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Optimizing the production and distribution system of bioenergy villages

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ABSTRACT

In bioenergy villages, local bioenergy plants are installed to supply electricity, which is fed into the national grid, and to heat households through a local heat distribution network. In this paper, a linear mathematical model, which economically optimizes local bioenergy production and distribution systems based on a given set of system components, is presented. The model simultaneously determines the optimal capacity of the system, the objects that should be connected to the heating network and the course of the network. Additionally, a combined heat and power (CHP) biogas plant builds the production system. The problem is modeled as a mixed integer linear program (MILP) and is applied to a village with n potential heat customers. This model offers the possibility of economically assessing various scenarios concerning different planning situations and optimizing the capacity planning for the biogas plant and the course of the district heating network.

1. Introduction

The increasing shortage of resources and climate change have led to a new energy policy in Germany during the last decade. A further development of renewable energy sources and higher energy efficiency, for example, by insulating older buildings, is expected to decrease the dependency of this country on fossil fuels and reduce the emissions of greenhouse gases (Hennicke and Bodach, 2010). To reach these goals, several different laws have been passed and include the Combined Heat and Power Act (BMU, 2002) and the Renewable Energy Act (BMU, 2000). These laws set monetary incentives to use renewable energy sources and install plants with combined heat and power generators (CHP), which should realize energy efficiencies of greater than 80% (Nowak and Arthkamp, 2010).

Combined heat and power generation in local heating networks can be optimized by Mixed Integer Linear Programs (MILPs) to find the optimal operating strategy (Casisi et al., 2008). By taking into account the set-up of microturbines and the lay-out of the heating network, Casisi et al. (2008) applied their model to a real, city-center situation and demonstrated the wide scope of optimizing the operation of such systems.

Biogas plants can incorporate the use of renewable energy sources, producing methane from biomass, and the combination of heat and power generation, providing the fuel for a CHP facility. However, a sufficient supply of biomass must be obtained, to run the plant effectively. Additionally, for this type of decision problem, MILPs, which model biomass locations, capacities, the logistics of transportation, and various biofuel conversion technologies, can be formulated and implemented (Kim et al., 2011). The model from this study optimizes all decisions regarding different processing plants, biomass allocation, the final products, and their transport, and considers the objective function of the overall profit. Likewise, Gronalt and Rauch (2007) proposed an evaluation method for forest fuel supply networks by comparing centralized to local approaches. This group configured wood biomass supply networks for potential heating and energy plants, and considered the overall system cost of alternative configurations.

With a primary energy potential of greater than 70,000 GWh per year, which is the energy demand of approximately 3.5 million average households, biogas is a potentially important renewable energy source in Germany, especially for decentralized, local energy concepts, because it is capable of providing baseload power and heat (Vogt, 2008). Nevertheless, biogas plants have recently become the subject of substantial criticism, and issues such as the competition for land use, rising leasing rates for arable land, mono-cropping and its negative consequences on the natural scenery and biodiversity have been discussed. To mitigate and solve some of these problems, new concepts for cultivating energy crops and higher energy efficiencies of technical facilities are needed. Some first steps may involve the use of combined heat and power technologies that are supplemented by location-specific heat concepts and the use of crop rotations in the place of mono-cropping.

In Germany, the first resource-efficient energy concept of this type was realized in the bioenergy village of Jühnde in 2004. Electricity and heat are produced from biogas in a combined heat

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and power generator. Liquid manure and crops, which are cultivated from the agricultural land around the village, are the feedstock for the generation of biogas in an anaerobic digestion plant. The resulting electricity is then fed into the national electricity grid. To transport heat to villagers, a local hot water grid is installed (Ruppert, 2008).[1]

In this context, the following questions on production planning and logistics arise: What is the optimal course of the heating network, which potential heat customers should be connected to this network, and what capacity for the energy station should be installed? To answer these questions, an optimization model has been developed, that is composed of the CHP biogas plant as a production system and the local pipeline network as the distribution system that supplies the heat to customers. Building legislation, physical restrictions, and other political regulations are not taken into consideration. However, the costs of installation, maintenance and operation, and the expected revenues from selling heat to local customers and feeding electricity into the national grid are incorporated into the model.

The model presented in this paper can be widely adjusted and allows for the representation of many different planning situations. It can be used to support decision-making during the strategic planning of an investment in local heating systems and offers the possibility to calculate an economic benchmark for any biogas plant, which is combined with a heating network, optimizing its course and the capacity of the plant. Furthermore, the model can compare various scenarios regarding, for example, the biomass availability or the willingness of households to be connected to the local heating grid. It thereby offers valuable information for potential investors and relevant stakeholders during the process of planning the installation of such a facility.

The next section presents the general set-up of a district heating system based on the biomass. In Section 3, the cost for biomass allocation is estimated. In Sections 4 and 5, the energy production and distribution systems are explained and economically assessed. In Sections 6 and 7, the optimization model is shown and applied to a village with $n=44$ potential heat customers. In Section 8, various conclusions are drawn and further steps for improving the model are discussed. The last section summarizes the results.

2. District heating based on the biomass

Biogas plants with combined heat and power generators offer the possibility of installing decentralized, district heating systems. Biomass is used as a renewable energy source in a highly effective manner. The chemical energy that is obtained from biomass is converted into heat and electricity, which is fed into the national grid. Furthermore, the thermal energy provides a local and independent heating source for the connected households. This section presents the general set-up of a district heating system that is based on a CHP biogas plant (see Fig. 1).

Most often, local farmers initiate these heating systems, which reduces the transportation costs of the biomass. These farmers provide the feedstock for the biogas plant by growing energy crops or other types of biomass on their arable land. It was estimated that the average distance between a production site and a biogas plant was 20 km (FNR, 2007). Biomass is fed into a fermenter, which produces methane through an anaerobic

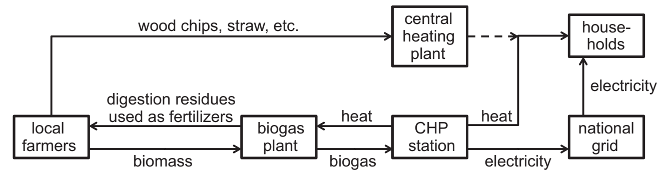

Fig. 1. General set-up of a district heating system based on a biogas plant with a CHP generator based on Fischer (2003).

fermentation process. Farmers can then use the residues from this process as fertilizers after fulfilling certain requirements of the German fertilizer directive (BMELV, 2008).

A combustion engine is fueled by biogas that consists of approximately 50% methane and produces electricity and heat (FNR, 2010). This electricity is not used locally but is fed into the national grid. A portion of the thermal energy (between 20% and 30%) is often used to regulate the temperature of the fermentation process if the CHP station is installed on the site of the biogas plant (FNR, 2010). However, most of the heat can be sold to local households, which are connected through a heating network. To have a backup system and for extremely cold days during the winter, a central heating plant can be installed.

The concept of using thermal energy from the combustion process for heating purposes should ensure independence from large, energy-producing companies and the volatile prices of fossil fuels. However, deciding which households to connect to the heating network and what plant capacity to install is complex. The costs of biomass allocation, investments into the production system and heating network, operating costs of the plants, and the revenues and allowances for selling electricity and heat must be considered.

Network flow models, which minimize the operating costs of existing micro-CHP systems, have been proposed by Cho et al. (2009); however, this group focused on operational planning. Gustafsson and Karlsson (1991) used a linear programming method to optimize the combination of electricity production, purchase and heat production in a district heating system while considering the lowest possible operating cost per year. Lahdelma and Hakonen (2003) presented an optimized linear programming algorithm that was based on an hourly load forecast to determine the cost-efficient operation of a CHP-system. They also focused on the day-to-day planning and operation of the facility and the mathematical details of the algorithm for solving the model. However, none of these models have been used for location planning or with the planning of a biogas production system.

3. Costs of biomass allocation

To estimate the economic consequences of installing a biogas plant and a heating network, the net present value method is widely used in investment decisions. The net present value (NPV) of an investment is the present value of all present and future cash flows that are generated within a certain planning horizon $t=1,\ldots,T$. A NPV ≥ 0 indicates that the investment is at least as profitable as an investment that returns the discount rate i. Therefore, the investment can be prioritized and recommended. For a NPV < 0, the investment should be rejected, at least from an economic point of view. To calculate the NPV of various plants with different capacities, the costs of operating the plant must be considered. This analysis includes an estimation of the biomass costs as a function of the installed capacity. The functions and variables that were utilized are shown in Table 1.

To minimize the costs of biomass delivery, storage, and transportation, a linear programming method can be used

[1] It should be noted that due to the regional aspect of the topic, much literature on the energy use of biomass in Germany is in German language and is issued by ministries and expert agencies such as the BMELV (Federal Ministry of Food, Agriculture and Consumer Protection) or FNR (Agency for Renewable Resources).

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