

Potential of Energy Saving for Bioethanol Plant by Polygeneration Integration

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ABSTRACT: Economic competitiveness of bioethanol production strongly depends on the amount of heat and power consumed during the production process. Integration of different energy conversion processes by polygeneration is one of solutions to maximize the use of energy resources to best meet user's the energy demands. In this study, biogas generation, fuel cell system and a greenhouse are integrated in the bioethanol plant to form a polygeneration system. Products of the polygeneration system include heat (steam), electric power and by-products (biogas, fertilizer, animal food, etc.). Simulation of the polygeneration system is carried out by Simulink, and the detailed energy flow and mass balances of the whole polygeneration plant were presented. Energy saving potential for the polygeneration plant is analyzed to find the optimum configuration by maximizing electricity production while producing sufficient heat from both the fuel cell system and pellets burning to satisfy the energy requirements of the whole plant. The result showed that for the studied polygeneration plant (84,000 ton/year bioethanol production), 65% of the stillage (60 ton/h) is used for biogas production; the rest is dried out and then burned to generate steam to cover the unsatisfied heat demand. After covering the energy demand of the whole plant, 3.6 MW of electricity can be sold to the grid. Additionally, some by-products can also be generated, such as forest fertilizer.

Keyword: Bioethanol; Biogas; Fuel Cell; Energy Saving; Polygeneration; Energy Integration

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1. INTRODUCTIONS

Public awareness of the need to reduce global warming and the drastic increases in oil price have encouraged many countries around the world to adopt new energy policies that promote renewable energy applications to meet energy demands and to protect the environment. In this context, the Swedish Government is therefore setting a new policy target: creation of the conditions necessary to break Sweden's dependence on fossil fuels by 2020 [1].

To meet this guideline, production of bioethanol as well as other alternative fuels from renewable resources is one way to reduce both consumption of crude oil and environmental pollution.

So far, many groups and research centers in different countries are continuously carrying out studies aimed at reducing ethanol production costs for a profitable industrial operation. But these investigations are often limited on the capability of separation the ethanol/water mixture [2-5]; and some are related to the steps of processing [6], nature of utilized feedstocks [7-10]; also some are focus on the tools of process engineering, such as process synthesis [11,12] and optimization [13-15] etc.

Here in this paper, to cope with the high energy demand and to improve benefits from the process, concept of polygeneration is applied aiming at taking advantage of the by-products released during transformation of feedstocks. Polygeneration means the production of heat (steam), electricity and by-products (biogas, fertilizer, pellets, etc.) in combination with the bioethanol process using residues of bioethanol. Furthermore, energy integration is also applied to be an important approach for the design of more intensive and cost-effective system configurations, using the energy flows generated inside the process to satisfy the energy demand with the aim of

reducing external energy consumptions, such as electricity and fossil fuels etc.

2. PROJECT DESCRIPTIONS

In Härnösand, middle of Sweden, a production plant of pellets from wood-chips exists today, and the pellets production is integrated with the municipal district heating system. In order to improve total economic performance of the system, some efforts has been made to configure a bioethanol based polygeneration plant which can satisfy its own electricity and heat demand by taking advantage of the by-products (stillage) released from bioethanol production unit. The key figures of the new bioethanol production unit are given in Table 1.

Table 1: Summary of the key parameters

Parameters	Performance
Raw material	277,000 ton wheat/year
Ethanol production	106,000,000 LPA*/year; 84,000 ton ethanol/year
Stillage	818,000 ton /year (8.6% TS*)
Electricity usage	0.197 kWh/LPA (2.4 MW)

*: LPA – Liter Pure Alcohol; TS – Total Solids.

The basic idea is to take part (x%) of the stillage and make biogas, then the biogas will be supplied to a Molten Carbonate Fuel Cell (MCFC) system, aiming to generate electricity and heat to cover the bioethanol production requirements. The clean CO₂-rich air exhausted from the Molten Carbonate fuel cell unit can be used in a nearby green house. At the same time, rest (1- x%) of the stillage is used to produce pellets, the pellets can be burn to generate steam to meet the heat demands of the entire plant that the fuel cell unit can not satisfy. System diagram of the proposed bioethanol based polygeneration plant including biogas

generation, fuel cell, and green house as well as pellets system is given in Fig.1.

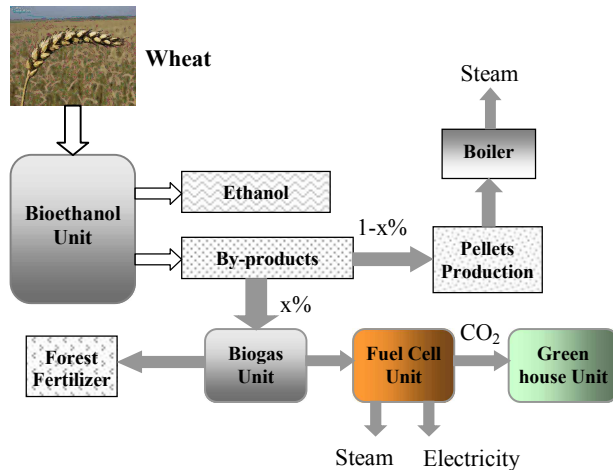


Fig.1. Diagram of the polygeneration plant

Objectives of this paper are to simulate the bioethanol based polygeneration plant to reduce energy demand of the entire plant by both polygeneration and energy integration concepts. Then try to find the optimum configuration for the biogas production, fuel cell, green house and pellets production units to generate as much electricity as possible and at the same time produce enough heat from both the fuel cell unit and pellets combustion to satisfy the heat demands of the entire plant.

3. SYSTEM MODELLING

In this part, a detailed description and modeling of the polygeneration plant will be given, includes the modeling of bioethanol production unit, biogas production unit, fuel cell unit, green house and pellets system.

3.1. Bioethanol production unit

Ethanol production from agricultural feedstock by fermentation is a well known process. Based on the research work presented

by Pfeffer et al. [16], the bioethanol production unit feed on wheat, after milling the raw material and mashing them with water in the mashing tub, the liquefaction and saccharification steps take place, where the fermentation mash is produced. Then, saccharose is converted to alcohol and carbon dioxide during fermentation. Purification of the ethanol consists of two rectification steps and starts with separation from the fermentation both using distillation in the distillation columns, the stillage is produced at the same time. And then the resulting ethanol solution is concentrated in the rectification column. Finally, ethanol is dewatered using adsorption where the bioethanol is produced.

Table 2 summarized the main heat demand and reusable heat from different steps of the bioethanol production process [16]. Positive values represent a heat demand, while negative values refer to the available heat. Data presented corresponds to the plant size of 84,000 ton/year bioethanol production.

Table 2: Heat Streams in Bioethanol Process

Process Step	Temperature [°C]	Heat [MW]
Mashing	10 → 60	5.6
Liquefaction	60 → 90	3.78
Saccharification	90 → 60	-4.06
Fermentation	60 → 35	-4.48
Preheat Feed Distil. Col.	35 → 95	7.56
Distil. Col., Condensor	78 → 77	-1.22
Distil. Col., Reboiler	104 → 105	13.44
Cooling Stillage Rectification, Condensor	105 → 35	-7.6 × x%*
Rectification, Reboiler	116 → 115	-13.72
Superheating	132 → 133	7.14
Adsorption	114 → 120	0.045
Cooling Product	100 → 50	-0.325

*: x%, See also Fig.1, means how many percent of the stillage from the bioethanol plant that is used to generate biogas.

Analysis of the bioethanol process shows that heat integration between distillation and rectification steps gives the largest reduction of heat demand. And considerable amount of heat saving in liquefaction and saccharification steps to adjust a temperature of 60°C and 90°C may also be possible from reusing the residual heat.

3.2. Biogas production unit

To improve economic performance of the polygeneration plants, by-products (stillage) from the bioethanol production unit can be used to produce biogas, and then the biogas will be supplied to the fuel cell unit to generate heat and electricity power.

The biogas plant is designed to generate biogas by using x% of the stillage from the bioethanol unit. The inlet raw material (stillage) has a total solid percentage (TS) of 8.6%. The biogas production process can generally be divided into two processes: fermentation process and storage for biogas process.

For the fermentation process, one fermentation tank is used. Most of the biogas will be generated in this fermentation tank. After fermentation, biomass leaves the fermentation tank and goes to the storage for biomass where more biogas will be generated (approximately 5-10% extra). The product left in the storage for biomass is called bio manure; it can be used as fertilizer.

ORWARE (Organic Waste Research), developed by the IWA (International Water Association) task group for mathematical modeling of anaerobic digestion processes, is a commonly used simple model of anaerobic digestion. It is a computer-based model for calculation of substance flows and environmental impacts. Such a model can be

used for getting a brief and rough overview of the anaerobic digestion process, and it has been successfully used in another study to simulate a biogas plant which is connected to a molten carbonate fuel cell and a green house [17,18]. The ORWARE model is used in this study to simulate the biogas production process.

3.3. Fuel cell unit

Fuel cell unit is part of the plant where electricity and heat is generated. The fuel cell planned to be used is a commercial grade Molten Carbonate Fuel Cell (MCFC) with a rated power output of 1,200 kW AC [19], capable of providing high quality electricity power by using anaerobic digester gas as fuel.

To make the fuel cell performance descriptions easy to follow, main items for one set of the mentioned fuel cell are summarized in Table 3.

Table 3: Performance for one set of fuel cell

Items	Performance
Rated power output	1,200 kW
Biogas consumption	399 m ³ /h
Water consumption	0.95 m ³ /h
10 bar saturated steam production	208 kW
Additional heat (Cooled to 55°C)	458 kW
CO ₂ emission	504 kg/h

3.4. Green house unit

Green house needs addition of CO₂ to boost plant growth. The CO₂ consumption depends on the amount of sun light and which kind of crops are in the green house. Roughly, one tomato producer with an area of 80,000 m² in Sweden uses 3,000 ton CO₂ per year. Unfortunately, in hot sunny weather, the green house has to be ventilated to prevent too high temperature, and this will ventilate out some of the CO₂, so the actual CO₂ consumption may be even higher.

The green house unit will also need some additional heat, it would be good to use the additional heat collected by cooling the fuel cell exhaust and the stillage as well as the ethanol product etc.

3.5. Pellets production and combustion

Due to the high heat energy demand in the bioethanol production unit, besides the steam generation by fuel cell unit, some part (1-X%) of the stillage need to be dried out to produce pellets, and then by burning pellets to generate saturated steam.

Energy efficiency of the pellets production process is assumed to be 64% according to the literature review [20]. Thermal value of the pellet is considered to be 18,500 kJ/kg, and the pellets boiler efficiency is assumed to be 80% constantly. Then the total steam power available from burning pellets based on the data from Table 1 is:

$$P_{\text{pellets}} = 21.13 \times (1 - X\%) \text{ MW}$$

4. SIMULATION AND DISCUSSIONS

Simulation of the bioethanol based polygeneration plant (including bioethanol production unit, biogas production unit, fuel cell unit, green house unit and pellets system) has been carried out by Simulink to find the optimum configuration for the polygeneration plant, this configuration can ensure to generate as much electricity as possible and at the same time to produce enough heat energy from both the fuel cell unit and pellets combustion to satisfy the energy demands of the entire plant.

4.1. Polygeneration of the plant

Fig.2 illustrated the steady state energy and mass balance of the polygeneration plant for the optimum configuration. Seen from steady state values presented in Fig.2, around 65% of the stillage (60 ton/h) is used for biogas production, all the generated biogas (1,980

m³/h) will then be consumed by the fuel cell unit (5 sets of fuel cells have been chosen) to produce 6 MW electricity and 3.4 MW heat energy. Part (1.1 MW) of the heat energy produced by the fuel cell unit is utilized to generate 10 bar saturated steam, and others (2.3 MW) are used to preheat the humidified biogas and then supplied to green house unit. With 2.5 ton/h CO₂ emissions from the fuel cell unit, 7 tomato producers (each with an area of 80,000 m²) are recommended in the plant.

Simulation result shows that heat energy generated by the fuel cell unit is not enough to supply the entire plant with heat. Pellets production and combustion to generate steam are necessary. Therefore, rest (33 ton/h) of the stillage is dried out to produce pellets (2.84 ton/h), and then 10 bar saturated steam (11.7 MW) will be generated by burning the pellets to cover the unsatisfied heat energy demands. Electricity produced by the fuel cell unit (6 MW) is sufficient to cover the electric power requirements of the entire plant (totally 2.4 MW). Overproduction of electricity (3.6 MW) can be sold to the grid. Table 4 summarized key parameters of the simulation results for the polygeneration plant.

Table 4: key parameters of the plant

Key parameter	Performance
Raw material	277,000 ton wheat/year
Ethanol production	9.6 ton/h (cooled to 50°C)
By-products (stillage)	93 ton/h (65% for biogas production, rest to make pellets)
Biogas generation	1,980 m ³ /h (all consumed by the fuel cell unit)
Fertilizer	58.6 ton/h (TS is around 8.6%)
Fuel cell capacity	5 sets of DFC1500MA Molten Carbonate Fuel Cell
CO ₂ supplied to green house	2.5 ton/h, sufficient for 7 tomato producers (80,000 m ² each)
Total heat supplied to green house	3.4 MW
Pellets production	2.84 ton/h (all are burned to generate steam, 11.7 MW)
Total electricity usage	3.6 MW can be sold to the grid
Total steam usage	No external steam is needed

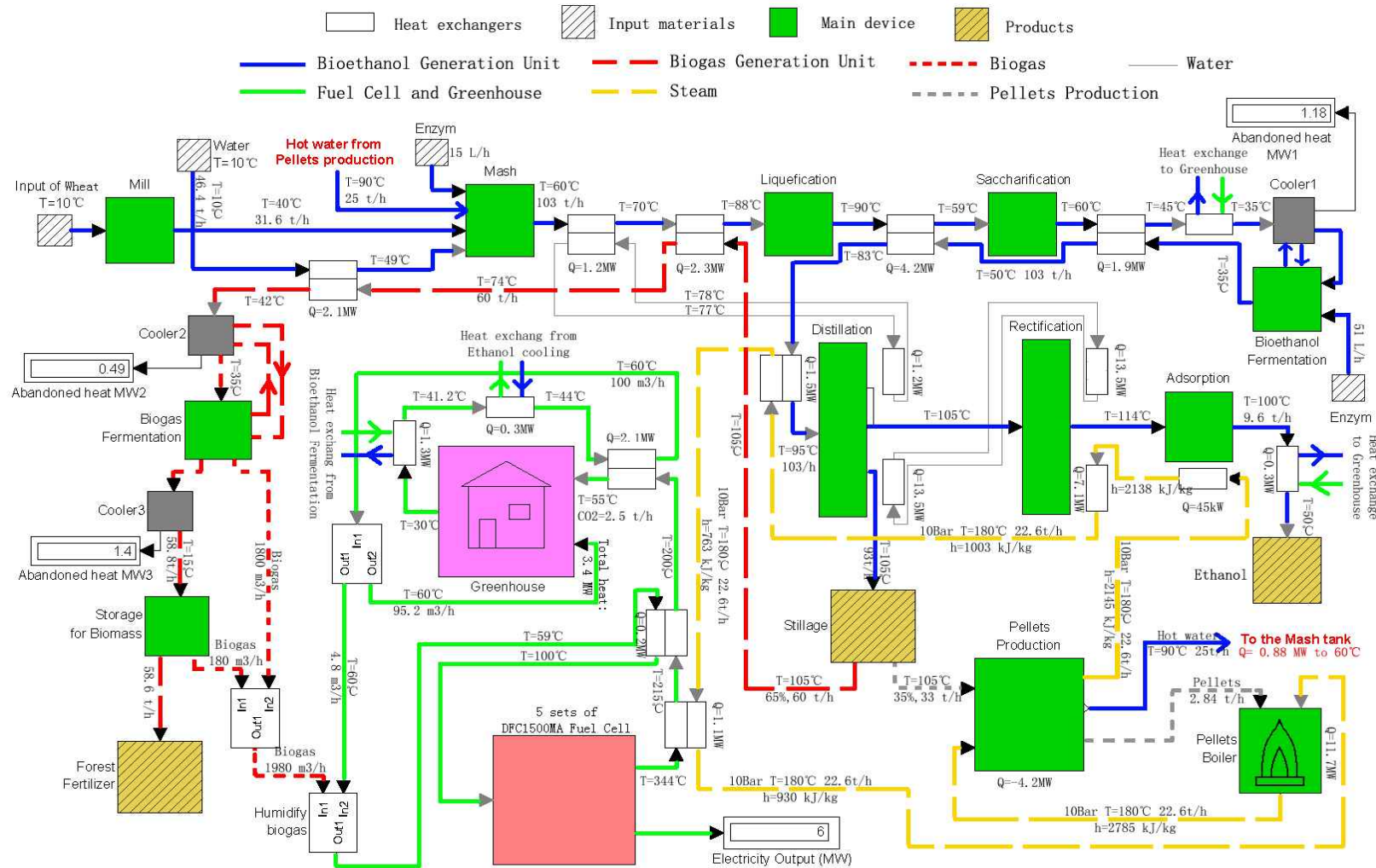


Fig.2. Steady state energy process for the bioethanol based polygeneration plant

4.2. Energy integration of the plant

Fig.2 also showed the possibility and importance of heat integration among the bioethanol production processes. For example, the heat demands can be reduced by heating the distillation reboiler with the overhead vapour of the rectification condenser; this gives the largest reduction of heat demand. Surplus heat from stillage cooling and surplus heat from the distillation condenser can be used for heating up the feed water to the mashing tub and the feed stream to the liquefaction step. Heat demand for preheating the feed stream to the distillation column can be partly served from cooling the stream to fermentation step.

Despite of recycling heat within the processes, it is important to consider the necessary of using extra heating or cooling in the bioethanol production unit, for example, the heat demand for heating the rectification reboiler need to be covered by external energy. If the biogas generation, fuel cell and green house units are taken into account, more opportunities of recycling the expelled heat will be available. For example, steam generation by the fuel cell unit can be used to partly satisfy the heat demands of bioethanol production unit; heat from cooling the stream to the bioethanol fermentation tank and the heat from ethanol cooling can be used to heat up the green house water, etc.

5. CONCLUSIONS

Possibilities of energy demand reduction for bioethanol production process have been investigated by considering both concepts of polygeneration and energy integration.

For the polygeneration aspect, biogas generation, fuel cell and green house units are integrated with the bioethanol production unit to form a polygeneration plant. The biogas generation unit feed on the stillage from

bioethanol production unit, and the generated biogas will be supplied to the fuel cell unit to produce heat and electricity power. All the CO₂ and low temperature heat generated during the processes will be used to satisfy the green house's demands. Products of the polygeneration system include heat, electricity and fertilizer etc.

For the energy integration aspect, efforts have made to find energy recycling possibilities among the bioethanol production processes. Furthermore, energy integration possibilities among different units (bioethanol unit, biogas unit, fuel cell unit, green house unit and pellets system) were also considered and more opportunities have been found.

Then carried out by MATLAB Simulink, the polygeneration plant was optimized to be a plant of heat energy self-satisfactory while with extra electricity output

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