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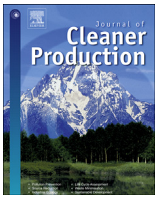

Efficient cogeneration and district heating systems in bioenergy villages: an optimization approach

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ABSTRACT

The availability of renewable energy sources and highly efficient technologies are two major considerations when evaluating a sustainable energy supply with low carbon emission. Bioenergy villages combine the use of biomass as a renewable energy source with the efficient cogeneration of heat and power. The planning of these bioenergy villages using biomass as a source of electricity and heat calls for the simultaneous identification of facility location, capacity planning, and network design for the heating grid. A linear mathematical model is presented, that optimizes the local bioenergy production and distribution system and considers various parameters such as biomass availability, the number of heat customers, or heat loss in the system. The model is applied and validated using a case study in a small village in Lower Saxony (Germany).

1. Introduction

Global climate change is one of the greatest challenges of our time, and several attempts have been made to control and reduce global greenhouse gas (GHG) emissions (UNFCCC, 1997, 2009). To achieve this goal, a sustainable and carbon neutral energy supply is needed. Along this line, the European Union promotes various measures and regulations to increase energy efficiency, reduce energy consumption and further the development of renewable energy resources (European Commission, 2011a,b). These efforts also aim at reducing the dependency on fossil fuels and the emission of GHGs. Biogas from energy crops or other biogenic substrates is a particularly versatile renewable energy source. This is due to the fact that it is capable of providing base load power, but can also be used to cover peak loads, by the use of biogas storage (Ostergaard, 2012; Ruppert, 2008). Furthermore, biogas can be used for the cogeneration of electricity and heat in combined heat and power stations (CHPs), potentially reducing the fuel consumption by 20–30 % compared to the conventional heat and power generation in separate plants (Andersen and Lund, 2007). In short, emissions of GHGs can be abated by reducing the general demand for primary energy.

While the combined generation of heat and power is highly efficient, it is necessary to have an adequate level of heat demand close to the plant site. In contrast to electricity which can be fed into a grid, the heat should be used in the proximity of the generation plant, to reduce heat loss during transportation and maintain an efficient heat supply. One possibility is to use the heat in decentralized heating networks especially in rural areas. Bioenergy villages offer cutting-edge solutions to the question of how to combine the concept of combined heat and power generation with the use of renewable energy sources. However, the network and capacity planning for such a decentralized heating system based on biomass poses a great challenge to the responsible decision maker.

In this paper, we present a mixed integer linear program to model the planning situation for these local heating systems as a network flow problem. This allows for the economic assessment of different planning scenarios and facilitates the implementation of profitable and ecologically advantageous bioenergy villages. We apply the model in the context of a case study, optimizing the plant location and heating network structure of a village in Lower Saxony (Germany). We then discuss and summarize the results.

2. Bioenergy villages

The first resource efficient bioenergy village was realized in the German village of Jühnde in 2004 (Ruppert, 2008). Fig. 1 displays the general setup of such a local energy supply based on cogeneration. Bioenergy villages use biomass from local farmers as a

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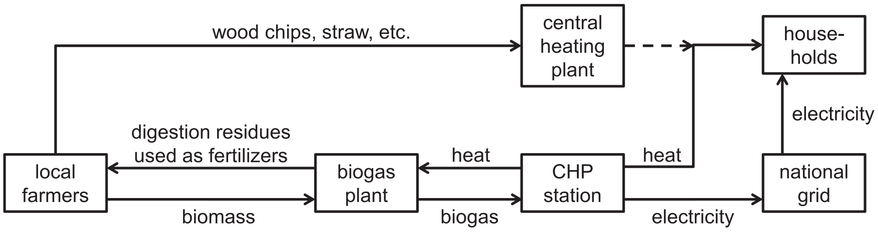

Fig. 1. General setup of a district heating with biomass fueled cogeneration, based on Uhlemair et al. (2014).

renewable energy source. Liquid manure from livestock breeding, energy crops, and other feedstock provide fuel for a biogas plant, where methane is produced in an anaerobic fermentation process. The residue from this process, known as digestate, can be used as fertilizer under the national requirements of the German Fertilizer Directive (BMELV, 2008). Fueling a biogas plant with liquid manure and using the digestate as fertilizer for arable land also contributes to the mitigation of GHGs, since it can reduce methane emissions associated with untreated manure (Meyer-Aurich et al., 2012), GHG emissions from fertilizer production (Upham and Smith, 2013) and nitrogen leakage through higher fertilization precision (Lukehurst et al., 2010).

Biogas derived from fermentation consists of about 50% methane and it fuels a cogenerating combustion engine that produces both electricity and heat (FNR, 2010). The generated electricity is then fed into a grid, and the heat from power generation can be used to both regulate the temperature of the fermentation process and heat local households that are connected through a heating network (Ruppert, 2008). A central heating plant can be installed as a backup system as well, to cover peak loads during the winter. This concept combines high energy efficiency with the use of renewable energy sources and thus, bioenergy villages have a positive impact on both GHG emissions and the energy balance, which are considered the two most important criteria when assessing sustainable bioenergy concepts (Buchholz et al., 2009).

Mangoyana and Smith (2011) have analyzed various decentralized bioenergy systems that contribute to climate change mitigation, support local development, and can create local employment. They found that small scale bioenergy projects allow for an ecologically, economically, and socially sustainable energy supply if they are implemented in a profitable way. Therefore, it is important to consider both economic and ecological aspects when planning a bioenergy village.

2.1. Decision problems in bioenergy villages

Designing a profitable bioenergy village using biomass as the primary energy source requires an efficient distribution of heat from the combined heat and power (CHP) plant and long-term planning of general system setup and capacity (Uhlemair, 2012; Uhlemair et al., 2014). The planning and realization of profitable bioenergy villages poses various challenges. Considering the general energy production system, critical issues include the number of installed power plants, their capacities, and the locations of these facilities (Plata, 2008). Problem-specific parameters such as the availability or allocation of biomass must also be considered. The planning of the distribution system raises questions such as how to select heat customers connected to the grid and how to design the course of the heating network, while considering heat loss, profitability, and the requirements of the German Renewable Energy Act among other factors (Uhlemair et al., 2014). The simultaneous consideration and optimization of these aspects is necessary to design an efficient and decentralized heat supply. Both facility location problems and general network flow problems can be modeled very efficiently as mixed integer linear programs (MILPs), allowing for a computer-based solving of these problems (Hamacher and Klamroth, 2006).

MILPs have previously been used to optimize the operation of CHP plants. Hochloff and Braun (2014) used an MILP to optimize the capacity of a single biogas plant considering flexible market prices. Storing the biogas and installing excess power capacity allowed for demand driven generation of electricity, resulting in higher profits. They analyzed the profitability of this excess capacity and calculated optimal biogas storage and power capacities for a given plant depending on prices. Amiri et al. (2013) used a cost-minimizing linear programming model to analyze the economic effects of connecting a combined heat and power plant to an existing biogas system. In this context, they investigated the connection of combined heat and power generation, and electricity certificate trading and prices, to evaluate the economic consequences of future changes in a given system.

Casisi et al. (2009) applied an MILP to a real city center situation to optimize the operational strategy of a heating system. This distributed urban cogeneration system included both a set of micro-turbines and a centralized internal combustion engine. The model determined the optimal operation strategy and system setup, minimizing the annual costs for owning, maintaining and operating the system. Furthermore, the supply of substrates for bioenergy systems can also be modeled using MILP. Kim et al. (2011) optimized the supply of biomass for various types of processing plants maximizing the objective function of overall profit. Their MILP considered both the number, location and capacity of the plants and the transportation logistics of biomass, intermediate, and final products between the different locations. The logistics management and efficient setup of the supply chain play a major role, when considering the circumstances for profitable and sustainable bioenergy production. Gold and Seuring (2011) provided an overview of the various issues and challenges in designing and operating biomass supply chains that can secure stable and competitively priced biomass allocation for bioenergy plants.

3. Modeling the source location and network flow problem

Bioenergy villages use renewable resources to fuel biogas plants and highly efficient CHP engines contributing to a sustainable energy supply with low GHG emissions. However, it is challenging to realize an efficient and profitable decentralized heating system because the layout of the heating network, the connection of the heat customers, the number and capacity of the CHP plants and their specific locations have to be considered among other aspects. In this section we present an MILP that can be applied when planning a bioenergy village. The following section is based on work from Karschin and Geldermann (2013), where we present a theoretical approach to the planning of bioenergy villages.

We used a specific approach in graph theory to model the planning situation of a bioenergy village. These network flow

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