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Exergy analysis of a combined heat and power plant with integrated lignocellulosic ethanol production

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ABSTRACT

Lignocellulosic ethanol production is often assumed integrated in polygeneration systems because of its energy intensive nature. The objective of this study is to investigate potential irreversibilities from such integration, and what impact it has on the efficiency of the integrated ethanol production. An exergy analysis is carried out for a modelled polygeneration system in which lignocellulosic ethanol production based on hydrothermal pretreatment is integrated in an existing combined heat and power (CHP) plant. The ethanol facility is driven by steam extracted from the CHP unit when feasible, and a gas boiler is used as back-up when integration is not possible. The system was evaluated according to six operation points that alternate on the following three different operation parameters: Load in the CHP unit, integrated versus separate operation, and inclusion of district heating production in the ethanol facility. The calculated standard exergy efficiency of the ethanol facility varied from 0.564 to 0.855, of which the highest was obtained for integrated operation at reduced CHP load and full district heating production in the ethanol facility, and the lowest for separate operation with zero district heating production in the ethanol facility. The results suggest that the efficiency of integrating lignocellulosic ethanol production in CHP plants is highly dependent on operation, and it is therefore suggested that the expected operation pattern of such polygeneration system is taken into account when evaluating the potential of the ethanol production.

1. Introduction

The integrated production of biofuels in thermal power plants has received increasing attention in the recent years due to the potential synergies from thermal integration. One example is the gasification-based coproduction of heat, electricity, Fischer–Tropsch fuels, dimethyl ether (DME), and hydrogen from biomass feedstocks [1], like switchgrass [2] and black-liquor [3]. Another important example is the integrated production of bioethanol and synthetic natural gas (SNG) with combined heat and power (CHP) production [4]. Among biofuels, bioethanol is the most widely used for transportation on a global basis and is consumed both as an individual fuel and in blends with gasoline [5]. Bioethanol can be produced from sugars, starch, and lignocellulosic biomass, of which the latter often is considered the most sustainable option as it offers the possibility of reducing CO_2 emissions from transportation without linking fuel prices and food prices directly [4]. This study treats the integrated production of lignocellulosic ethanol in an existing CHP plant.

Several studies have focused on thermal integration synergies in systems with integrated production of power, heat, lignocellulosic ethanol, and SNG [6–10]. Daianova et al. [6] and Ilic et al. [7] both report better energy economy for the integrated system compared to stand-alone systems, while Bösch et al. [8] reports a potential increase in both first law energy efficiency and exergy efficiency when integrating the processes. Modarresi et al. [9] applied pinch analysis to improve the heat integration of the system, which yielded an integrated exergy efficiency of 88% for the ethanol process. Gassner and Maréchal [10] have investigated process integration in such polygeneration systems and conclude that both first and second law energy efficiencies are increased significantly by integrating lignocellulosic ethanol and SNG production in a CHP plant. Furthermore, a case study by Starfelt et al. [11] reports higher first-law energy efficiency for integrating lignocellulosic ethanol production in an existing CHP plant compared to a scenario with separate production. These results explain the industrial interest in retrofitting existing CHP units to obtain the mentioned polygeneration system benefits.

A previous study by the authors [12] evaluated the energy economy of integrating lignocellulosic ethanol production based on the hydrothermal pretreatment technology IBUS[1] [13] in the existing

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[1] IBUS (Integrated Biomass Utilization System) is a patented lignocellulosic biomass pretreatment technology. The patent is owned by the Danish company Inbicon A/S, a subsidiary to DONG Energy.

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Danish CHP unit Avedøreværket 1 (AVV1). During integration, the hot utility demand of the ethanol facility was met by steam extracted from the turbines of AVV1, and when integration was not feasible due to high CHP loads or periods of CHP shut-down, a natural gas boiler was used to deliver the necessary heat while the power demand was met by power bought from the power market. The study suggested an ethanol production energy cost of 0.14 Euro/L on average during integrated operation, and 1.22 Euro/L on average during separate operation, underlining the potential benefits of integrating the production. Based on existing production patterns for AVV1, the study further suggested that the duration of separate operation over a year would be significant, reducing the overall benefit from the integration and questioning the average yearly efficiency of the ethanol production.

The overall objective of this study is to determine the irreversibilities related to the integration of lignocellulosic ethanol production in CHP units at various operation modes. This objective is targeted through a case study of a polygeneration system in which lignocellulosic ethanol production based on IBUS technology is integrated in the Danish CHP unit AVV1. Exergy analysis [14] is applied to a model of the ethanol production facility previously developed in Lythcke-Jørgensen et al. [12] to identify exergy flows in the ethanol production facility and its heat integration network. Exergy efficiencies are calculated for the individual process steps, and the exergy efficiency of the overall ethanol production is evaluated in six different operation points, covering both integrated and separate operation, zero and full district heating production in the ethanol facility, and various loads in the CHP unit. Based on the outcomes, the impact of polygeneration system operation on the average exergy efficiency of the ethanol production is discussed. The novelty of this paper lies in the evaluation of the average system exergy efficiency by combining exergy analysis with the performance analysis in the boundary points of the feasible operation range.

In this paper, the polygeneration system design, modelling and operation are presented in Section 2 together with the exergy analysis approach. Results of the analysis are presented in Section 3 and discussed in Section 4. Finally, a conclusion on the study is given in Section 5.

2. Methodology

2.1. Polygeneration system model

A numerical model of a polygeneration system that integrates lignocellulosic ethanol production based on IBUS technology in the Danish CHP unit AVV1 was previously developed and presented by the authors [12], and the same model is used in the present study. This section presents the system design and the modelling approach, system operation, and obtained data that are used in the exergy analysis. A simplified process layout of the modelled polygeneration system is presented in Fig. 1.

2.1.1. Modelling of AVV1

A numerical model of AVV1, developed by Elmegaard and Houbak [15] in the energy system simulator Dynamic Network Analysis (DNA) [16], was used for simulating flows and operation of AVV1. The model accuracy was evaluated at various loads by comparing electrical efficiencies, η_{el}, and first law energy efficiency, η_I, obtained in the model with efficiencies reported by the plant operator [17]. The two efficiencies are defined by the following equations:

$$\eta_{el} = \frac{P}{\dot{Q}_{fuel}} \tag{1}$$

$$\eta_I = \frac{P + \dot{Q}_{DH}}{\dot{Q}_{fuel}} \tag{2}$$

In the equations, P is the power production, $\dot{Q}_{DH}$ is the district heating production, and $\dot{Q}_{fuel}$ is the fuel input. The comparison was limited to condensation mode and full back-pressure mode operation as they represent the extreme cases of plant operation. Calculated and reported efficiencies are summarized in Tables 1 and 2.

It was found that the model assumed slightly larger fuel consumption in condensation mode than what was reported by the plant owner, resulting in electrical efficiencies that were between 2% and 8% lower for the model. For back pressure operation, the first law energy efficiency accuracy was found to be within a range of 2%, while the electrical efficiency deviated by up to 6%. The inaccuracy of the model was found to be related to the prediction of fuel consumption mainly, and the model was therefore considered adequate for use in the present study.

2.1.2. Modelling and dimensioning of the ethanol facility

In the ethanol facility, the lignocellulosic structure of the straw is broken down through treatment with pressurized steam in the hydrothermal pretreatment stage, whereupon the straw-steam mixture is split into a fibre fraction and a liquid fraction. The fibre fraction is liquefied by glucose-forming enzymes before fermentation is initiated in Simultaneous Saccharification and Fermentation (SSF) tanks. Ethanol is distilled from the resulting fermentation broth, leaving a fibre stillage which is treated in various separation stages alongside the pretreatment liquid fraction, generating a solid biofuel fraction, a molasses fraction, and a waste water fraction. The molasses fraction can be used in anaerobic fermentation to produce biogas [9] or as animal feed [18], while the solid biofuel can be used for combustion or gasification.

A model of the ethanol facility based on heat and mass balances over the system process steps was developed in a previous study by the authors [12] using the software Engineering Equation Solver (EES) [19]. The model was based on the layout reported by Larsen et al. [18] and Østergaard et al. [20]. Mass balances were calculated over each process step as

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{3}$$

In flows with multiple compounds, the mass fraction of a compound i is termed x_i. The fraction of compound i recovered in a given output flow, $\varepsilon_{(flow),i}$, was defined as

$$\varepsilon_{(flow),i} = \frac{\dot{m}_{(flow)} x_{(flow),i}}{\sum_{n=inlet\,flows} \dot{m}_n x_{n,i}} \tag{4}$$

In process steps with compound conversion or degradation, the relation of output to input mass flow of a compound i, $\eta_{(flow),i}$, was defined as

$$\eta_{(flow),i} = \frac{\sum_{k=outlet\,flows} \dot{m}_k x_{k,i}}{\sum_{n=inlet\,flows} \dot{m}_n x_{n,i}} \tag{5}$$

The steam mass flow $\dot{m}_{steam}$ into the hydrothermal pretreatment process was modelled as a constant, K_{steam}, times the input biomass mass flow, $\dot{m}_{biomass}$, as suggested by Bentsen et al. [21].

$$\dot{m}_{steam} = K_{steam} \dot{m}_{biomass} \tag{6}$$

To determine resulting heating or cooling demand $\dot{Q}_j$ for a process j, the energy balance over the process step was calculated as

$$\dot{Q}_j = \sum_{n=inlet\,flows} \dot{m}_n h_n - \sum_{k=outlet\,flows} \dot{m}_k h_k \tag{7}$$

Here, h_i is the specific enthalpy of the flow i. The only exception to this was the distillation process, for which the hot and cold utility