm management practices and area restrictions before application ((Energy information Administration (EIA)U.S. Department of Energy (2013)) and The United States Environmental Protection Agency (EPA), 1994).