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Design optimization of a polygeneration plant producing power, heat, and lignocellulosic ethanol

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ABSTRACT

A promising way to increase the energy efficiency and reduce costs of biofuel production is to integrate it with heat and power production in polygeneration plants. This study treats the retrofitting of a Danish combined heat and power plant by integrating lignocellulosic ethanol production based on wheat straw with the aim of minimizing specific ethanol production cost. Previously developed and validated models of the facilities are applied in the attempt to solve the design optimization problem. Straw processing capacities in the range of 5–12 kg/s are considered, while plant operation is optimized over the year with respect to maximal income and with the limitations that the reference hourly district heating production has to be met while reference hourly power export cannot be exceeded.

The results suggest that the specific ethanol production cost increased continuously from 0.958 Euro/L at a straw processing capacity of 5 kg/s to 1.113 Euro/L at a capacity of 12 kg/s, indicating that diseconomies-of-scale applies for the suggested ethanol production scheme. A thermodynamic evaluation further discloses that the average yearly exergy efficiency decreases continuously with increasing ethanol production capacity, ranging from 0.746 for 5 kg/s to 0.696 for 12 kg/s. This trend results from operating constraints that induce expensive operation patterns in periods of high district heating loads or shut-down periods for the combined heat and power plant. A sensitivity analysis indicates that the found optimum is indifferent to major variations in fossil fuel prices. The results question the efficiency of the suggested retrofitting scheme in the present energy system, and they further point toward the importance of taking operating conditions into consideration when developing flexible polygeneration plant concepts as differences between design-point operation and actual operation may have a significant impact on overall plant performance.

1. Introduction

Biomass, being the only renewable resource of highly concentrated carbon, is often considered a cornerstone in renewable energy systems because of its storability and potential conversability to biofuels with high energy densities [1]. The biomass resource, however, is limited [2], and competition between food and energy production pose a sustainability challenge [3]. Efficient use and conversion of sustainably available biomass are therefore of crucial importance in renewable energy systems [4].

Among biofuels, ethanol is presently the most widely used for transportation on a global basis and it is consumed both as an individual fuel and in blends with gasoline [5]. Ethanol produced from lignocellulosic biomass is of special interest here because it may yield reduced CO_2 emissions from transportation without linking fuel prices and food prices directly [4]. Furthermore, ethanol is a bulk-volume chemical used in industrial and consumer products and lignocellulosic ethanol presents a green chemistry [6][1] alternative to the existing ethanol production from ethene hydration or through fermentation of sugars and starch [7]. However, the energy intensive nature of lignocellulosic ethanol production is a challenge with respect to production efficiency and economy.

In an extensive work on the integrated production of biogas, heat and power based on biomass gasification, Gassner and Maréchal [8] concluded that biofuel plants may increase energy- and cost-efficiency simultaneously by applying process systems engineering approaches and by considering integration with other processes in polygeneration plants (PGPs). Similarly, a promising

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[1] Green chemistry consists of environmental friendly, sustainable chemicals and processes the use of which results in reduced waste, safer outputs, and reduced or eliminated pollution and environmental damage [6].

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Nomenclature

Latin letters

C	cost (Euro)
c	specific cost (Euro/GJ)
D	dimension (–)
$\dot{EX}$	exergy flow (MJ/h)
ex	specific exergy flow (MJ/kg)
I	investment (Euro)
M	mass (kg)
M_f	capacity power factor (–)
$\dot{P}$	power production (MW)
Q	heat (MJ)
$\dot{Q}$	heat flow (MJ/s)
$\dot{Q}_{fuel}$	fuel input (MJ/s)
V_{eth}	volume ethanol production (L/h)

Greek letters

α	back-pressure operation parameter (–)
β	relative district heating production in the ethanol facility (–)
η_{eth}	mass efficiency of lignocellulosic-biomass-to-ethanol conversion (–)
η_{ex}	standard exergy efficiency (–)
κ	choice between integrated or separate operation (–)
λ	combined heat and power unit load (–)
ρ	density (kg/L)
σ	straw processing capacity of the ethanol production (kg/s)

Subscripts

add	additives
enz	enzymes
eth	ethanol
i	hour of the year
I	investment depreciation
O&M	operation and maintenance
ref	reference production
0	reference value

Abbreviations

AVV1	Avedøreværket 1
CHP	combined heat and power
DH	district heating
L&D	(exergy) losses and destruction
O&M	operation and maintenance
SSF	simultaneous saccharification and fermentation

way to increase energy- and cost-efficiency of lignocellulosic ethanol production is to integrate it with heat and power production [4]. Plants integrating the production of power, heat, bio-methane, and lignocellulosic ethanol have been investigated by several groups, both as grassroot design problems and retrofit design problems. Regarding grassroot design problems, Daianova et al. [9] and Ilic et al. [10] both reported better energy economy for integrated PGPs compared to stand-alone production of the same energy products, assuming constant energy prices over the year. Bösch et al. [11] discussed how the energy economy of a system producing lignocellulosic ethanol, biogas and district heating (DH) might be increased by integrating power production. For a similar system, Modarresi et al. [12] conducted a pinch analysis and reported that heat integration can reduce the hot and cold utility demands by up to 40%, assuming operation in design point solely. Leduc et al. [13] conducted a sensitivity analysis of the important parameters for such systems in Sweden and found that incomes from heat and power sales were the most significant contributors toward reducing the specific ethanol production costs. With regard to retrofitted systems, Palacios-Bereche et al. [14] studied the integration of lignocellulosic ethanol production in the conventional first-generation sugarcane ethanol process and reported higher exergy efficiency for the integrated scheme when considering only design point operation. Lythcke-Jørgensen et al. [15] investigated the introduction of lignocellulosic ethanol production in an existing combined heat and power (CHP) and also reported higher exergy efficiencies for integrated operation. In a study of conversion routes for winter wheat to ethanol, Bentsen et al. [16] suggested that energy savings could be achieved by integrating lignocellulosic ethanol production in existing CHP units. Starfelt et al. [17] investigated the integration of lignocellulosic ethanol production in an existing biomass-based CHP unit in Sweden and concluded that for the same production of heat, power, and ethanol, the total biomass consumption would be lower for the integrated system than for a separate scenario. And in a later study, Starfelt et al. [18] concluded that the integration of lignocellulosic ethanol production in Swedish CHP units with fixed heat-to-power ratios may be profitable if excess heat capacity is available in the CHP unit for a certain amount of time over the year.

In principle, the development and optimization of PGPs can be considered at three levels, similar to the optimization of energy systems [19] and distributed energy supply systems [20]: Synthesis level, design level, and operation level. At the synthesis level, the configuration of the PGP is optimized by either retrofitting an existing plant (retrofit design) or by developing a new plant concept (grassroot design),[2] which entails the selection of the desired products and processes. At the design level, one considers process dimensioning, process integration, required components, and technical specifications of the equipment. Finally, at the operation level, the operation mode of the given plant is optimized in the surrounding energy system; this is done by taking expected demands for, and costs of, energy services and utilities into account as well as interactions with other energy producers in the system. The operation level is especially important for flexible operating PGPs, e.g. those set to balance production from intermittent renewable energy sources [21] whenever economically advantageous [22]. Optimization on operation level has been investigated in literature for polygeneration plants producing power, heating, cold and fresh water, e.g. in a sequential optimization methodology presented by Uche et al. [23]. Grisi et al. [24] further illustrated how commodity market prices may affect operation decisions in a sugarcane biorefinery producing power, sugar, sugar- and bagasse-based ethanol, and biogas. However, to the authors' best knowledge the impact of flexible plant operation on economic performance has not been treated comprehensively in previous studies of the integrated production of power, heat, and lignocellulosic ethanol.

This study assesses the impact on economic and thermodynamic performance of integrating lignocellulosic ethanol production with flexible heat and power production. The study treats a retrofit design problem where lignocellulosic ethanol production

[2] A grassroot design is *a priori* always a solution to a retrofit design optimization problem [20].