



Thermodynamic and economic analysis of integrating lignocellulosic bioethanol production in a Danish combined heat and power unit

Lythcke-Jørgensen, Christoffer Ernst; Haglind, Fredrik; Clausen, Lasse Røngaard

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THERMODYNAMIC AND ECONOMIC ANALYSIS OF INTEGRATING LIGNOCELLULOSIC BIOETHANOL PRODUCTION IN A DANISH COMBINED HEAT AND POWER UNIT

C. Lythcke-Jørgensen^{a,*}, F. Haglind^a, L.R. Clausen^a

^a Technical University of Denmark, DTU Mechanical Engineering, Section for Thermal Energy
Nils Koppels Allé, building 403, 2800 Kgs. Lyngby, Denmark

* Corresponding author. Contact: +45 30 42 72 00, celjo@mek.dtu.dk

ABSTRACT: Integrating lignocellulosic bioethanol production with combined heat and power (CHP) production in polygeneration systems is considered an efficient and competitive way to produce a sustainable fuel for the transportation sector. This study assessed the energy economy of integrating lignocellulosic bioethanol production in the Danish CHP unit Avedøreværket 1. Numerical models of the plants were developed, and feasible integration solutions were identified and optimised using exergy analysis. Hour-wise production simulations were run over a reference year, and market prices and economic parameters from the literature were used to evaluate the production economy. A competitive energy cost limit for the bioethanol production was found to be 0.22 Euro/L. The optimised system produced bioethanol at a mean cost of 0.14 Euro/L during integrated operation and 1.22 Euro/L during separate operation. Maintenance shut-downs and periods of high power demand resulted in 3375 hours of separate operation over the year, giving an average bioethanol energy cost of 0.56 Euro/L. The results suggest that the polygeneration system cannot produce lignocellulosic bioethanol competitively under the given conditions, which questions the economic viability of the polygeneration system if operated in grids with periodically large power demands, for instance those caused by the operation of wind turbines and photovoltaic cells with a large capacity.
Keywords: Analysis, bioethanol, economic aspects, modelling, polygeneration

NOMENCLATURE

Latin letters

C	absolute cost [Euro]
c	specific cost [Euro/kJ]
$c_{ethanol}$	specific cost of ethanol [Euro/L]
h	enthalpy [kJ/kg]
K_{steam}	steam to biomass ratio [-]
\dot{m}	mass flow [kg/s]
t	residence time [h]
P	amount of power produced [kJ]
Q	amount of heat produced [kJ]
\dot{Q}	heat flow [kJ/s]
V	volume [L]
x	mass fraction [-]

Greek letters

$\varepsilon_{j,i}$	fraction of component i recovered in flow j [-]
$\eta_{i,k}$	recovery of component i in process k [-]

Subscripts

i	compound
j	flow
k	process

Abbreviations

<i>AVV1</i>	Avedøreværket 1
<i>CHP</i>	Combined heat and power
<i>IBUS</i>	Integrated Biomass Utilization System

1 INTRODUCTION

Second-generation bioethanol, processed from inedible and renewable biomass and acting as a direct substitute for fossil fuels in internal combustion engines, can decrease greenhouse gas emissions from the transportation sector while reducing the dependency on

imported oil in countries without domestic resources. Within the European Union, especially the processing of lignocellulosic biomass is considered a promising second generation bioethanol technology [1].

Due to the energy intensive nature of lignocellulosic bioethanol production, it is considered advantageous to integrate bioethanol production facilities with the production of other energy products in polygeneration systems. Systems containing heat, power, lignocellulosic bioethanol and biogas production have been studied at the system level in several papers [2-4]. [2] and [3] both report better energy economy for integrated operation of the various facilities compared to stand-alone operation, while [4] reports a better first law efficiency for the integrated system. Similarly, higher first law efficiency for integrated operation has been reported by [5] for a polygeneration system in which lignocellulosic bioethanol production was integrated with an existing combined heat and power (CHP) unit. However, none of these studies take market restrictions or load fluctuations into account. The importance of the operational flexibility of a polygeneration plant operating in a fluctuating market environments was investigated by [6], who claimed that flexible plants can obtain better plant economies than static ones due to hour-wise and seasonal-wise variations in product prices. The impact of production flexibility was investigated in the present work.

This paper examines the integration of a lignocellulosic bioethanol production facility based on the IBUS (Integrated Biomass Utilization System) in the existing CHP unit Avedøreværket 1 (AVV1) outside Copenhagen. First, the polygeneration system was designed and modelled numerically. Second, the energy economy of the system was evaluated by conducting hour-wise production simulations over a reference year. The production demands for AVV1 during the reference year were used to determine the outputs to be delivered by the polygeneration system, while the energy economy was evaluated using actual electricity, heat, bioethanol, gas and coal prices. The results of the study are significant for evaluating the economy of polygeneration

systems in a constrained and fluctuating market.

The thermodynamic modelling is described in Section 2, while the approach that was used in the economic analysis is described in Section 3. The results of the analysis are presented in Section 4 and discussed in Section 5. The conclusions that can be drawn from the total analysis are given in Section 6, while a list of the references is provided in Section 7.

2 THERMODYNAMIC MODELLING

The thermodynamic modelling consisted of two major parts: a modelling part in which numerical models of the polygeneration system facilities were developed, and a design part where the facility integration was designed and optimised.

2.1 Polygeneration system modelling

The polygeneration system studied consisted of the existing Danish CHP unit AVV1 and a bioethanol production facility running the IBUS (Integrated Biomass Utilization Process) technology, which has been described in detail in several papers [7-10].

A numerical model of AVV1 was developed and described by [11] using the energy system simulator DNA [12]. With the authors' permission, their model was used in this study. A simplified component layout of AVV1 is found in Figure 1.

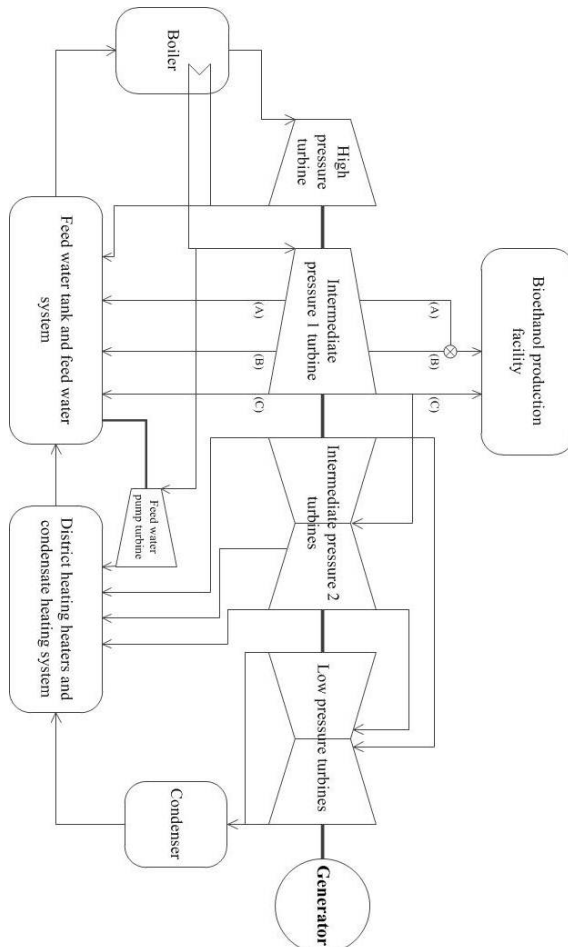


Figure 1: Simplified layout of the numerical model of AVV1

The model accuracy was evaluated at various loads by comparing electrical efficiencies and energy utilization values obtained with efficiencies reported by the plant operator [13]. This comparison was limited to condensation mode and full back-pressure mode operation as they represent the extreme cases of plant operation. All values are summarized in Tables 1 and 2.

Table 1: Comparison of model efficiencies and reported plant efficiencies in condensation operation

Load	Condensation mode operation		
	Electrical Efficiency		
	Model	Reported	Deviation
1.0	0.41	0.42	-2%
0.8	0.40	0.42	-5%
0.6	0.39	0.42	-7%
0.4	0.37	0.40	-8%

Table 2: Comparison of model efficiencies and reported plant efficiencies in full back pressure operation

Load	Full back pressure mode operation					
	Electrical Efficiency			Energy Utilization		
	Model	Reported	Deviation	Model	Reported	Deviation
1.0	0.36	0.34	6%	0.91	0.92	-1%
0.8	0.35	0.34	3%	0.91	0.92	-1%
0.6	0.33	0.33	0%	0.90	0.91	-1%
0.4	0.30	0.30	0%	0.88	0.90	-2%

It was found that the model assumed a larger fuel consumption in condensation mode than what was reported by the plant owner, resulting in energy efficiencies that were between 2% and 8% lower for the model. For back pressure operation, the energy utilization accuracy was found to be within a range of 2%, while the electrical efficiency deviated by up to 6%.

A numerical model of a bioethanol production facility based on the IBUS process was developed using layout and yields reported by [7] and [14]. The model, which uses heat and mass balances to model the process, was developed in the software EES (Engineering Equation Solver) [15]. The modelled process layout is illustrated in Figure 2.

In the IBUS process, input biomass is sent into a pretreatment stage where it is chopped and washed. It is then fed into a hydrothermal pretreatment reactor where the lignin structure is broken down by treatment with pressurised steam. The biomass product from the reactor is pressed afterwards to remove excess water, leaving a fibre fraction and a stillage fraction. The fibre fraction is cooled and liquefied by glucose-forming enzymes before fermentation is initiated in simultaneous saccharification and fermentation (SSF) tanks, producing an ethanol-containing broth. Bioethanol is distilled from the broth, leaving a fibre stillage that is mixed with the stillage from the pretreatment. Solid biomass compounds remaining in the stillage are filtered out and dried to form a high-quality solid biofuel with low alkali and moisture content. Ethanol and some of the water contained in the remaining stillage is evaporated from the stillage, leaving behind a molasses mixture with high C5 sugar content.

Mass balances were assumed over each component for useful flows. The mass balances were calculated for each component as:

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

For both reactions, molar weight ratios were used to relate the weight fraction increase of the reaction products to the weight fraction decrease of the reactants.

Component energy balances were used to evaluate the resulting heating or cooling demand:

$$\dot{Q}_{(component)} = \sum_{j=inlet\ flow} \dot{m}_j h_j - \sum_{k=outlet\ flow} \dot{m}_k h_k$$

The exception to this was the distillation component, for which the heating and cooling demands were calculated using the Aspen Plus distillation column model.

As reported by [10], the power consumption of an IBUS facility was set to 220kWh/ton of biomass treated.

2.2 Modelling assumptions and parameters

Degradation of hemicelluloses was assumed to occur only during pretreatment. No degradation or dissolving of lignin was assumed during the processes. Hydrolysis was assumed to be the only means of cellulose conversion. The addition of yeast and enzymes was neglected in mass balance calculations. Cellulose, hemicellulose, lignin and glucose were assumed to have constant heat capacities in then relevant temperature ranges. Mixtures of water and ethanol with low ethanol mass fractions below 0.1 have been treated as if the water and ethanol were separated. Heat losses were neglected for all components.

The parameters used to describe the system are summarized in Table 3, together with reported parameter values from literature and the values used in the model.

The accuracy of the IBUS facility model was evaluated by comparing model yields with reported yields from the literature, see Table 4. Reported yields varied significantly. Compared to the yields reported the most recently, the model deviated by up to 6.5% [8].

Table 4: Comparison of model yields and yields reported in the literature. All numbers are in kg/ton of biomass

	Model yield	[7]	[8]	[9]	[10]
Bioethanol	150.0	143	144	143.3	153.3
Solid biofuel	406.8	353	435	433.3	-
Molasses	371.0	420	371	370.0	-

2.3 System dimensioning and integration design

With an estimated average yearly production of 196,000 tons, winter wheat straw is the lignocellulosic biomass with the highest local production within a distance of 50km from AVV1 [16]. The system was dimensioned to process all locally available winter wheat straw, resulting in a facility processing capacity of 22.4 tons of straw per hour all year round. A linear relation between capacity and energy consumption was used for determining the energy demand of the bioethanol production facility.

Based on requirements for the temperature and pressure of the steam to be delivered to the bioethanol facility, only the three existing steam extraction points in the Intermediate Pressure 1 turbine of AVV1, marked (A), (B) and (C) in Figure 1, were considered for steam extraction.

For each feasible integration solution, pinch analysis [17] was used to identify the necessary amount of heat flow to be extracted from the various steam extraction

points. District heating production was assumed to form part of the bioethanol production facility. A 10K pinch temperature difference was used, as suggested by [18] for a similar facility. Models were developed for each integration solution, and simulations were run for various loads to determine the operational range for the heat and power production. Exergy analysis [19] was applied to identify the integration solution having the lowest overall exergy destruction within the polygeneration system.

Table 5: Economic parameters used in the analysis

	Specific cost
CHP fuel	4.36 Euro/GJ [13]
Gas	9.26 Euro/GJ [13]
Electricity	Dependent on the hour i [20]
Bioethanol	0.55 Euro/L ^f [21]
Bioethanol production costs without energy costs	0.33 Euro/L ^g [7]

^f The average bioethanol price on the European market for the period 2008-2010 was used

^g Calculated from values from a feasibility study of a 50ton/h IBUS facility located in the US. The number includes the expected income from selling the molasses and solid biofuel bi-products

3 ECONOMIC ANALYSIS

To evaluate the energy economy of the system, hour-wise simulations were run for the polygeneration system production over a year. The cost difference between operating AVV1 and operating the polygeneration system was taken to be the cost of bioethanol production.

3.1 Energy economy data

Costs of consumed resources, products and operation were used to evaluate the energy economy of the polygeneration system. The values used are summarized in Table 5.

A competitive limit of 0.22 Euro/L for the energy cost of the bioethanol production was obtained by subtracting the bioethanol production cost without energy costs from the expected bioethanol selling price.

3.2 Production simulations and energy cost calculations

The polygeneration system was set to deliver the same hour-wise production of heat and power as AVV1 did in the reference year. In periods where production loads or shut-downs prevented integrated operation of the bioethanol production facility, a gas boiler with a first law efficiency of 96% [22] was used for providing the required steam, and the required power was assumed to be bought from the electricity market at a price corresponding to that of the Nord Pool Spot electricity market.

The energy cost of operating AVV1, $C_{energy,AVV1}$, was determined as the sum of the hour-wise fuel consumption of the plant $Q_{i,AVV1}$ over the year times the fuel cost c_{fuel} :

$$C_{energy,AVV1} = \sum_{i=1}^{8760} Q_{i,AVV1} \cdot c_{fuel}$$

The energy cost of operating the polygeneration system, $C_{energy,poly}$, was estimated as the hour-wise sum of the CHP unit energy cost plus the cost of IBUS operation in periods without integrated operation.

$$C_{energy,poly} = \sum_{i=1}^{8760} Q_{i,CHP} \cdot c_{fuel} + \sum_{i=1}^{8760} L_{i,IBUS} \left(\frac{1}{\eta_{boiler}} Q_{IBUS} C_{gas} + P_{IBUS} C_{i,electricity} \right)$$

$Q_{i,CHP}$ is the hour-wise fuel consumption of the CHP unit in the polygeneration system, while Q_{IBUS} and P_{IBUS} are the heat and power consumption of the bioethanol facility. $L_{i,IBUS}$ is a variable taking the value 1 when IBUS is operated separately and 0 when IBUS is operated as an integrated part of the CHP unit. Note that $Q_{i,CHP}$ is not equal to $Q_{i,AVV1}$ as the CHP unit consumes more fuel in integrated operation to maintain the IBUS facility operation.

The specific bioethanol production energy cost $c_{energy,ethanol}$ was calculated as the difference in energy cost of the polygeneration system and AVV1 divided by the volume of the yearly ethanol production $V_{ethanol,year}$.

$$c_{energy,ethanol} = \frac{C_{energy,poly} - C_{energy,AVV1}}{V_{ethanol,year}}$$

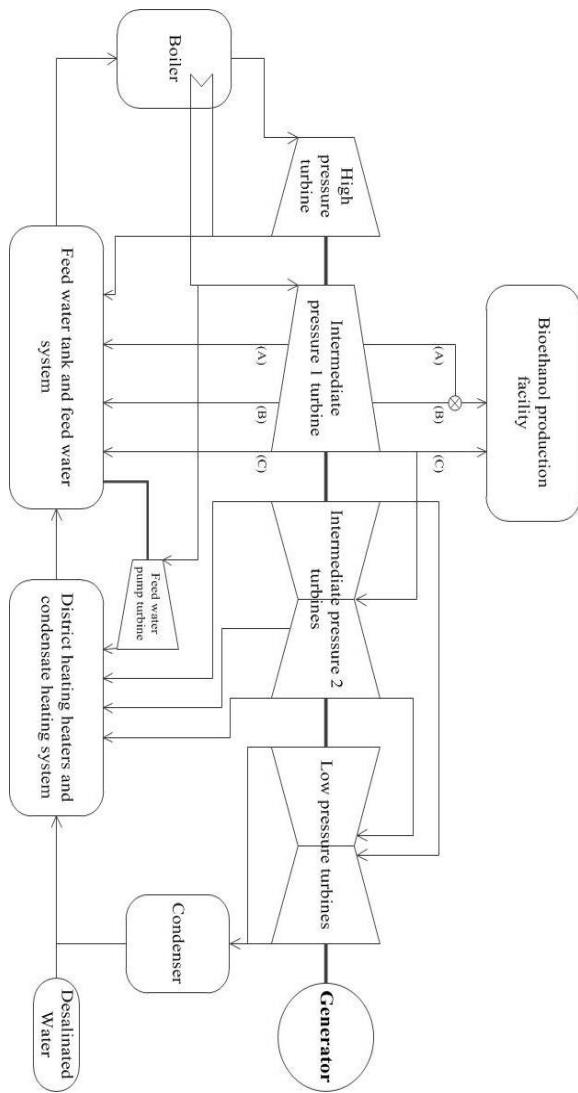


Figure 3: Simplified layout of the polygeneration system that was modelled

4 RESULTS

4.1 System design and operation

A combined exergy and pinch analysis was conducted to investigate the various integration solutions studied. The results indicate that an optimal steam extraction pattern, with optimal meaning minimal exergy flow from the CHP unit to the bioethanol production facility, includes steam extracted from the extraction points (A), (B) and (C) in Figure 3. In the optimal steam extraction pattern, hydrothermal pretreatment steam was extracted from node (B) at loads above 60%, and from node (A) at loads below 60%. The hydrothermal pretreatment steam had to be conditioned to meet the exact temperature and pressure requirements of the hydrothermal pretreatment component. Heat released from steam conditioning was used internally in the bioethanol production facility. The remaining heat demand of the bioethanol production facility was covered by steam extracted from (C).

Composite curves from the pinch analysis of the bioethanol production facility, for the optimal integration solution and at various loads, are shown in Figures 4 and 5. At zero district heating production, a pinch point occurred at 100°C. At full district heating production, two pinch points occurred due to the optimal use of the available heat: one at 91°C at 50°C.

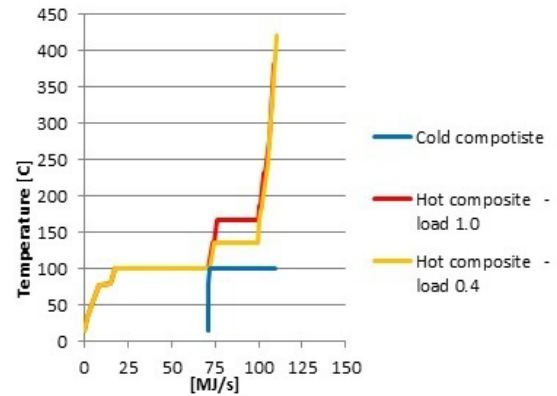


Figure 4: Composite curves for the bioethanol production facility at zero district heating production for various loads in the CHP unit

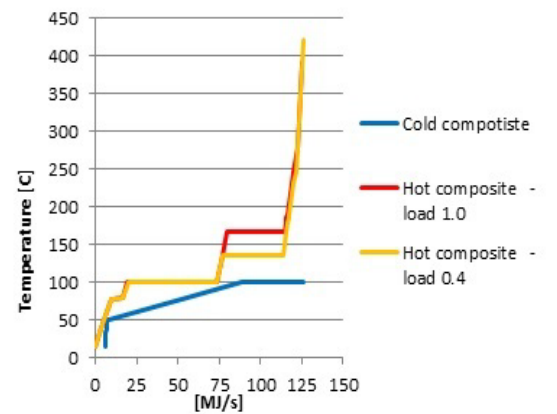


Figure 5: Composite curves for the bioethanol production facility at full district heating production for various loads in the CHP unit

5 DISCUSSION

The models of AVV1 and the polygeneration system with the integration solution selected were simulated to evaluate production and operation patterns for the heat-and-power production of the two plants. The results indicate that the power production potential was lower for the polygeneration system than for AVV1 alone, while the district heating potential of the polygeneration system tended to be slightly higher than that of AVV1, as seen in Figure 6.

The hour-wise heat and power production of the polygeneration system was set to be equal to that of AVV1 over the reference year. When integrated operation was prevented by either power demand or shut-down of the CHP unit, the bioethanol facility was operated separately. The reasons for this, and the corresponding total duration of the periods with separate operation during the year are summarized in Table 6.

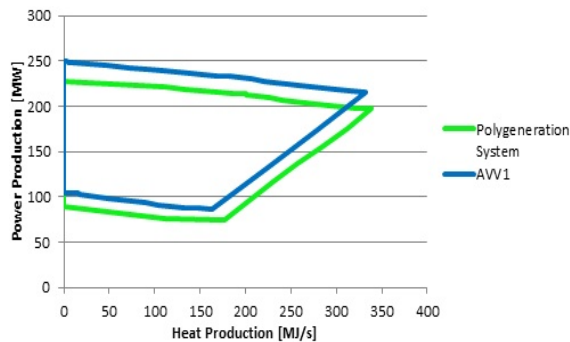


Figure 6: Operational heat-and-power production ranges for AVV1 and the polygeneration system

Table 6: Causes of separate operation in the polygeneration system during the reference year

Cause of separate operation	Total duration
High power demand	1685 hours
CHP unit shut-down	2060 hours
Total separate operation	3375 hours

4.2 Energy economy

With a biomass processing capacity of 22.4 ton/hour, the bioethanol production facility was found to produce a total of 29,434 tons, or 37,080,000 L, of ethanol during the reference year when assuming full load operation at all 8760 hours.

The extra energy costs of running the polygeneration system compared to running AVV1 alone was found to be 20.7 M.Euro. The average energy cost for producing bioethanol was found to be 0.145 Euro/L during integrated operation and 1.218 Euro/L during separate operation. Overall, the results suggest that the average bioethanol energy cost over the year was 0.558 Euro/L. The resulting energy costs for AVV1 and the polygeneration system over the reference year obtained from model simulations are summarized in Table 7.

Table 7: Energy costs for AVV1 and the polygeneration system during the reference year

	AVV1	Polygeneration system
CHP fuel cost	49.8 M.Euro	53.1 M.Euro
Gas cost	0 M.Euro	9.1 M.Euro
Electricity cost	0 M.Euro	8.3 M.Euro
Total cost	49.8 M.Euro	70.5 M.Euro

The competitive bioethanol production energy cost limit was estimated to be 0.22 Euro/L for the bioethanol production based on the IBUS process. During integrated operation, the bioethanol production energy cost was found to be economically competitive, agreeing with the results obtained by [2] and [3]. However, the energy cost during separate operation was found to be uncompetitive, and due to the long duration of separate operation over a year, the results suggest that the polygeneration system that was modelled cannot produce bioethanol at a competitive price on average.

In order to achieve competitive operation, the average production costs must be reduced. This can be done by either lowering the production cost of separate operation, or by increasing the duration of integrated operation. An option for reducing the production cost of separate operation would be to replace the gas boiler with a cheaper heat source for steam generation, for instance by using the lignin-fuel produced by the system. However, this was not considered in the present study.

Assuming the average values calculated in this study are accurate, it is suggested that competitive production would be obtained by maintaining integrated operation during 8150 hours of the year, 2765 hours longer than what was assumed in the study. However, it must be mentioned that during the reference year, the CHP unit was shut down for a longer period than would be expected in the future. However, this uncertainty is not significant enough to affect the overall conclusion that the average operation would be uncompetitive over the year.

An option for increasing the duration of integrated operation would be to improve the integration design by adding steam extraction points in the CHP unit that fit the bioethanol production steam requirements better. As seen in the composite curves in Figure 4, extracted steam is delivered at a temperature much higher than required. Better fitting of the extracted steam to the requirements of the bioethanol facility would reduce the system exergy destruction, allowing for higher power production levels and thereby reducing the duration of separate operation due to high power demand. The same effect could be obtained by lowering the temperature requirements of the IBUS facility, but this is related to the conversion technology and not to the system design.

Another way to increase the integration duration would be to simply reduce the heat demand of the bioethanol production facility, especially in the hydrothermal pretreatment process. The simplest way to achieve a reduction in the heat demand would be to down-scale the facility, but another interesting option would be to investigate the technology used, to determine if the amount of heat used per unit of straw treated could be reduced. Such investigations are beyond the scope of the present study.

A third option would be to reduce the demands on power production, eliminating all separate operation due to high power demands. Decreased income from power sales must be included when evaluating this approach. Whether or not this is a realistic approach to evaluate the plant economy depends on the grid in which the polygeneration system operates, as a decreased power production capacity during peak loads could cause shortages. It should be noticed that the bioethanol production facility considered was dimensioned for

handling 22.4 tons/hour of biomass, which is less than half the size of the designed capacity of 50tons/hour for facilities using IBUS technology [7]. However, increasing the scale of the IBUS facility would reduce the power production potential further, emphasizing the need for further consideration of the power production operation.

The question of decreased power production is especially relevant in grids with large capacities of intermittent power sources such as wind turbines or photovoltaic cells which cannot be switched on as a function of the power demand. On the one hand, polygeneration systems like the one treated might be forced to maximize power production at the cost of integrated operation in periods with high power demand and low or zero production from intermittent sources. On the other hand, the polygeneration system is able to reduce its power production further than the CHP unit alone, which is advantageous in periods with high power yields from intermittent sources and low demands, resulting in low or even negative power prices. The dominant of the two trends would have to be determined to draw any conclusions about system economy as a function of the installed intermittent power capacity in the grid. This study therefore recommends that a holistic approach should be taken when designing and evaluating a system with integrated heat, power and bioethanol production.

6 CONCLUSION

The study treated the integrated production of heat, power and lignocellulosic bioethanol in a polygeneration system based on an existing combined heat and power unit. The energy economy of producing bioethanol in the system was evaluated over a year. The average energy cost of bioethanol production during integrated operation was found to be 0.145 Euro/L, and during separate operation the average energy cost was found to be 1.218 Euro/L. Over a year, 3375 hours of separate operation was necessary to meet large power demands on the grid and shut-downs of the combined heat and power unit. The resulting average energy cost for bioethanol production over a year was found to be 0.558 Euro/L. With an estimated competitive limit for the energy cost of 0.22 Euro/L, the simulation results suggest that the polygeneration system modelled cannot produce lignocellulosic bioethanol at a competitive energy cost due to the duration of separate operation.

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