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Process analysis of a biomass-based quad-generation plant for combined power, heat, cooling, and synthetic natural gas production

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ABSTRACT

A new concept for upgrading distributed co-generation plants to quad-generation plants, which combine the production of power, heating, cooling and synthetic natural gas (SNG), is designed and analyzed. Five cases with SNG production ranging from 0% to 100% of total energy outputs are designed to simulate different modes of operation. The quad-generation system is simulated using ASPEN PLUS and described by simulating different portions of the system. This paper also describes the new process, which is of particular interest for improving the total first law efficiency. With this system, it is possible to increase the efficiency of natural resource utilization, minimize the environmental impact in distributed generation, and, by providing flexible operation, better support the integration of intermittent renewables such as wind power. Straw is used as a biomass feedstock for this simulation. The net energy efficiency is used to evaluate the performance of the quad-generation system. The results show that the most efficient case of the proposed system is providing 89.8% net energy efficiency, which is almost 7.6% higher than the lowest efficient case. Based on the flowsheet simulation, this energy assessment compares the proposed quad-generation system to the existing district heating system.

1. Introduction

The increasing demand for energy, environmental concerns, and trends toward the deregulation of energy markets have become integral parts of energy policy planning. Flow-based energy resources are largely incompatible with the current energy infrastructure, and a new and more complex structure is required to produce a more sustainable energy system [1]. The development of energy-efficient production technologies has made cogeneration and tri-generation possible [2,3] and now, the development trend is moving toward quad-generation and poly-generation. Meeting the future demand for power, heat, cooling, and bio-fuels with highly limited and fluctuating resources will require carefully planned allocation of the available renewable resources and a highly flexible system. All of these aspects have added new dimensions to energy planning. One of the renewable resources that could fulfill all of these demands is biomass, and one of the most efficient ways of utilizing this biomass is gasification [4,5]. Thus, this study proposes and studies a novel hybrid configuration for a biomass-based quad-generation system. It shows how the plant owners can utilize their total capacity by producing different fuels according to the local demands.

In Denmark, there are a substantial number of biomass-fired district heating plants, and approximately 10 straw- or wood-chip-fired decentralized combine heat and power (CHP) are also in operation. The rest of the decentralized CHP plants are fuelled by natural gas. One in three of the decentralised DH plants and one in seven of the decentralised CHP plants use environmentally friendly biomass fuels such as straw, wood chips, wood pellets, and wood waste). But the majority of rest of the plants – use natural gas as a fuel [6]. From this starting point, a scenario framework has been suggested in which the Danish system is converted to 100% renewable energy sources (RES) by the year 2060, including reductions in space heating demands by 75% [7]. The European Commission has also developed political strategies to increase the share of renewable and sustainable energy in fulfilling the overall energy demand [8,9].

Biomass conversion can be divided into two main pathways: thermochemical conversion and biochemical conversion [10]. The main thermochemical pathway for dry biomasses can be divided into combustion, gasification and pyrolysis [11]. Gasification converts the biomass into a syngas that can subsequently be used to generate heat and power or converted into fuels or other chemicals [12]. In this study, the existing methodology is replaced

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by gasification as it is one of the most efficient conversion methods.

The most stable state-of-the-art gasification technologies combined with the possibilities of cogeneration through the gasification of biomass have been described and compared in a Danish context [1], and it has been shown that the thermal gasification of biomass is both highly flexible and efficient. There are a number of scientific publications that address some novel concepts for polygeneration system design and energy analysis using different input fuels [13,14]. These papers found that system integration with gasification technology made a significant contribution to the improvement of performance. The concepts of polygeneration and energy integration have been described using various examples of systems [15–17], and some papers have published the mathematical modeling and simulation of polygeneration energy systems [18–22]; however, these papers focus on the evaluation of new plants and technologies concerning the configuration design of the processes. With the aim of achieving higher efficiency and lower emissions, innovations in both power generation technologies and process integration strategies were taken into account in the development of a fully integrated plant [23–26]. The high efficiency of small-scale biomass gasification quad-generation based on gas engines provides an opportunity for converting natural gas fired heating plants into efficient quad-generation plants that have not been used previously. Natural gas-fuelled gas engine quad-generation plants can either be converted into pure biomass-based plants or dual fuel plants, operating on producer gas, natural gas or mixtures of both. The main advantage of the conversion of such plants is that the gas engine is already installed, and this is normally a major part of the total investment. For high chemical conversion and effective energy utilization, a new biomass-based quad-generation system using existing gas engines and an additional synthesis unit for power, heat, cooling and SNG production is proposed in this paper.

Research into large-scale investment planning to convert existing plants to quad-generation energy systems is limited, albeit clearly crucial for strategic policy-making in regions and countries. This paper includes different scenarios according to the fuel demands of the specific plants and attempts to provide an overview of possible technical outcomes of a new green field quad-generation system regarding fuel production efficiency. It also endeavors to select the best case among the possible alternatives, in accordance with explicit technical objectives, i.e., efficiency.

2. Scope of this work

The Brovst district heating plant (DHP) is one of the district heating plants in the Jammerbugt municipality in Northern Denmark. Fig. 1 shows the heat production of the Brovst DHP. Scenario- 1 represents the existing capacity of the Brovst DHP and assumed that is constant. The distance between the heat production curve and scenario 1 line embodies the free capacity. In the summer, especially from June to August, heat production is lower than in the rest of the year as it has less heat demand. During this period, it is necessary to shut down heat production from the engine. The motivation of this work is to utilize this free capacity between the plant capacity and the actual production by upgrading the existing system to quad-generation. It will also be possible to scale up the production like scenario 2 in Fig. 1. Scenario 2 line represents the extended capacity for the quad-generation. Scenario 2 includes power, heat, cooling, and fuel demand and also constant energy demand. Feedstock selects 100 ton of biomass per day according to satiate the energy demand which represents in scenario 2 (own calculation) from Fig. 1. The district heating requirements are based on historical requirements from an existing Brovst DHP, while the district cooling requirements are loosely estimated based on what could be the space cooling requirements of the area's commercial buildings. By installing a quad-generation system, the plant can satisfy public demand for heat while also producing power, cooling and SNG according to the demand and the market value of each. The use of fossil fuels is also associated with many concerns, among which are the security of the supply and the resulting air pollution. One of the ways to reduce the transportation sector's dependency on fossil fuels is to use biofuels from quad-generation plants. In this region, a large amount of power is produced by wind farms, but the output is variable according to the availability of wind. In cases of excess power production from wind, the excess can be utilized to produce H_2 for CH_4 synthesis. Therefore, a quad-generation power plant can be used in conjunction with wind energy because it has flexible output.

3. Process description

3.1. Description of existing plant

The Brovst DHP uses natural gas for the production of heat and power. Heat demand is approximately 37,200 MW h/year. The system inside the dotted line in Fig. 2 represents the existing plant. Presently, it has two natural gas generator sets with an output of 3.1 MW of power and 4.1 MW of heat together, with the power being sold to the national grid. It also has two condensing hot water boilers with a total of 8.15 MW of heat production. A 1600 m^3 storage tank has also been installed in this plant.

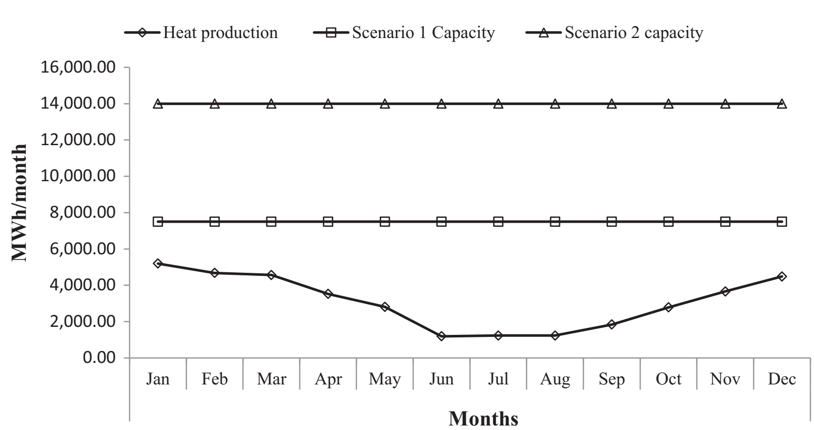

Fig. 1. Heat production and total capacity over a year for the Brovst DHP.