




SLUTRAPPORT

Kraftvärme från biogas / CHP from biogas

Energimyndigheten - Dnr 2005-04068



		Technical Report		SECRC/TS/TR-2007/447	
Corporate Research					
Issued by department	Last edit date	Lang.	Revision	Page	
ZCRD/SECRC/TS	2007-12-03	Eng/Sve	01	1/56	
Customer	Energimyndigheten / Swedish Energy Agency		Classification	Normal	
Doc. title	Kraftvärme från biogas / CHP from biogas.				
Project name/ID	Kraftvärme från biogas/CHP from biogas.		Status of document	Final	
Main Author	Markku Rissanen 	Project ID (CRID) or Order no	L471218		
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Distribution	Energimyndigheten/ Swedish Energy Agency, ABB				
Keywords	Biogas, fuel cell, MCFC, electricity, heat, bioethanol				
Attested by Reviewer					
Approved by	Helena Malmqvist 	Final Approval Date	2007-12-03		

9ADB1-002_Technical_Report.dot Rev 2.05

Summary in Swedish:

Projektet avser att undersöka förutsättningarna för att integrera ett miljövänligt småskaligt kraftvärmeverk, och då speciellt en MCFC (Molten Carbonate Fuel Cell) i biogasprocessen för att generera el och värme tillbaka till biogasanläggningen – här kallat konceptet. Projektet avsåg ursprungligen, när ansökan lämnades in, att i detalj studera den biogasanläggning som har studerats i "Case 1". Under tiden har det även dykt upp andra biogasanläggningar, såväl existerande som under planering, som skulle kunna använda sig av integrationskonceptet. Ytterligare tekniska möjligheter har också uppdagats där man utöver el och värme också effektivt kan ta hand om den koldioxid som bildas i t.ex. ett växthus.

Målet med projektet är att utvärdera främst de tekniska men även de ekonomiska förutsättningarna. De miljömässiga möjligheterna för en kraftvärmeanläggning med hög verkningsgrad, integrerad med en biogastillverkning har också undersökts. Utöver detta har även en kombinerad bioetanol- och biogasanläggning studerats. Resultaten från studien visar att tekniken finns för att genomföra de studerade projekten. De smältkarbonatbränsleceller som avses att användas har betydande positiva miljöeffekter genom en högre verkningsgrad och inga utsläpp av NOx, SOx, eller partiklar.

Ekonomiskt har dylika projekt för enbart en biogasanläggning beräknats ha en återbetalningstid på ca. 6-7 år för bränslecellsinstallationen om man har avsättning för den genererade rena koldioxiden. Konceptet, att integrera en MCFC i bränsleproduktionsprocessen, kan även användas i en kombinerad bioetanol- och biogasanläggning. I denna anläggning rötas dranken från etanoltillverkningen till biogas. Sverige såsom internationellt ledande på biobränsleområdet har här en ypperlig chans att bygga en världsunik kommersiell anläggning. Något liknande har inte kunnat ses hittills. Delar av totalkonceptet finns i USA och Tyskland.

Finansiering av anläggningarna bedöms kunna ske av gasleverantörerna själva eventuellt med exempelvis KLIMP-bidrag. I det fall då den biobränslebaserade koldioxiden används i ett växthus finns goda möjligheter att pilotanläggningen får statusen "Guldklimp".

ABB kommer att fortsätta diskussionerna med potentiella kunder i syfte att bygga en biogas-/bioetanolanläggning med integrerad internproducerad kraftvärme enligt principerna som har studerats i denna rapport.

TABLE OF CONTENTS

1	SUMMARY	4
2	INTRODUCTION	5
2.1	PURPOSE.....	5
2.2	SCOPE.....	6
3	CASE 1 – BIOGAS PLANT	7
3.1	BACKGROUND – DESCRIPTION OF THE PLANT.....	7
3.1.1	Receiving tank	9
3.1.2	Hygienization	9
3.1.3	Anaerobic digestion tank	9
3.1.4	Storage for biomass.....	11
3.2	THE CHP SYSTEM/FUEL CELL SYSTEM.....	11
3.3	BURNER.....	11
3.4	TORCH.....	11
3.5	OUTGOING BIOGAS	11
3.5.1	Pressurized water	12
3.5.2	PSA – Pressure Swing Adsorption	12
3.5.3	Chemical absorption	12
3.6	AN EXTENDED PLANT CONFIGURATION.....	12
4	CASE 2 – COMBINED BIOETHANOL AND BIOGAS PLANT	13
4.1	BACKGROUND	13
4.2	OBJECTIVE.....	13
4.3	BIOETHANOL PLANT	15
4.4	BIOGAS PLANT.....	17
4.5	FUEL CELL SYSTEM.....	18
4.6	GREENHOUSE	19
4.7	HEAT EXCHANGER	19
4.8	PELLETS	19
5	MOLTEN CARBONATE FUEL CELLS	20
5.1	GENERAL.....	20
5.2	FILTER BEFORE THE FUEL CELL	22
5.3	HOTMODULE SYSTEM.....	23
6	MODELING	24
6.1	STATIC MODEL	24
6.1.1	ORWARE.....	24
6.1.2	The effects of ammonia in the MCFC and the anaerobic digestion	26
6.1.3	Heat exchangers.....	27
6.1.4	Fuel cell.....	31
6.1.5	The greenhouse.....	34
6.1.6	Economical situation.....	36
7	SIMULATIONS – CASE 1	37
7.1	SIMULATIONS FOR A PROCESS SCHEME	37
7.1.1	ORWARE.....	37
7.1.2	The heat exchangers	37
7.1.3	The fuel cell.....	38
7.1.4	The greenhouse.....	38
7.1.5	Economical calculations	38
8	RESULTS – CASE 1 MODELING	39



Technical Report

Corporate Research

SECRC/TS/TR-2007/447

Doc. title

Revision

Page

Kraftvärme från biogas/CHP from biogas.

01

3/56

8.1	STATIC MODEL	39
8.1.1	ORWARE	39
8.1.2	Heat exchangers	42
8.1.3	MCFC	43
8.1.4	Greenhouse	45
8.1.5	Economy	45
9	RESULTS – CASE 2.....	46
10	DISCUSSION AND CONCLUSIONS.....	51
10.1	CASE 1 – BIOGAS PLANT.....	51
10.1.1	System configuration and economy	51
10.1.2	Ammonia.....	51
10.2	CASE 2 – COMBINED BIOETHANOL AND BIOGAS PLANT.....	52
10.3	ENVIRONMENTAL CONSIDERATIONS	52
11	PROPOSED FUTURE WORK	55
12	REFERENCES	55
13	PRESENTATIONS	56

1 SUMMARY

This project investigates the conditions to integrate an environmental friendly small-scale combined heat and power (CHP) plant in a biogas process plant to generate electricity and heat back to the biogas process – here called the concept. The project aim initially, when the project proposal was sent, was to in detail study the biogas plant in “Case 1”.

During the time other biogas plants have come into consideration, both existing and planned, that could use the integration concept. Further technical possibilities have been considered where, in addition to electricity and heat, the carbon dioxide that is generated also can be efficiently utilized in a greenhouse.

The goal with the project is to mainly evaluate the technical but also the economical prerequisites and the environmental possibilities for a CHP-plant that generates electricity and heat with a high efficiency integrated with biogas production. In addition to this a combined bioethanol- and biogasplant has been studied.

Simulations and process modeling, have been made on the anaerobic digestion process. System simulations were performed on different configurations of an anaerobic digestion process connected to the CHP-plant/molten carbonate fuel cell. The fuel cell will supply the system with electricity and heat. A nearby greenhouse will receive all carbon dioxide produced in the fuel cell. A feasible solution, taking both technical and economical aspects into account, was found to perform the hygienization before the fermentation and to operate the process in the mesophile temperature interval. The result and final configuration choice, including greenhouse and fuel cell, are presented in a process scheme where flows and temperatures in all parts of the process have been calculated.

The results from the study show that the technology exists to implement the studied combination concepts. The Molten Carbonate Fuel Cells (MCFC) that are intended to be used have considerable positive environmental effects thru a high efficiency and no emissions of NO_x, SO_x and particles. Economically a MCFC integrated in a biogas plant has a calculated pay-back time of about 6-7 years if there is a market for the generated clean carbon dioxide.

The concept can also be used in a combined bioethanol and biogas plant where the stillage/rest product from the biogas production is used to generate biogas. There is an excellent opportunity for Sweden as an international leader in the biofuel area to build a world unique commercial plant. Anything like this has not been seen yet. Parts of the concept have been built in the US and in Germany.

The financing for the plants is estimated to come from the gas suppliers themselves possibly together with co-financing from the Swedish KLIMP-funds.

ABB will continue the discussions with potential customers with the aim to build a biofuel plant with an integrated internal CHP production according to the principles in this report.

Due to confidentiality reasons some background data and results are not presented in this public (Normal) version of the report.

2 INTRODUCTION

2.1 Purpose

The use of biofuels in the transportation area increases for each year as a result of increasing oil prices and a more environmental way of thinking. Biofuels are also expected to give a significant contribution when changing over to a sustainable energy system for electricity and heat, especially in the Nordic countries. The discussions about the greenhouse effect and the questions about the climate change has accelerated as a result of articles in public press, newspapers and through Al Gore's movie. Recent years have also seen the discussions about peak-oil production and global warming getting more and more intense, and the research and development of alternative non-fossil energy sources is growing.

The largest development efforts, at least in Sweden, has been concentrated to how the biofuels will be produced, whereas less effort has been put on studying environmental friendly and efficient use of the biofuel and generation of electricity and heat. The conventional technologies used today to produce electricity from biofuels are often not environmentally friendly and not very efficient.

This report studies an energy efficient combined heat and power (CHP) solution to generate electricity and heat from biofuels by using fuel cells at a high operational temperature. The advantages are; a high efficiency when compared to conventional technologies, both electricity and heat is produced and that considerably less amounts of pollutants are emitted to the environment. A bonus is that a very clean carbon dioxide is produced which for example can be used in a greenhouse to increase plant growth.

In this study a biogas plant under planning is described and modelled. This report describes also another plant under consideration, a bioethanol plant from which the stillage can be used to produce biogas, where the CHP solution could be used.

Among the special features with this project is the idea to connect a molten carbonate fuel cell (MCFC)/CHP module, to the plant. The fuel in an MCFC is methane extracted from biogas and the products are electricity, heat and carbon dioxide. This means that a biogas plant connected to an MCFC can be self supporting in both electrical power and heat. The plant can be situated close to a greenhouse to where the CO₂ from the MCFC can be sold.

2.2 Scope

The scope of the project is to investigate the possibilities for an integrated environmental friendly small-scale combined heat and power plant in the biogas production process. The project aimed originally when the project proposal was written to, in detail study the plant in "Case 1". As time has gone other interesting similar plants have shown up, both existing and under planning, which could use and benefit from using the integration concept.

The main work has been on Case 1; a biogas plant connected to a CHP plant/fuel cell system which is then connected to a greenhouse.

The purpose of the Case 1 work can be summarized with the following items:

1. Process scheme for the biogas plant

Biogas is produced by anaerobic digestion of biological material, in this case mostly manure. The gas consists mainly of CH_4 and CO_2 . CO_2 is removed from the gas before upgrading it to fuel. In the studied plant it is planned to connect a molten carbonate fuel cell (MCFC) to the process, aiming to make the plant produce its own electricity and heat, by using some of the biogas as fuel. From the fuel cell a CO_2 -rich air is exhausted, which can be used in a nearby greenhouse. To be able to construct the proposed plant, a better understanding of the biogas process is necessary. Simulations will be performed on different possibilities to be able to investigate the best solution, economically and technically.

2. Maximizing ammonia production

The normal fuel in a MCFC is methane (CH_4), but it is also possible to use ammonia (NH_3) as fuel. It is therefore interesting to investigate how much ammonia can be extracted from the anaerobic digestion, since more NH_3 means that more electricity and heat can be produced in the fuel cell without using more biogas. This investigation will include the amount of NH_3 that is possible to extract, and what effects large concentrations of NH_3 will have on the digestion process.

The Case 2; a bioethanol plant from where the rest product/stillage is taken to a biogas plant which is then connected to a CHP plant/fuel cell system and then additionally connected to a greenhouse is discussed in short.

3 CASE 1 – BIOGAS PLANT

3.1 Background – Description of the plant

In this section some background information will be given of all the parts in the biogas plant when both the fuel cell and the greenhouse are considered to be parts of the system.

The biogas plant considered in this work is projected to be built in Sweden. Before going closer into the technical issues of this work it is important to understand how the plant is supposed to be constructed and how the different parts of the plant work.

A proposal on how to construct the plant has been made by a Swedish consultancy company working with solutions e.g. for biogas plants. This proposal is shown in Figure 1 where everything, except for the fuel cell and the greenhouse, was included in their original proposal. However, in some parts of the system there are a number of different configurations to choose from, therefore this chapter will state possible configurations and ideas on how to construct the plant. The assumptions and simplifications will also be given. A detailed description of the different parts of the system will be given, including the purpose of the parts. To make the description easy to follow the parts will be described in the order shown in Figure 2.

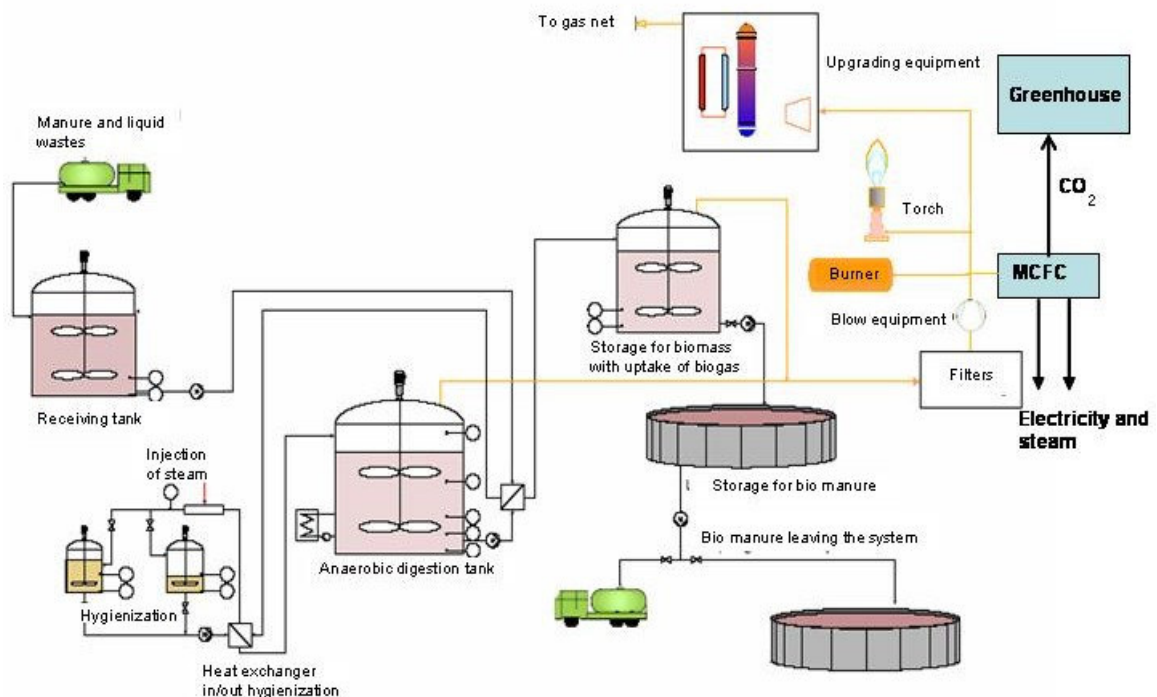


Figure 1: The proposal for the plant.

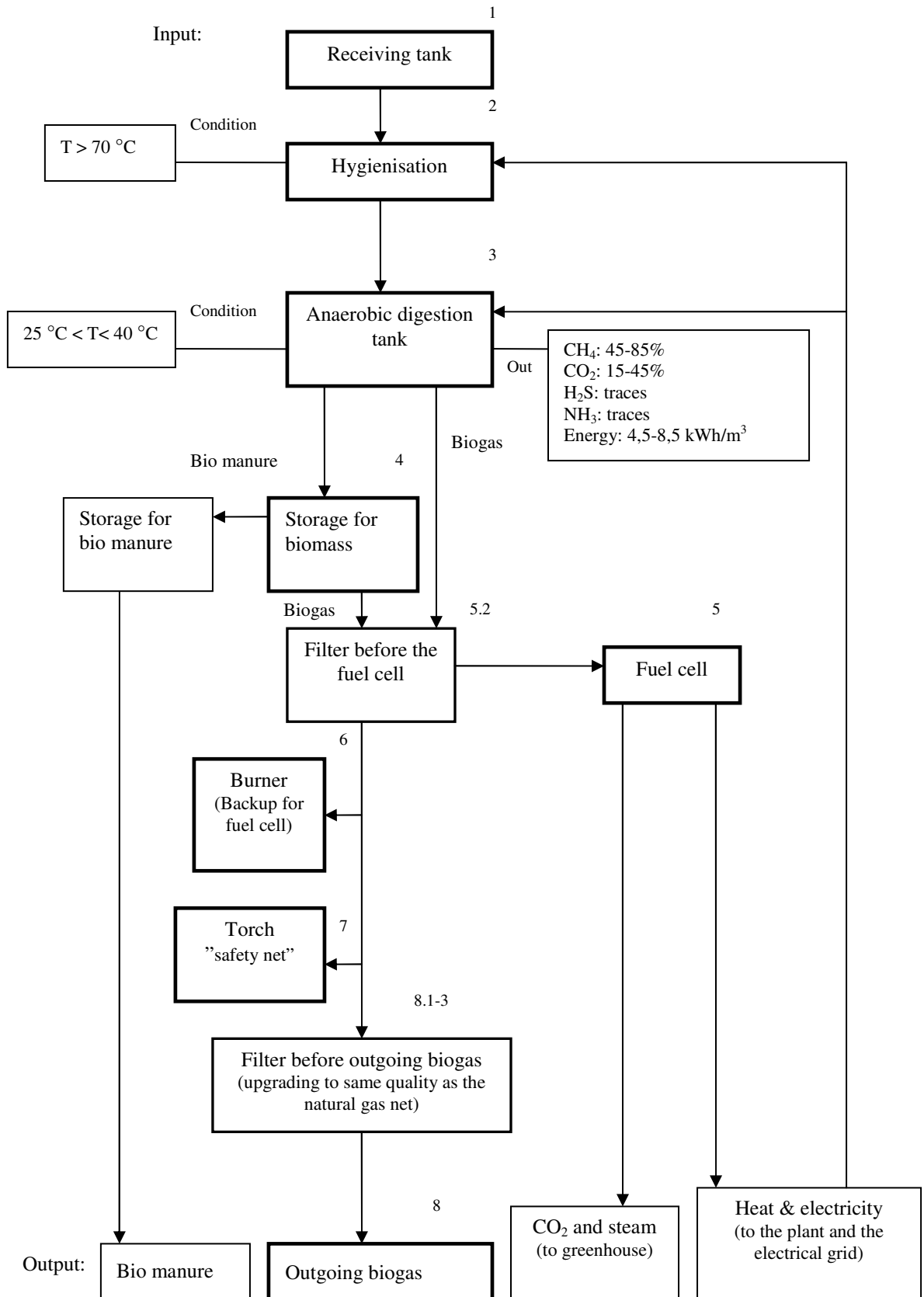


Figure 2: A brief schematic picture of the different parts in the biogas plant.

3.1.1 Receiving tank

The receiving tank is, as the name suggests, the tank to where the incoming material is delivered. The plant is designed to receive 80 000 tons of raw materials per year. 70 000 tons are pig- and cattle manure whereas the rest is organic waste from industries and stores [1]. The ingoing raw material to a biogas plant is called substrate. The substrate in this system has a total solid percentage (TS) of 8%. This means that 92% of the material is water and the substrate can be assumed to have the same density as pure H₂O. The receiving tank will be continuously stirred for efficient homogenization.

3.1.2 Hygienization

In the hygienization tanks the biomass is heated to 70 °C during one hour to prevent diseases from spreading. It must be made sure that the temperature in the tank is never below 70 °C. For optimizing the biogas production, the hygienization takes place in two or three tanks, so that one tank can empty while the others are filling and being hygienized. No effort in this work has been put in deciding which of the hygienization configurations to use. There are, however, a few different suggestions regarding where in the process the hygienization is to take place. The most common, and only one applied in Sweden, is to have the hygienization before the anaerobic digestion. In this way, the substrate is considered free of contaminants when entering the anaerobic digestion and the handling is easier. This is the way proposed by the consultant company.

It is also possible to put the hygienization after the anaerobic digestion. Even if this is legally allowed, it will however be more expensive because of the extra precautions needed when having a larger contaminant zone [2]. The advantage of this configuration would be that more NH₃ is released when the material is heated after the anaerobic digestion, since the biomaterial consists of more NH₃ after the fermentation than before. NH₃ is a possible fuel for the fuel cell, and it can therefore be worth the extra precautions taken with a dirty anaerobic digestion for the benefit of more power extracted from the fuel cell without the need of more biogas.

3.1.3 Anaerobic digestion tank

Biogas is a product when lipids, carbohydrates and proteins are breaking-down in the absence of oxygen in a so called anaerobic digestion or fermentation.

After the hygienization – or before – the substrate is brought to the anaerobic digestion tank. In this tank, most of the biogas is produced. The biogas production process is divided into three steps; first large molecules are reduced to smaller ones, such as free long chain fatty acids, sugars and amino acids. This is called hydrolysis. In the next step acidogenic bacteria reduce the molecules to acids. In processes called acidogenesis and acetogenesis. Finally, these acids are converted to CH₄ and CO₂ by methanogenic bacteria in a process called methanogenesis. The biogas production process is shown in Figure 3.

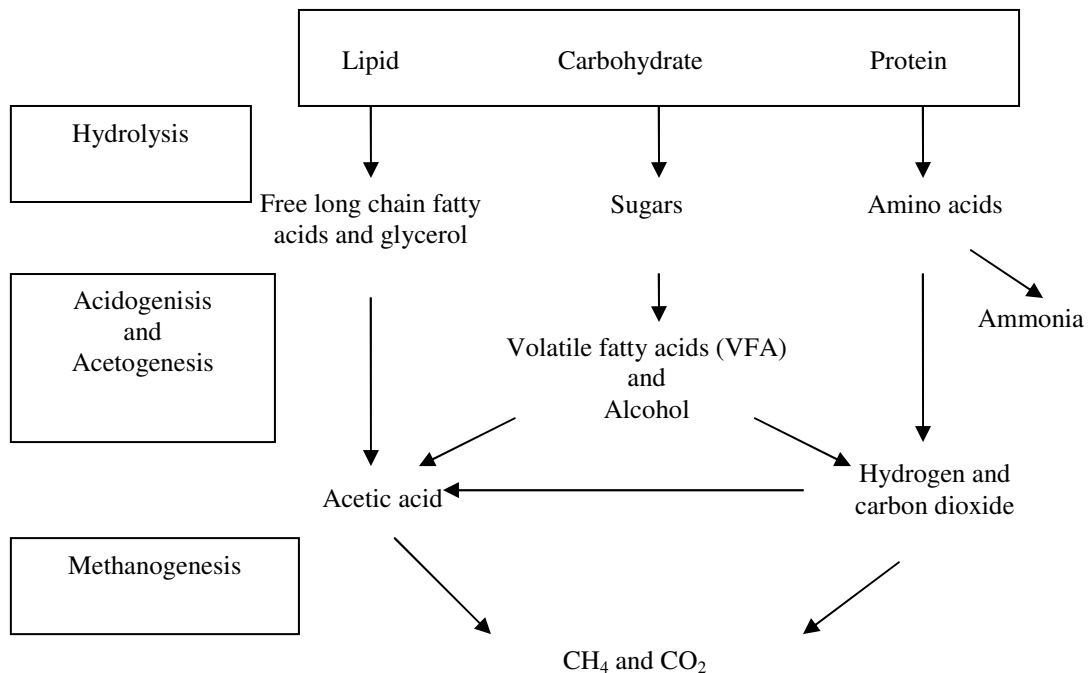


Figure 3: Schematic presentation of the anaerobic degradation process, (Accettola et al. 2004).

The anaerobic digestion is normally performed either in a one-step or a two-step reactor. A one-step reactor is simply one tank where the whole fermentation process takes place. In a two-step reactor there are two tanks. The first tank is designed to optimize the first two steps in the biogas production process, and the second tank to optimize the third step, the acid to CH₄ and CO₂ process. In this case a one-step reactor will be used.

The reactor to be used is a so called continuously stirred tank reactor, CSTR. This means that the reactor is filled up and when more substrate is put into the tank, the same amount will leave the tank. To make sure that the same substrate that was just filled in does not leave the tank, it is continuously stirred.

At different temperatures the anaerobic digestion process will behave differently. There are three different temperature groups; psychrophilic, mesophilic and thermophilic which correspond to the following temperature intervals 4-25 °C, 25-40 °C and 50-60 °C, respectively. Generally the process is faster at higher temperatures, but there is no big difference between mesophilic and thermophilic temperature regarding the amount of biogas produced. For the psychrophilic temperature on the other hand, the amount of biogas produced for a given volume of substrate decreases [3]. Because of the reduced biogas production at psychrophilic temperatures, that kind of process will not be considered. It is however debated whether mesophilic and thermophilic temperature produces the same amount of biogas. It has been stated that more biogas is produced in thermophilic digestion [4]. Here a mesophilic and thermophilic process will be investigated and the technically and economically best solution will be chosen.

Those processes have different optimal retention times. The faster thermophilic process can use a lower retention time than the slower mesophilic process. Since a CSTR is to be used, the difference in retention time means that the tank gets different in size depending on which process is used. The tank volume is calculated through Equation 1:

$$V = \frac{T}{d_{year}} \cdot q \quad (1)$$

where V is the required tank volume [m^3], T is the retention time [days], d_{year} is the number of days in one year and q is the inflow of substrate [$\text{m}^3 \text{year}^{-1}$].

As stated earlier, the density of the substrate is assumed to be equal to the density of water due to the total solid percentage of 8%.

For thermophilic digestion the optimal retention time is 15-20 days. When the input of substrate is 80 000 tons per year and a retention time of 18 days is used, the tank volume obtained is 4000 m^3 . For mesophilic digestion the optimal retention time is 20-25 days and, when a retention time of 23 days is used, the tank volume becomes 5000 m^3 .

3.1.4 Storage for biomass

The biomass leaves the fermentation tank and goes to the storage for biomass. In this storage, more biogas is produced (approximately 5-10% extra). The product left in the storage for biomass is called bio manure. This rest product is led to storage for bio manure and will from there be distributed to farmers in the neighborhood. An advantage with this manure over ordinary manure is that it does not smell as badly, still retaining the same content of nutrition as before [1].

3.2 The CHP system/fuel cell system

See chapter 5.

3.3 Burner

If the fuel cell does not work as planned a burner is needed to provide the plant with heat. The burner is supposed to be a back up so that heat is delivered to the hygienization tank and the anaerobic digestion tank even if the fuel cell is out of order.

3.4 Torch

The torch is a "safety net". It has the capacity to burn out all of the produced gas if that would be necessary. The torch can burn 250 m^3 of gas per hour at 850 °C [1].

3.5 Outgoing biogas

The production of biogas is expected to be 14 GWh per year with an amount of substrate of 80 000 tons per year. Outgoing produced biogas is supposed to be delivered to the natural gas net. Therefore the biogas has to be filtered so that the composition of the gas is the same as for natural gas. What basically needs to be done

is to remove carbon dioxide, water and hydrogen sulphide from the gas. There are three different methods that can be used for this purpose:

- Pressurized water
- Pressure swing adsorption (PSA)
- Chemical absorption

3.5.1 Pressurized water

The pressurized water method uses the fact that CO₂ is better absorbed in water than CH₄. A pressure is added to the biogas and then it is led through an absorption tower where it meets water. When the biogas leaves the tower at the other end almost all the carbon dioxide is removed. A disadvantage is that some of the methane is also absorbed by the water, therefore the water is led to a flash tank where the pressure is decreased and some of the gas is taken back. Most of the methane absorbed by the water is returned to the biogas in this way, although some methane losses occur [1].

3.5.2 PSA – Pressure Swing Adsorption

The PSA (Pressure Swing Adsorption) is a system based on different adsorption of CO₂ and CH₄ on zeolites or activated carbon. The process takes place in four different tanks and a ventilation system is used to switch the function of the different tanks. This makes it a semi-continuous system. A disadvantage is that water and hydrogen sulphide are adsorbed irreversibly, and therefore both water and hydrogen sulphide needs to be cleaned out before the PSA. Because of this, the outgoing gas from the PSA has a very low level of vapor and sulphate compounds. Unfortunately, the zeolites or activated carbon in this method also adsorbs some CH₄. However, most of the CH₄ is returned to the system due to a decreasing of the pressure in the tanks in several steps [1].

3.5.3 Chemical absorption

Chemical absorption is a process where a chemical compound reacts with the CO₂ to separate it from the gas. Since this method is based on a chemical reaction between the absorbent and the CO₂, very little methane is absorbed. No water is needed for the process and no liquid wastes occur. A disadvantage is that some chemical outlets will occur [1].

3.6 An extended plant configuration

In the previous subsections a plant that produces 14 GWh per year was described, but there also exists a configuration with a plant that generates 22 GWh per year. The reason for this is that during the course of this work new information was obtained about the size of the plant. The project group for the plant decided to construct a plant for 22 GWh, instead of the original 14 GWh. This means that the input of substrate will be larger, the fermentation tank will be of greater volume and more biogas will be produced. To produce 22 GWh per year, the input of substrate has to be approximately 120 000 tons per year, according to the project group.

There also came some new information about the fuel cell. The company MTU, that is constructing the MCFC, informed that it is developing a new HotModule with the maximum electrical power 450 kW instead of 250 kW. What they have done is actually to increase the number of cells in the stack; apart from that, the performance is the same. It is therefore possible to calculate the fuel cell performance in the exact same way for both fuel cells and only change the value for electrical power to match the corresponding fuel cell.

Since this information arrived very late, much of the results for the smaller plant already existed and was therefore kept in this report. So the results for the smaller plant will be presented, but the process scheme will only be shown with results from the larger plant.

4 CASE 2 – COMBINED BIOETHANOL AND BIOGAS PLANT

4.1 Background

Ethanol production from agricultural feedstock by fermentation is a well known process. However, the production process, especially concentration and dewatering of ethanol by distillation, requires a large amount of thermal energy. Thus, the economic competitiveness of the ethanol production strongly depends on the amount of heat and power consumed during the process. To cope with this high energy demand and to improve the benefits from the process, the concept of polygeneration is of growing interest to satisfy the requirements of ecology and local development. Polygeneration means the production of heat (steam), electric power and by-products (biogas, fertilizer, animal food, etc.) in combination with the bioethanol process using residues of bioethanol.

4.2 Objective

This second case is to investigate the possibilities to improve the performance of a bioethanol plant by polygeneration through integration and optimization. Rest products of the bioethanol production plant have been investigated for biogas production and conversion to heat and electricity power to cover the energy demand in the whole plant. Carried out by MATLAB Simulink, the polygeneration was optimized to be heat energy self-satisfactory while with extra electricity output.

In the modelled plant 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 and to produce bioethanol for cars, a new bioethanol production unit which uses wheat as feedstock with pellets production is now under consideration. Some approximate figures and the conceptual sketch of the new bioethanol production unit is given in Table 1 and Figure 4 respectively:

Table 1: Summary of the key parameters for the bioethanol unit

Key parameters	Performance
Raw material	< 300 000 tons wheat/year
Rest product production	< 900 000 ton/year (8.6% TS*)

*: TS – Total Solids.

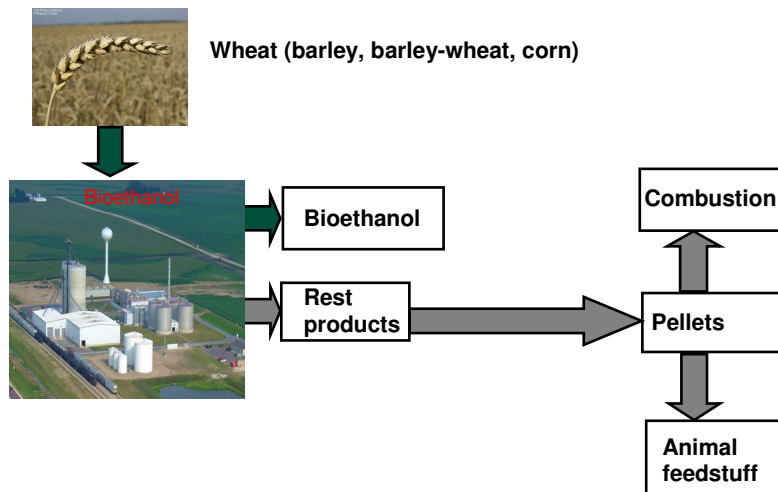


Figure 4. Diagram of the bioethanol and pellets production

In order to further improve the plant performance, the aim is to configure a bioethanol based polygeneration plant which can satisfy its own electricity and heat demand by using the rest product (stillage) from the bioethanol unit.

The basic idea is to take a part (x%) of the stillage from the bioethanol unit and make biogas, then the biogas is supplied to a Molten Carbonate Fuel Cell (MCFC) system, aiming to generate electricity and heat to the bioethanol production unit. The clean CO₂-rich air exhausted from the fuel cell system can be used in a nearby greenhouse. At the same time, the other part (1-x%) of the stillage is used to produce pellets, the pellets can be burn to generate steam to meet the heat requirements of the entire plant that the fuel cell system can not satisfy. The system diagram of the proposed bioethanol based polygeneration plant including biogas generation, fuel cell, and greenhouse as well as pellets system is given in Figure 5.

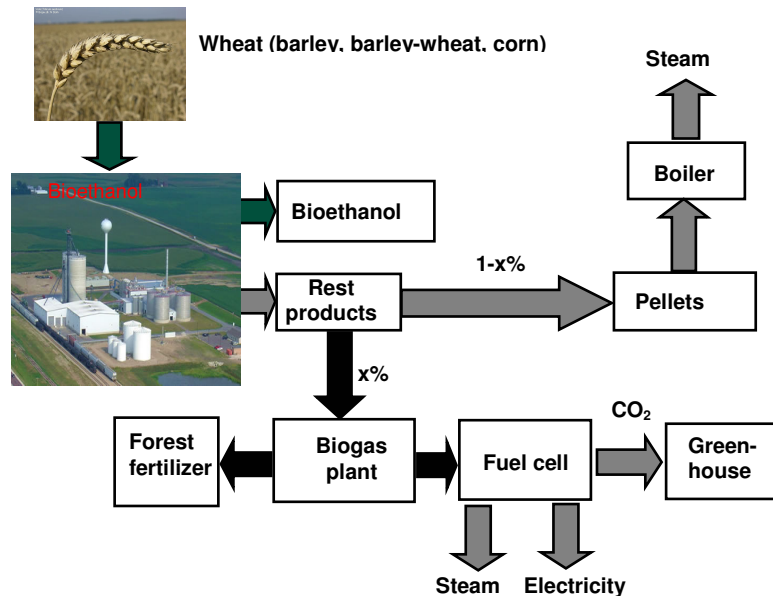


Figure 5. Diagram of the polygeneration plant

The project objectives are to simulate the whole polygeneration plant to study the mass and energy balance as well as their impacts on plant performance. And then try to find the optimum configuration of the biogas plant, fuel cell, greenhouse and pellets systems to generate as much electricity as possible and at the same time produce enough heat from both the fuel cell system and pellets burning to satisfy the whole requirements of the plant.

The result of this modeling is presented in Chapter 9.

4.3 Bioethanol plant

Ethanol production from agricultural feedstock by fermentation is a well known process. Many references are available [5,6]. The basic flow diagram of the bioethanol production process is given in Figure 6 based on the research work of Pfeffer et al.[7].

The bioethanol feed on wheat, after milling the raw material (wheat) 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. The purification of ethanol consists of two rectification steps and starts with separation from the fermentation both using distillation in the distillation column, 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.

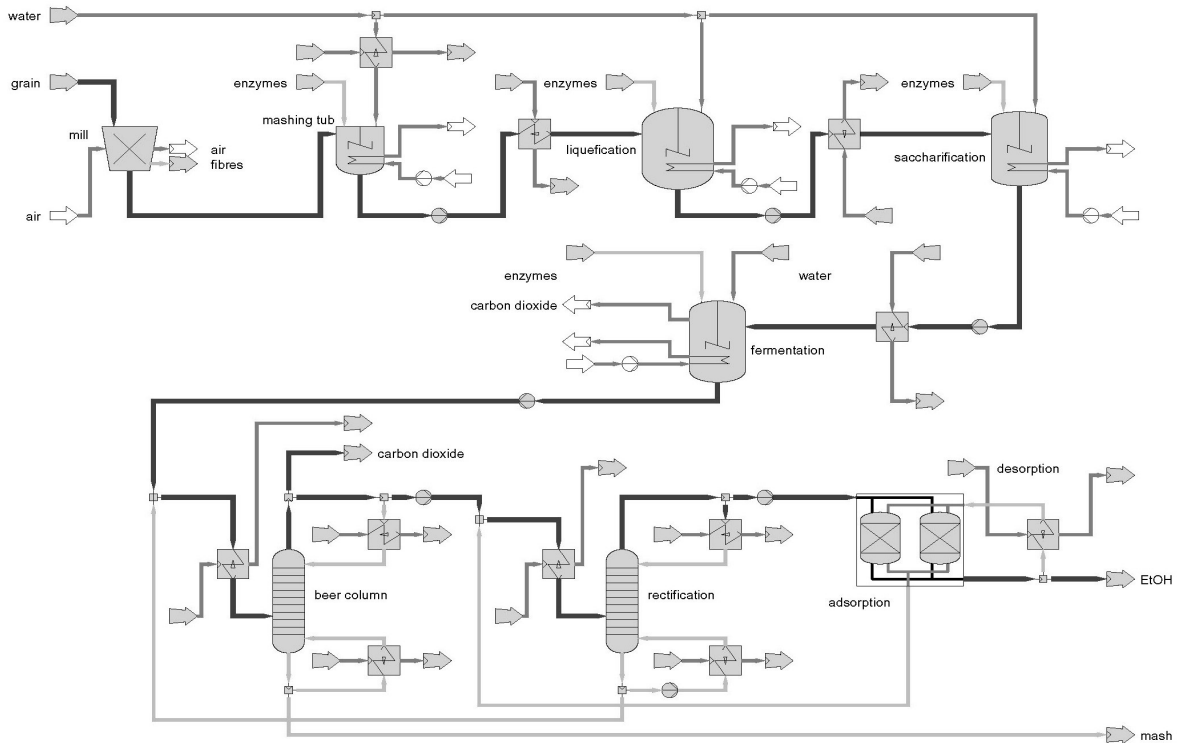


Figure 6. Flowsheet of the bioethanol production process

Table 2 summarizes the main heat demand and reusable heat from different units of the bioethanol production process based on the research work of Pfeffer et al.[7], and all the data are calculated from the reference work [7]. Positive values represent a heat demand, where negative values refer to available heat. Data presented corresponds to a plant size of 84,000 ton/year bioethanol production.

Table 2: Heat Streams in Bioethanol Production

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
Preheating Feed Distillation Col.	35 → 95	7.56
Distillation Column, Condensor	78 → 77	-1.22
Distillation Column, Reboiler	104 → 105	13.44
Cooling Stillage	105 → 35	-7.6 × x% *

Rectification, Condensor	116 → 115	-13.72
Rectification, Reboiler	132 → 133	7.14
Superheating Adsorption	114 → 120	0.045
Cooling Product	100 → 50	-0.325

*: x%, See also Figure 2, 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 of distillation and rectification gives the largest reduction of heat demand. And considerable amount of heat saving in liquefaction and saccharification section to adjust a temperature of 60 °C and 90 °C may also be possible from reusing the residual heat. But if the biogas generation, fuel cell and greenhouse systems are taken into account, more opportunities of reusing the residual heat will be available.

4.4 Biogas plant

To improve the economic performance of the polygeneration plants, the stillage from the distillation column can be used to produce biogas, and then the biogas can be converted to heat and electric power by the fuel cell system.

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 in this case. Most of the biogas will be produced in this fermentation tank.

After the fermentation process, the biomass leaves the fermentation tank and goes to the storage for biomass. In this storage, more biogas is produced (approximately 5-10% extra). The product left in the storage for biomass is called bio manure, which can be used as forest fertilizer.

Simulation models for anaerobic digestion processes are very complex and to develop such a model would be too time-consuming for this work. Instead, a literature study was performed to find a model that was suitable for this work.

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 greenhouse [8,9].

The ORWARE model is used in this study to simulate the biogas production process.

4.5 Fuel Cell System

The fuel cell system is the part of the plant where electricity and heat is produced. The fuel cell planned to be used is a commercial grade Molten Carbonate Fuel Cell (MCFC) with a rated power output of 1200 kW AC [10], capable of providing high quality electricity power by using anaerobic digester gas as fuel.

The fuel cell system consumes approximately 265 m³/h natural gas (at 34638 kJ/m³) when operating at full rated output. For biogas, although the biogas composition depends on a variety of factors, a heating value of around 23000 kJ/m³ is estimated to be in the right region for this study. Then the volumetric biogas consumption by one fuel cell unit can be estimated by the following general relationship:

$$\text{Biogas consumption: } (265 \text{ m}^3/\text{h} * 34638 \text{ kJ/m}^3 \div 23000 \text{ kJ/m}^3) = 399 \text{ m}^3/\text{h}$$

During full power operation, the overall water consumption of one fuel cell unit is approximately 22.8 m³/day.

At full power, the fuel cell exhaust temperature is < 400 °C; however, at other operating conditions the exhaust temperature can reach < 600 °C. The fuel cell exhaust can be used to generate saturated steam. At higher pressures, the saturation temperature increases, thus decreasing the temperature differential available for heat recovery. For the 10 bar saturated steam, which will be generated and used in the modeled polygeneration plant, the estimated steam production by one fuel cell subsystem/unit is < 250 kW.

Significant additional latent heat energy can be obtained when water is condensed out of the exhaust by cooling the exhaust to a lower temperature. The estimated heat energy available for heat recovery is a function of the temperature to which the fuel cell exhaust is cooled. For example if an exhaust temperature of 55 °C (which is designed to be supplied to the greenhouse in the plant) is concerned, besides the steam generation, another < 500 kW heat is available.

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

Table 3: Performance summarization of one fuel cell unit

Items	Performance
Rated power output	1200 kW
Biogas consumption	399 m ³ /h
Water consumption	0.95 m ³ /h
10 bar steam production	< 250 kW
Additional heat (Cooled to 55 °C)	< 500 kW

4.6 Greenhouse

A greenhouse needs addition of CO₂ to boost plant growth. The carbon dioxide consumption depends on the amount of sun light and what crops are in the greenhouse. Roughly, one tomato producer with an area of 80000 m² in Sweden uses 3000 ton CO₂ per year. Unfortunately, in very sunny weather, the greenhouse has to be ventilated to prevent a too high temperature, and this also ventilates out some of the CO₂, so the actual CO₂ consumption may be even higher.

The greenhouse will not only need CO₂, but also heat. Therefore it would be good to use the excess heat generated in the fuel cell system for this purpose by cooling the exhaust.

4.7 Heat exchanger

Since the substrate would cause clogging in the pipes, the flows in the heat exchangers cannot consist of substrate. Water is therefore used as the medium heated, or cooled, by the corresponding flow of substrate.

The logarithmic mean temperature difference (LMTD) is used to calculate the temperature difference between the two streams (water and substrate):

$$\Delta T = \frac{T_{h,in} - T_{c,out} - (T_{h,out} - T_{c,in})}{\ln \frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}} \quad (1)$$

where $T_{h,in}$ is the hot fluid inlet, $T_{h,out}$ is the hot fluid outlet, $T_{c,in}$ is the cold fluid inlet and $T_{c,out}$ is the cold fluid outlet.

4.8 Pellets

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

The energy efficiency of the pellets production process is assumed to be 64% according to the literature review [11]. The thermal value of the pellet is considered to be 18500 kJ/kg, and the pellets boiler efficiency is assumed to be 80% constantly.

Then the total steam energy available from burning pellets based on the data from Table 1 is:

$$Q_{\text{pellets}} = (1 - X\%) \times 8.6\% \times 818000 \text{ ton/year} \times 64\% \times 80\% \times 18500 \text{ kJ/kg}$$

5 MOLTEN CARBONATE FUEL CELLS

In this project we have had contacts with the two largest MCFC (Molten Carbonate Fuel Cell) manufacturers in the world, CFC Solutions in Germany and Fuel Cell Energy (FCE) in the US. The information from these contacts is provided below and throughout the report.

5.1 General

The basic structure of a fuel cell is that it has an anode (negative electrode), a cathode (positive electrode) and an in-between electrolyte (ion conductor). The fuel, consisting of hydrogen, is taken into the fuel cell at the anode and the oxidation reaction occurs (electrons are released). At the cathode, oxygen (air) is led in and the reduction reaction occurs (electrons are absorbed). The resulting gas at both electrodes in all fuel cells is water. Neither of the electrodes are reactants in the reaction, their function are simply to catalyze the process and to lead out the electrons to the outside circuit. The anode and cathode reactions cause either negative ions in the electrolyte to be transported to the anode or positive ions to be transported to the cathode and close the circuit as in Figure 7 [12].

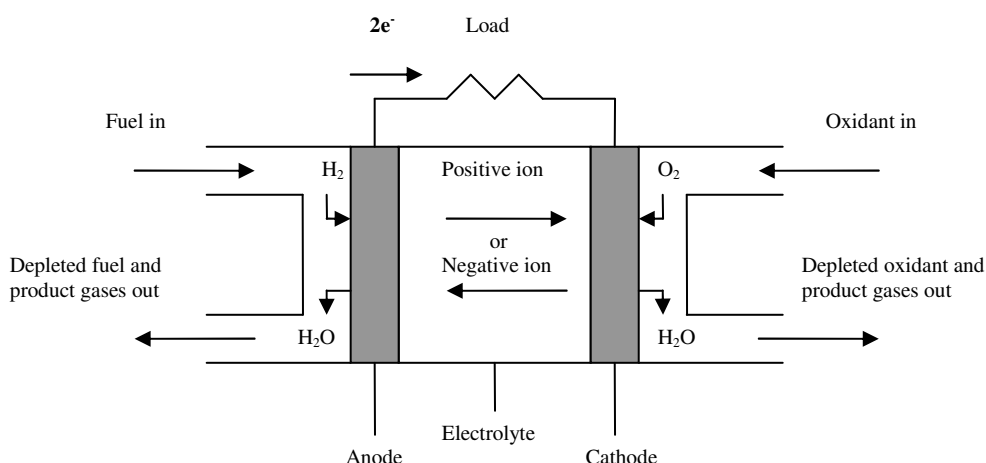
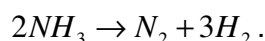


Figure 7: Schematic presentation of a fuel cell [12].

One individual fuel cell does not produce enough power for industrial applications. The cells are therefore connected in series and combined into so called fuel cell stacks to obtain the desired power.

The fuel cell planned to be used in the plant is a molten carbon fuel cell (MCFC). The MCFC has molten carbonate salt as electrolyte, often a mixture of Li_2CO_3 and K_2CO_3 or Li_2CO_3 and Na_2CO_3 . It operates at a high temperature, 600-700 °C. This high temperature gives the advantage of internal reforming of methane, instead of using a reformer for pre-reformation of the gas before it enters the cell. The main fuels for the MCFC are methane, reformed biomass and other hydrogen carrying fuels. Recently NH_3 has also been tried with success as a fuel. The gases are humidified and heated, to

avoid condensation, before entering the cell. The water has a dual function; it acts as a reactant in the reform process and helps to avoid deposition of carbon [13]. Inside the fuel cell the gas is heated to working temperature. In the gas flow channel of the anode the gas passes a catalyst and is converted to hydrogen, carbon dioxide and carbon monoxide. The ammonia is converted to hydrogen in the following reaction:



The methane reacts with the water added to the gas in an internal steam reforming reaction



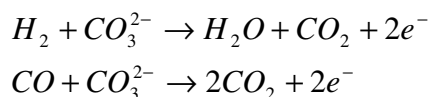
While the carbon monoxide then reacts with water,



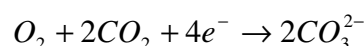
Since these reactions take place at the anode, no chemical equilibrium occurs because, as shown below, both CO and H₂ are reduced in the anode reaction [14].

At the cathode, carbonate ions (CO₃²⁻) are formed and transported through the electrolyte to the anode. There they react with the H₂ and form H₂O and CO₂. The chemical reactions are, according to [12] written as:

Anode reactions



Cathode reaction



A fan will be used to transport the CO₂ from the anode to the cathode, since no extra CO₂ will then be needed. Tests have also shown that the more CO₂ at the anode, the higher the voltage generated by the fuel cell [12]. In spite of this fact, there will be an overproduction of CO₂. This CO₂ is very clean. It can therefore be used in a greenhouse situated about 300 meters away from the planned biogas plant. The electricity and heat produced in the fuel cell can be used to run the plant, and the steam will be used to heat the hygienization and the fermentation.

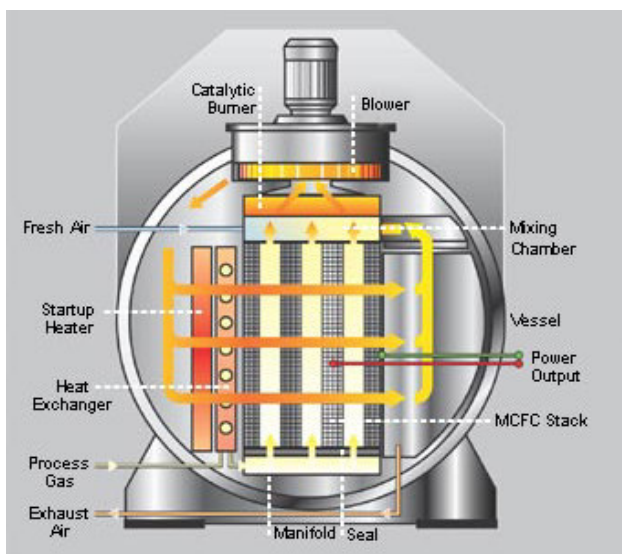


Figure 8: MTU:s MCFC unit, also called the HotModule vessel (www.mtu-online.com).

It is worth noting that using NH_3 as fuel is a relatively new concept. In a test on the HotModule, 99% of the initially added ammonia (5 000 ppm) was removed in the HotModule system and decomposed into hydrogen and nitrogen [12]. Figure 8 shows a picture of the HotModule vessel.

5.2 Filter before the fuel cell

Gas incoming to the fuel cell has to be cleaned in order not to damage the fuel cell. Three substances are especially harmful. First of all sulphur compounds which damage the system in two ways, they make the corrosion rate higher and they react with the nickel based catalysts which slows down the process and eventually makes it stop completely. Second, halogen-containing compounds (HCl and HF) since they lead to corrosion in the system. Third, NO_x in oxidant gases which harm the cell voltage because it increases the internal resistance, but this effect seems to decrease with increasing operating time. Table 1 shows the highest accepted levels of different contaminants in the fuel gas [12].

Table 4: Limits for different contaminants

Contaminants	
H ₂ S	< 10 ppm
HCl	< 1 ppm
HF	< 2.3 ppm
As	< 9 ppm

There are a couple of different methods to clean the gas from contaminants. One is to use activated carbon as adsorbing material. By impregnating the surface with different catalysts the selectivity can be improved, but it is still pretty bad compared to other methods. Another disadvantage is that activated carbon is sensitive to vapor since

humidity easily condensate on the activated surface. Because of the high humidity in the fuel, this is a big disadvantage.

A very common chemical method for removal of sulphur compounds is to transfer the sulphur into hydrogen sulphide. The hydrogen sulphide can then be trapped by a zinc oxide filter and the resulting compound is zinc sulphide. Another type of adsorbing material, mostly based on a mixture of reactive metal oxides, has recently been offered by catalyst manufacturers such as BASF and Sued Chemie. It can operate in room temperature and it has the same characteristics as activated carbon but with higher capacity, according to the manufacturers [12].

There are also some methods to clean the gas when hydrogen sulphide is the only sulphur compound. The first is to let the fuel pass through an iron oxide filter. Lab experiments show very good results of this method. Less than 0.2 ppm of hydrogen sulphide was detected after the filter. The other method is to let the fuel pass through a microbiological filter where the bacteria convert the hydrogen sulphide to sulphur [12].

5.3 HotModule system

The HotModule system, Figure 9, is planned to be used in this biogas plant. It is a system developed by MTU CFC Solutions GmbH in Germany and it consists of several parts. The three most important are:

- The fuel cell stack, which is put in a vessel
- The fuel processing unit, where the gas is cleaned and pre-reforming takes place
- The DC/AC converter, which converts the DC produced in the fuel cell to AC that can be sent to the power grid.

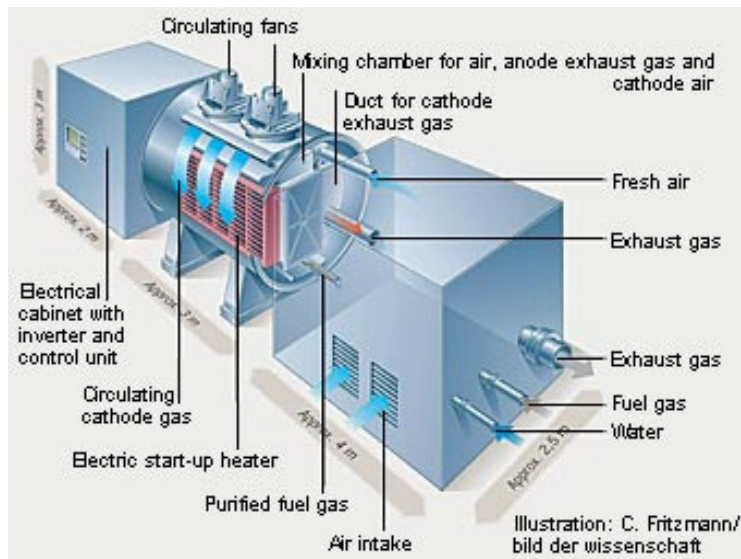


Figure 9: The HotModule system (www.mtu-online.com).

The power range of the HotModule is about 250 kW and the thermal performance at $T_{min}=55\text{ }^{\circ}\text{C}$ is 180 kW [12]. The power is increased with the use of NH_3 .

6 MODELING

Realistic models for anaerobic digestion processes are very complex and to develop such a model would be too time-consuming for this work. Instead a literature study was performed to find a model that suited the purpose of this work. In this study, a couple of suitable models were found. It was realized that two different models would be feasible in this study. For making a process scheme a static model would be appropriate, and for studying control strategies a dynamic model would be required. Since the main purpose of this study was not to make an independent implementation of a model, it was decided, with input from people at JTI (Swedish Institute of Agricultural and Environmental Engineering), to use a model that had already been implemented. Two model implementations were available: the Matlab/Simulink implementations of ORWARE (ORganic WAste Research), a static model, and ADM1 (Anaerobic Digestion Model no 1) which is a dynamic model.

6.1 Static model

To solve the first problem stated in Section 2.2 static models were used. As already stated ORWARE was used for the anaerobic digestion process, for the MCFC a model presented by [13] was used. Models based on thermodynamics were used for the heat exchangers in the anaerobic digestion process and the greenhouse.

6.1.1 ORWARE

ORWARE is a very simple model of anaerobic digestion. It should be used for getting a brief and rough overview of the anaerobic digestion process. The Simulink implementation of ORWARE is shown in Figure 10.

6.1.1.1 Input description

The input data is the substrate that will be used in the anaerobic digestion tank. ORWARE uses a vector with 74 elements for this purpose. The first 43 elements contain the chemical compounds of the substrate. The remaining elements are set to zero since they are not used for the anaerobic digestion model in ORWARE. Inflow and reactor temperature are not inputs to ORWARE, those are instead model parameters.

After studying all the steps in the ORWARE-model, it is clear that the only input variables needed for calculating the biogas production and the remaining bio manure in this model are the different carbon components, VS (volatile solids) and TS (total solids).

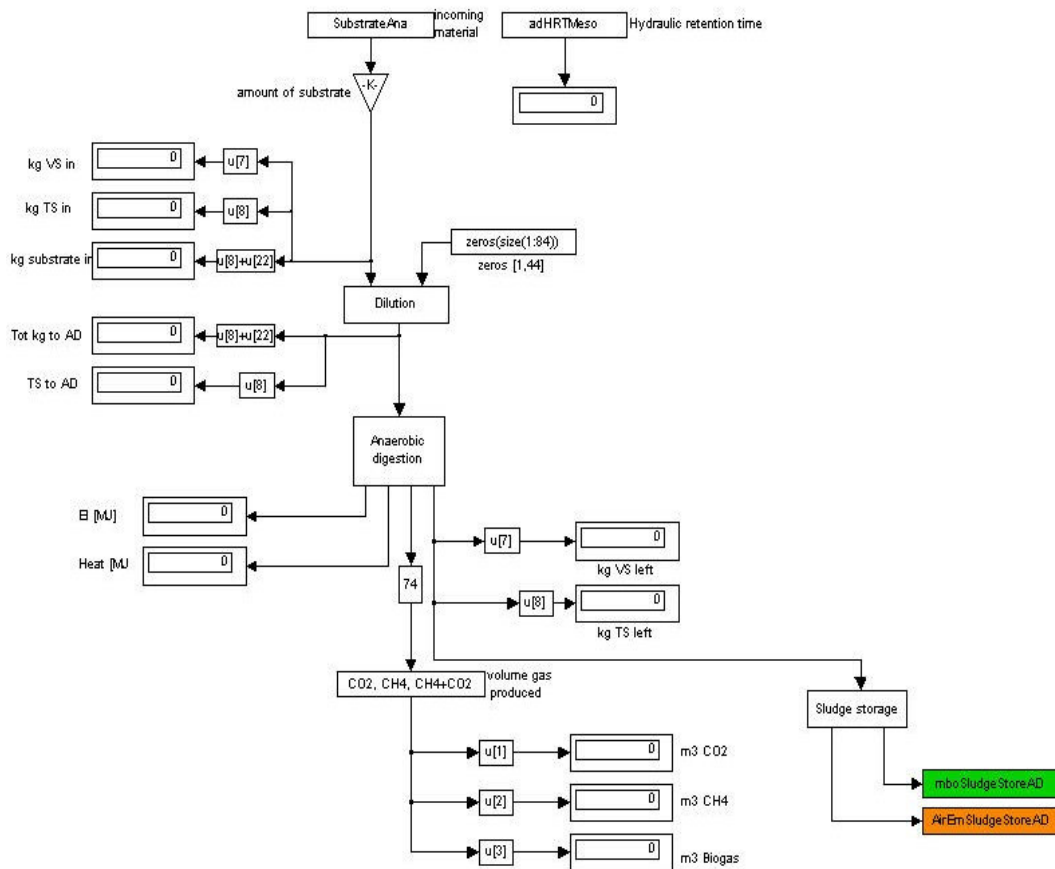


Figure 10: Simulink interface of ORWARE.

6.1.1.2 Output description

ORWARE generates output in form of the yearly biogas production, the bio manure and the energy and electricity consumption in the plant. For our application, only the outputs concerning the biogas production and the bio manure are important, since the energy consumption is calculated in a different way. The model generates outputs for the biogas production and the methane and carbon dioxide components separately and the outgoing TS and VS. There are also two vectors generated for the composition after the storage for biomass, one for the gas and one for the bio manure. Those vectors have the same structure as the input data vector. Other output vectors with the same structure as the input vector exist for other parts in the process, but these are not used in this application. In the ORWARE model, there is also a block for dilution, but since the TS is only 8%, there is no need for dilution and the added fresh water component is therefore set to zero.

A disadvantage with this model is that it assumes optimal biogas production and does not take into account interruptions of the process. A very common problem in biogas systems is so called wash-out of bacteria. This is when the digestion stops because the bacteria have been washed out of the system.

6.1.1.3 Determination of inputs

The input vector is determined by using a table in an IVL-report [15], where most inputs to ORWARE model are explained. There is data for swine manure, cattle manure and organic rest products from butcheries and stores. The composition of those waste in the substrate is assumed to be:

- Cattle manure: 5300 tons
- Swine manure: 1700 tons
- Rest products from butcheries: 680 tons
- Rest products from stores: 320 tons

For the larger plant the exact same composition of substrate is assumed but here the total amount of substrate is 120 000 tons instead of 80 000 tons.

6.1.1.4 Different temperature

Due to the simplicity of the ORWARE model it is very easy to switch between mesophilic and thermophilic digestion. The only thing that needs to be done is to change the temperature and a couple of other temperature related parameters at a few places in the model.

From a literature study on the special characteristics of mesophile and thermophile digestion it was realised that thermophile digestion is much more sensitive to disturbances in temperature, pH and toxic substances [16]. This makes thermophilic processes more difficult to control, since there are more variables that require careful monitoring and control than for mesophilic digestion.

6.1.1.5 Precautions with ORWARE

It is necessary to keep in mind that ORWARE is a very simple model. This makes it important to be very careful when drawing conclusions based on the result from this model. Since ORWARE only looks at yearly average and optimal biogas production, it is important not to connect the results from ORWARE with results from other models for anaerobic digestion, such as the ADM1. The ORWARE model is good to use when comparing different configurations with each other. The results from comparisons can be used for conclusions on what the optimum configuration is. It is also a good model for getting an overview of the anaerobic digestion system, and the results serve as order-of-magnitude estimates of the real results.

6.1.2 The effects of ammonia in the MCFC and the anaerobic digestion

The effects that NH_3 have on biogas production have been studied by several groups. One study [17] have investigated the possibility to control the ammonia concentration in the biogas. It was observed that the ammonia concentration in the biogas was higher when the free ammonia concentration in the reactor was high, rather than the total concentration of ammonia. Since ammonia is a product in the hydrolysis step, see Figure 3, more ammonia is generated when the substrate contains more protein. A substrate that produces ammonia efficiently is swine manure. The highest concentration of ammonia in biogas was found to be 450 ppm [17]. Kawase et al. [18] has tested the MCFC with an addition of ammonia of 500 ppm, which resulted in no change of the cell

voltage. So unfortunately, an addition of 450 ppm does not increase the power in the fuel cell, although it is also worth noting that it does not decrease the cell voltage either, which is positive. The results in [18] show that no further investigation of the effect by ammonia on the fuel cell are relevant and that the presence of ammonia in the biogas is not harmful for the MCFC. Ammonia can be very harmful for other types of fuel cells, for example the solid oxide fuel cell (SOFC). In the case of using an SOFC, the biogas needs to be cleaned from ammonia before entering the fuel cell.

There have been numerous studies on how ammonia affects the anaerobic digestion process, although most papers describe how to lower the amount of ammonia in the process. The reason to keep the concentration of ammonia low is that it inhibits the biogas production. Unionized (free) ammonia is more toxic than ionized ammonia since it penetrates through cell membrane more easily [16]. The fraction of unionized ammonia increases with increasing temperature and increased pH. This means that a process at high temperature is more vulnerable to changes in pH or temperature because of the inhibition by ammonia. Direct effect of this result is that it is probably not preferable to have a high ammonia concentration in the biogas, since this concentration depends on the free ammonia concentration in the reactor.

Ammonia is however, as described earlier, a natural part of the biogas process as one of the products in the hydrolysis. Also the anaerobic bacteria need nitrogen as a nutrient. For this reason, the ammonia concentration needs to be at least 40-70 mg N l⁻¹, but the unionized ammonia is not recommended to go over 55 ± 11 to 150 mg NH₃ l⁻¹, depending on which study is considered. It is therefore good to be able to monitor the ammonia concentration to prevent a decrease of biomass activity [17]. Such monitoring is however beyond the scope for this work, but can be advantageous to consider in a future work.

To summarize the conclusions from this study, the concentration of ammonia that exists in the biogas does not affect the fuel cell and attempts to increase this concentration only leads to a decrease in the biogas production. Therefore the idea of using ammonia as a fuel in the MCFC has to be abandoned.

6.1.3 Heat exchangers

The plant will consume energy in the form of electricity and heat. The electricity is consumed by pumps, stirring equipment in the tanks etc. The project group for the plant, made an estimation of the electric energy needed. When electricity consumption is calculated, the amount of substrate has to be taken into account. For a plant that receives 120 000 tons of substrate per year, the electricity consumption is estimated to be 80 kW [19] and for a plant that receives 80 000 tons the electricity consumption is calculated as $80 \text{ kW} \cdot 80\,000 / 120\,000 = 53 \text{ kW}$.

There are particularly three parts in the system that consumes energy in the form of heat. Those are the hygienization, the fermentation and the fuel cell. There will also be heat losses in the hygienization and the fermentation tank. The heat losses in the fermentation tank are negligible [20]. It is reasonable to assume that, to be sure that the temperature in the hygienization tanks are 70 °C during one hour, the input temperature needs to be 73 °C [21].

In this work the temperature control of the fermentation tank and the hygienization tanks are not considered since their effect on the total energy consumption in the plant is small. In a real plant, it is of course necessary to control the temperature to make sure that the target temperature is kept.

Depending on where in the process heat exchangers are placed –and what heat flows are connected – the total energy consumption of the plant will vary. The placement of the heat exchangers is dependent on the results from the anaerobic digestion and the fuel cell and how those are connected. Here follows a description of how the heat exchangers concerning the anaerobic digestion will be placed if the hygienization is done before the fermentation and vice versa. Both configurations assume a system with two heat exchangers and an extra heater that will supply the system with the extra heat needed to achieve the desired conditions.

The flows in the heat exchangers cannot consist of substrate, since the substrate would cause clogging in the pipes. Water is therefore used as the medium heated, or cooled, by the corresponding flow of substrate.

No more effort in this work will be put in to describing this technique in detail since it is assumed to not affect the results very much. But in other situations as when the plant is to be constructed this is important to consider.

6.1.3.1 Hygienization before fermentation

If the hygienization is done first, heat exchanger 2, in Figure 11 will ensure that the fermentation gets the desired heat, and then as much heat as possible will be delivered to the hygienization. In this way, all the extra heat needed will be added to achieve the hygienization working temperature, see Figure 11.

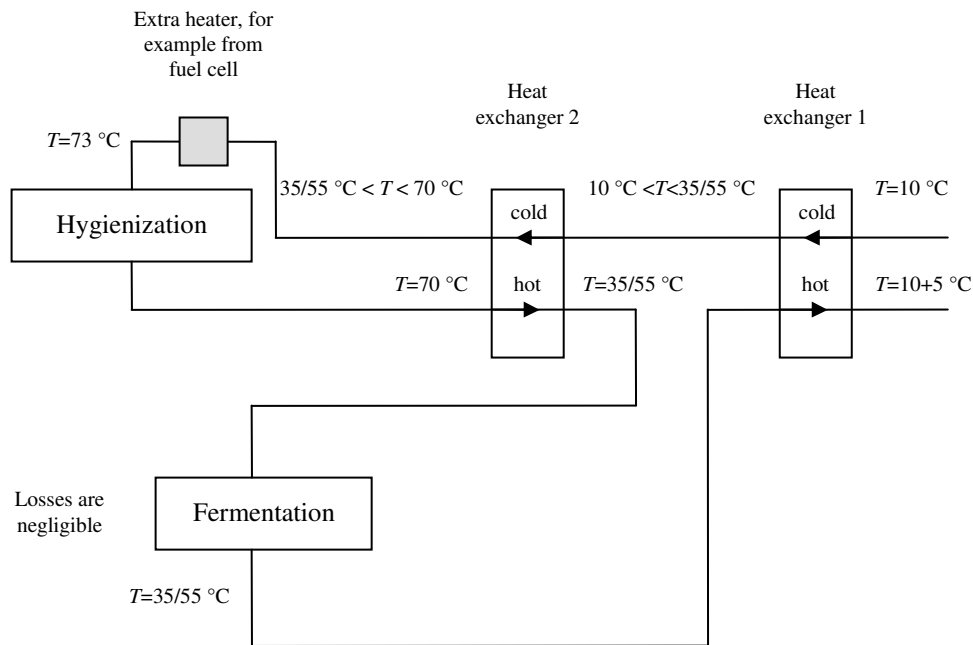


Figure 11: The heat exchanger system when hygienization is performed before fermentation.

The hot flow in heat exchanger 1 will be the leading flow in that heat exchanger. From the temperature change and the starting temperature in the cold flow, the exiting temperature for the cold flow will be determined.

In heat exchanger 2, it is also the hot flow that determines the characteristics of the heat exchanger. Since fermentation losses are negligible it is sufficient to put in substrate with a temperature of 35 °C or 55 °C for mesophilic and thermophilic digestion respectively. Here, the exiting temperature for the cold flow determines how much extra heat must be added to the system to achieve the desired input temperature to the hygienization.

The energy Q_1 accessible in heat exchanger 1 is given by

$$Q_1 = m_{h1} c_p \Delta T_{h1}$$

where m_{h1} is the mass flow corresponding to the hot flow in heat exchanger 1, c_p is the specific heat capacity for water and ΔT_{h1} is the temperature change of the hot flow in heat exchanger 1 (20 or 40 °C).

From this, the exit temperature $T_{c,out}$ of the cold flow can be determined as

$$T_{c,out} = \frac{Q_1}{m_{c2} c_p} + T_{c,in}$$

where $T_{c,in}$ is the ingoing temperature of the cold flow.

The same equations are then applied to heat exchanger 2 to determine the exit temperature from the cold flow in that exchanger. It is valuable to note that all the mass flows will be the same, except for the hot flow in heat exchanger 1, which will be a little lower. This is because some of the mass will become biogas in the fermentation step, decreasing all mass flows after the fermentation. The vaporization in the hygienization is negligible in proportion to the total mass flow.

When the temperatures have been found, the required heat transfer area of the heat exchanger can be determined, i.e. the area available for the flow to heat. This is done by using the relation between the energy and the heat transfer area [22].

$$Q = UA \theta_m$$

where U is the overall heat transfer coefficient with the unit $Wm^{-2}K^{-1}$, A is the heat transfer area in m^2 and θ_m is the average temperature difference. Since the flows are in opposite directions (countercurrent flow), see Figure 12, the logarithmic mean temperature difference can be used

$$\theta_m = \frac{T_{h,in} - T_{c,out} - T_{h,out} + T_{c,in}}{\ln \frac{T_{h,in} - T_{c,out}}{T_{h,out} - T_{c,in}}}$$

where $T_{h,in}$ is the hot fluid inlet, $T_{h,out}$ is the hot fluid outlet, $T_{c,in}$ is the cold fluid inlet and $T_{c,out}$ is the cold fluid outlet [22].

Heat exchanger

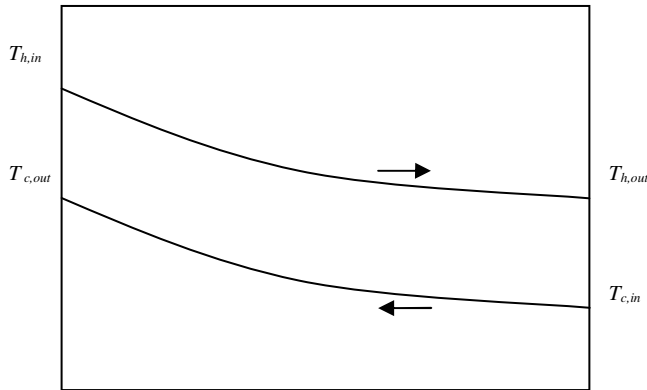


Figure 12: Principle sketch of a counter current heat exchanger.

6.1.3.2 Fermentation before hygienization

When the fermentation is performed before the hygienization, the placement of the heat exchangers will be a little different, see Figure 13. Heat exchanger 1 will see to that the temperature in the fermentation tank is 35 °C or 55 °C. From that condition the input temperature to the hot flow in heat exchanger 1 is given. Heat exchanger 2 then increases the temperature to the hygienization as much as possible. Again an extra heater will be needed to achieve the last temperature increase.

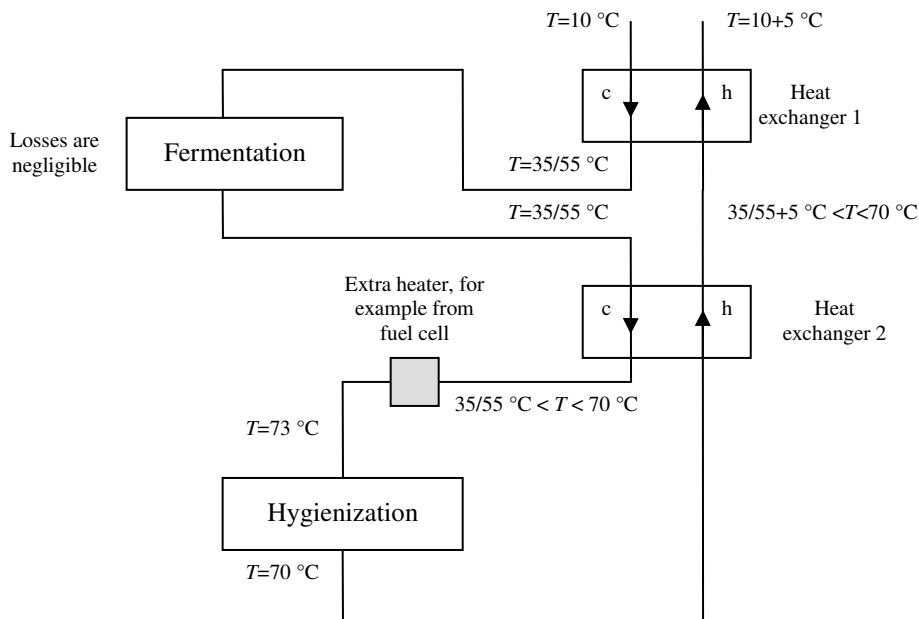


Figure 13: The heat exchanger system when fermentation is performed before hygienization.

Note that there will be a difference in the mass flows. Since the fermentation comes first, all the mass flows, except for the cold flow in heat exchanger 1, are flows after the fermentation, which are lower than the flows of input substrate.

6.1.4 Fuel cell

The MCFC is the part of the system where electricity and heat is produced. The idea is to use some of the produced biogas for this purpose. Since the required electrical power is known, the amount of biogas needed for this purpose can be calculated. To do this, polarization curves have been used.

6.1.4.1 Polarization curve

A polarization curve shows the relation between power per m^2 cell area and current density in the fuel cell; this has been used to calculate the power. A power-current density curve has the shape of the curve in Figure 14. To achieve good performance, it is of course important to be on the left side of the maximum of the curve since it is not desired to have a decrease in power when the current density is increased. For every polarization curve, the fuel utilization for that specific curve needs to be stated. The fuel utilization describes the fraction of the fuel used in the fuel cell. At first sight it looks as the fuel utilization should be as high as possible. However, this is not the case. When fuel is used the cell performance for the last cells in the stack drops due to lack of fuel and the performance is decreased. It can also lead to that the lifetime of the stack decreases very much.

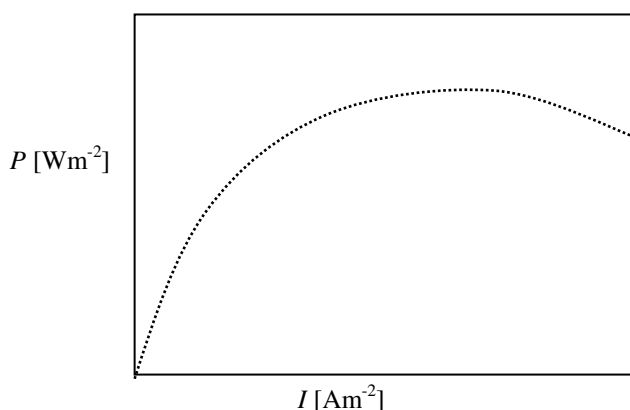


Figure 14: Principle sketch of a polarization curve, increasing the current density I only leads to an increasing power per m^2 P to a certain point.

A polarization curve for the HotModule was received from MTU in Germany. Since this specific polarization curve only is given to the left of the power density maximum, there is no risk in taking the highest point on the curve. The fuel utilization for this curve is 0.75, which means that 25 % of the input fuel to the fuel cell will not be used at the anode. Since the cathode will be damaged if the fuel passes it, the unused fuel has to be burned before passing the cathode.

6.1.4.2 Fuel cell calculations

Since the power is known and a place on the polarization curve is chosen, the area A of the electrode can be calculated using

$$A = \frac{P_{\text{wanted}}}{P_{A,\text{chosen}}}$$

where P_{wanted} is the electrical power generated by the fuel cell and $P_{A,\text{chosen}}$ is the power per m^2 chosen in the polarization curve.

The current is now

$$I = iA$$

where I is the current and i is the current density corresponding to the chosen point in the polarization curve. Now Faraday's law gives the molar flow

$$I = -NzF$$

where N is the molar flow, z is the charge transported in the electro-chemical reaction and $F = 96\,485 \text{ A s mole}^{-1}$ is Faraday's number.

Since the fuel is methane and one methane molecule generates eight electrons in the fuel cell $z = -8$. In this way the molar flow will be the molar flow of methane and not hydrogen. The molar flow calculated in this step is the molar flow used in the fuel cell, but the fuel cell can not use all fuel, some will leave the anode unused. This fuel has to be burned since the depleted gas at the anode is transported to the cathode, and there must be no fuel at the cathode. The resulting molar flow, $N_{\text{CH}_4\text{in}}$, into the fuel cell has to be larger than N ; the needed flow is

$$N_{\text{CH}_4\text{in}} = \frac{N}{y_{\text{fuel}}}$$

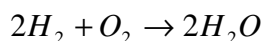
where y_{fuel} is the fuel utilization.

In Figure 15 it can be seen that addition of water and air is needed. The needed water is given by equation 2 and 3, from this the water amount, $N_{\text{H}_2\text{Oin}}$, is

$$N_{\text{H}_2\text{Oin}} = 2N_{\text{CH}_4\text{in}}$$

The water temperature is $95 \text{ }^\circ\text{C}$, as explained in Section 6.1.5.

Oxygen is needed to burn the hydrogen not used. Since the reaction is



the required oxygen, $N_{\text{O}_2\text{in}}$, will be

$$N_{\text{O}_2\text{in}} = 2(N_{\text{CH}_4\text{in}} - N)$$

The oxygen is taken from air, which can be assumed to consist of 21% oxygen and 79% nitrogen.

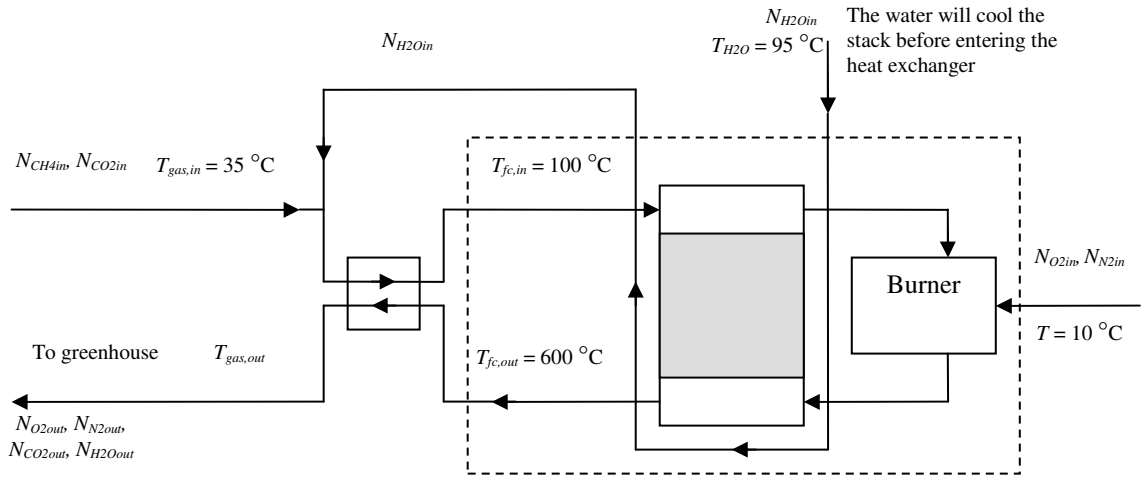


Figure 15: Flows in and out of the fuel cell.

The fuel cell has to be kept at the correct working temperature, which means that heat has to be transferred either from or to the fuel cell can be expressed

$$Q_{transf} = \dot{H} - W_{el}$$

where Q_{transf} is the heat transferred to the fuel cell to keep the working temperature, \dot{H} is the change of enthalpy and W_{el} is the electrical work performed by the fuel cell. A positive Q_{transf} means the cell must be heated and a negative Q_{transf} implies the cell must be cooled.

$$\dot{H} = H_{out} - H_{in}$$

The flows in H_{out} and H_{in} are shown in Figure 15

$$H_{out} = N_{CO_2out} \Delta \hat{H}_{CO_2out} + N_{O_2out} \Delta \hat{H}_{O_2out} + N_{N_2out} \Delta \hat{H}_{N_2out} + N_{H_2Oout} \Delta \hat{H}_{H_2Oout}$$

$$H_{in} = N_{CH_4in} \Delta \hat{H}_{CH_4in} + N_{CO_2in} \Delta \hat{H}_{CO_2in} + N_{H_2Oin} \Delta \hat{H}_{H_2Oin} + N_{N_2in} \Delta \hat{H}_{N_2in} + N_{O_2in} \Delta \hat{H}_{O_2in}$$

where

$$\Delta \hat{H} = \Delta \hat{H}_f^\circ + \int_{T_{ref}}^T C_p dT \approx \Delta \hat{H}_f^\circ + \bar{C}_p (T - T_{ref})$$

and

$$T_{ref} = 25 \text{ }^\circ\text{C}$$

$\Delta \hat{H}_f^\circ$ and \bar{C}_p are taken from tables

The gas out of the fuel cell contains more CO₂ than ordinary air and is therefore planned to be used in a greenhouse near the plant. For this purpose, the gas first has to be cooled to a temperature of about 55 °C. The heat extracted from the gas will be used in other parts of the biogas-fuel cell system by the use of a heat exchanger. The heat (in Watts) that can be extracted from the depleted gas is expressed in

$$Q_{ext} = (C_{pN_2} N_{N_2out} + C_{pO_2} N_{O_2out} + C_{pCO_2} N_{CO_2out}) \Delta T + C_{pH_2O} N_{H_2Oout} (T_{fc,out} - T_{out}) + N_{H_2Oout} \cdot \Delta h_b$$

where N_x is the molar gas flux out of the fuel cell and $\Delta T = 600-55=545$ °C is the decrease in temperature, see Section 6.1.5).

Figure 15 shows that there will be an internal need for heat in the fuel cell to heat the biogas and the water to a steam of 100 °C. Since Q_{transf} will most likely be negative, we will assume in the following that the stack needs cooling.

To heat the water to 100 °C, and vaporize it, requires the energy

$$Q_{H_2O} = C_{pH_2O} M_{H_2O} (T_{fc,in} - T_{H_2O}) + M_{H_2O} \Delta h_b \cdot$$

For the biogas, the power needed to heat the gas to 100 °C is

$$Q_{biogas} = (C_{pCH_4} N_{CH_4} + C_{pCO_2} N_{CO_2}) (T_{fc,in} - T_{gas,in}),$$

which results in a total internal consumption of

$$Q_{int} = Q_{H_2O} + Q_{biogas} \cdot$$

When the internal consumption is known, the temperature of the outgoing gas can be determined. The heat transferred in the heat exchanger is given by

$$Q_{fc,he} = Q_{int} + Q_{transf}$$

where Q_{transf} is negative. The temperature $T_{gas,out}$ is then

$$T_{gas,out} = T_{fc,out} - \frac{Q_{fc,he}}{C_{pN_2} N_{N_2} + C_{pO_2} N_{O_2} + C_{pCO_2} N_{CO_2} + C_{pH_2O} N_{H_2O}} \cdot$$

Whereas the heat left for other parts of the process will be

$$Q_{out} = Q_{ext} - Q_{fc,hes} \cdot$$

These equations have been implemented in a Matlab function, fuelCell. The input parameters to the Matlab function are points on the polarization curve and the fuel utilization. The outputs are the molar fluxes in and out of the fuel cell, Q_{int} , Q_{transf} and Q_{ext} .

6.1.5 The greenhouse

A greenhouse needs addition of CO₂ to boost plants growth. The optimum concentration of carbon dioxide in the air depends of the amount of sun light and what crops are in the greenhouse.

To get a better idea of how much CO₂ a greenhouse needs, contacts have been taken with Hoffrekullens greenhouse where tomatoes are grown. Tomatoes demand more CO₂, compared to other crops, and Glenn Eriksson at Hoffrekullen estimates that tomatoes need 600-1100 ppm CO₂ in the air, also depending on the weather. Unfortunately, in very sunny weather, the greenhouse has to be ventilated to prevent a too hot temperature, and this also ventilates out the CO₂. With conventional methods, it is not economically sustainable to produce more CO₂ than 300 kg h⁻¹, which will maintain a concentration of 400-450 ppm in the greenhouse during those conditions.

The greenhouse will not only need CO₂, but also heat. Therefore it would be good to use the excess heat generated in the fuel cell for this purpose.

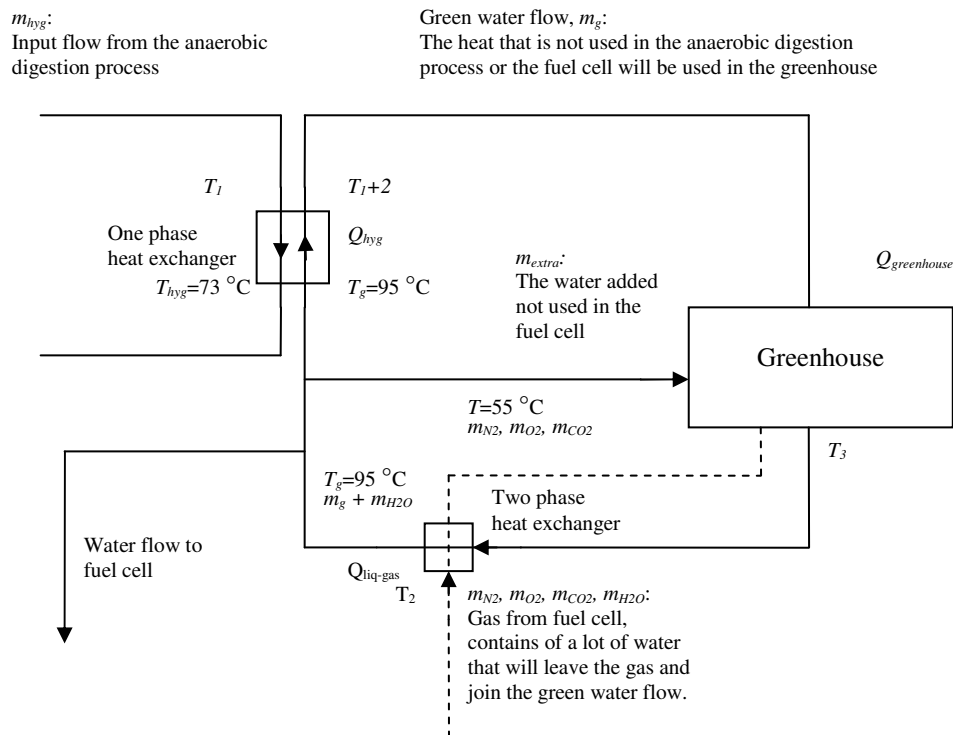


Figure 16: The green water flow and the heat exchangers related to the greenhouse.

In Figure 16, the flow called the green water flow is described. This flow is the connection between the anaerobic digestion process, the fuel cell and the greenhouse. The fuel cell will generate heat that can be used in other parts of the process. This heat enters at the bottom in Figure 16 in the form of a gas flow with high temperature. This gas flow contains much water which will condense when the gas passes through the green water flow. Thereby the water will follow the green water instead of the gas with a following increase in the green water flow after the heating. Since the fuel cell needs addition of water, the process water can simply be taken from the green water, and the rest of the added water can be led directly for heating of the greenhouse. After the added water has been removed, the green water is directed to the heat exchanger for adding the extra heat needed in the hygienization. When the temperature T_1 is known,

the green water flow can be determined from the heat transferred in the one phase heat exchanger

$$Q_{hyg} = m_{hyg} c_p (T_{hyg} - T_1)$$

which gives

$$m_g = \frac{Q_{hyg}}{c_p (T_g - (T_1 + 2))}$$

in the same way as described in Section 6.1.3.

The next step is to determine the exchanged heat in the liquid-gas heat exchanger. To do this, the heat received from the water will be determined first and then the heat received from the gas components.

There are more steps in this heat exchanger because the water vapor will condense and join the green water flow, the flows will change after the heat exchanger and the heat extracted from the water can be expressed

$$Q_{H_2O} = m_{H_2O} c_{p1} (T_2 - 100) + m_{H_2O} h_b + m_{H_2O} c_{p2} (100 - T_g)$$

where T_2 is calculated. The heat extracted from the other gases can be expressed

$$Q_{gas} = (m_{N_2} c_{pN_2} + m_{O_2} c_{pO_2} + m_{CO_2} c_{pCO_2}) \cdot (T_2 - 55)$$

where the number 55 is the temperature of the gas when it enters the greenhouse, chosen so high to make sure that the liquid inflow to the two-phase heat exchanger, m_g has the lowest temperature, T_3 . T_3 is probably around 40 °C, the exact value will be given in Section 8.1.4. The heat that can be exchanged here is then

$$Q_{liq-gas} = Q_{H_2O} + Q_{gas}$$

and now T_3 can be determined

$$T_3 = T_g - \frac{Q_{liq-gas}}{m_g c_p}$$

Heat that is not needed in any other parts of the process will, as already stated, be used in the greenhouse. Except for the inflow of gas at 55 °C, this heat comes from the green water flow (when lowering the temperature from T_1+2 to T_3), and the 95 °C water left when the flow to the fuel cell is removed. If we assume that the greenhouse can lower the temperature in this water to 20 °C, the heat transmitted to the greenhouse is

$$Q_{greenhouse} = m_g c_p (T_1 + 2 - T_3) + m_{extra} c_{p2} (T_g - 20)$$

6.1.6 Economical situation

It is of course very interesting to investigate whether it is feasible or not to invest in a HotModule. In this work the HotModule investment is compared to the original idea of using a small part of the produced biogas to ensure the need of heat in the anaerobic digestion process and buy the needed electricity from the grid. Note that the original idea does not include the greenhouse.

Some important economical data was collected in order to make accurate calculations. This data is presented in Table 5.

Table 5: Economical data.

Electricity price	0.65 SEK/kWh
Electricity certificate	0.18 SEK/kWh
Gas price	0.32 SEK/kWh
Natural gas price	0.25 SEK/kWh
Carbon dioxide price	1.40 SEK/kg

7 SIMULATIONS – CASE 1

This chapter presents the simulations and process calculations that have been made in this work to produce the results.

7.1 Simulations for a process scheme

To produce a process scheme of the whole biogas process, simulations are performed as described in Section 6.1. In the following, the exact simulations that generate the results in Section 8.1 are given.

7.1.1 ORWARE

The ORWARE simulations performed in this work are for mesophilic and thermophilic digestion in the small plant, and for mesophilic digestion in the large plant.

As discussed earlier the possibility of using thermophilic digestion has not been investigated carefully in this work. No time has been devoted to investigating what measurements are needed for accurate control of thermophilic processes. In the static model, the thermophilic digestion will be considered to get an indication of differences between thermophilic and mesophilic digestion regarding methane production and needed energy. So that no misunderstandings occur regarding the control strategies, the thermophilic digestion is left out of the dynamic model. It is however an interesting future work to consider control laws for thermophilic digestion.

7.1.2 The heat exchangers

A couple of different configurations are considered regarding the anaerobic digestion heat exchangers. Since ORWARE is used on the small plant for both mesophilic and thermophilic digestion, the two heat exchanger configurations – hygienization first and fermentation first – are used on both of them.

For the large plant the ORWARE simulation is only preformed for the mesophilic temperature. The heat exchanger calculations are therefore only made for this condition. In total, there are six heat exchanger calculations, four for the small plant and two for the large plant.

7.1.3 The fuel cell

The first simulation for the fuel cell is to use all the points in the polarization curve to show what the outputs of the fuel cell function are for all those points. In this case the small HotModule of 250 kW is used.

The second simulation is for the highest point on the polarization curve, but with the electrical power varying from 50 to 250 kW in five steps. This simulation shows what amount of heat that is produced and the amount of biogas needed for the different electrical power out of the fuel cell. It is required that the fuel cell can deliver the requested heat to the anaerobic digestion process, which sets a lower boundary on the electrical power.

As mentioned earlier there exists a larger HotModule that can deliver a maximum electrical power of 450 kW. The same simulations are therefore preformed for the electrical power output of 300, 350, 400 and 450 kW.

Since the process scheme considers the large anaerobic digestion process, an investigation of the possible fuel cell configurations is made in order to determine the best choice for the fuel cell. When this is done, the outputs for the fuel cell function are given for that chosen configuration.

7.1.4 The greenhouse

The determination of the equations stated in Section 6.1.5 are only made for the final version of the large anaerobic digestion process and the chosen fuel cell configuration since the equations are only interesting in combination with the results for the rest of the plant.

7.1.5 Economical calculations

The economical situation in this report is investigated by determining whether the decision of making the fuel cell investment gives a positive or negative annual profit. If the annual profit of the investment is positive, the pay back period is determined.

Due to confidentiality agreements with respect to economical information, the details of the economical calculations are not disclosed here.

8 RESULTS – CASE 1 MODELING

8.1 Static model

In this section the results for the static model will be presented. When there are more than one possible configuration to choose from the motivation for the selected choice will be given in discussion/conclusions. The final process scheme, resulting from the chosen configuration is presented in figure 17.

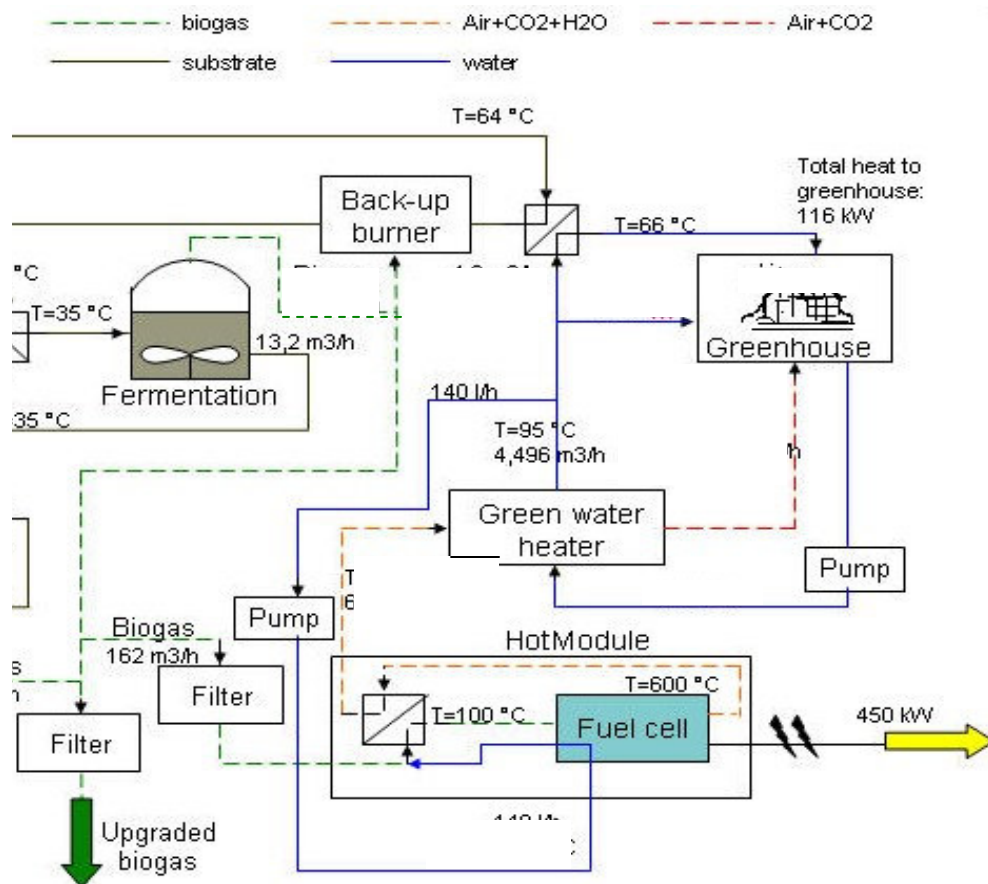


Figure 17. Part of process scheme with some results from modeling.

8.1.1 ORWARE

The results for the mesophilic digestion for the small plant, which was the original idea of the project group, are presented in Table 6 and Table 7. Table 6 presents the biogas produced in the anaerobic digestion tank and Table 7 presents the biogas produced in the storage for biomass.

Table 6: Mesophilic digestion of the small plant

	Volume [m ³ year ⁻¹]	Amount [mole year ⁻¹]
Biogas	2.4·10 ⁶	
CH ₄	1.4·10 ⁶	62.1·10 ⁶
CO ₂	1.0·10 ⁶	44.3·10 ⁶

Table 7: Production of biogas in storage for biomass (10% of production in fermentation tank)

	Volume [m ³ year ⁻¹]
Biogas	0.24·10 ⁶
CH ₄	0.14·10 ⁶
CO ₂	0.10·10 ⁶

The mass flow from the anaerobic digestion tank will be the input substrate minus the biogas produced in the anaerobic digester:

$$m_{flow} = 80.0 \cdot 10^6 - (1.0 \cdot 10^6 \cdot 1.95 + 1.4 \cdot 10^6 \cdot 0.71) = 44.3 \cdot 10^6 \text{ kg year}^{-1}$$

where 1.95 kg m⁻³ is for CO₂ and 0.71 kg m⁻³ is for CH₄.

The results for the thermophilic digestion for the small plant are presented in Table 8 and Table 9. This simulation is only made to show the result from the thermophilic digestion configuration, more work with this process configuration will be needed before it can be proposed. Table 8 presents the biogas produced in the anaerobic digestion tank and Table 9 presents the biogas produced in the storage for biomass.

Table 8: Thermophilic digestion of the small plant.

	Volume [m ³ year ⁻¹]	Amount [mole year ⁻¹]
Biogas	2.7·10 ⁶	
CH ₄	1.6·10 ⁶	69.8·10 ⁶
CO ₂	1.1·10 ⁶	51.5·10 ⁶

Table 9: Production of biogas in storage for biomass (10% of production in fermentation tank).

	Volume [m ³ year ⁻¹]
Biogas	0.27·10 ⁶
CH ₄	0.16·10 ⁶
CO ₂	0.11·10 ⁶

The mass flow from the anaerobic digestion tank will be the input substrate minus the biogas produced in the anaerobic digester:

$$m_{flow} = 80.0 \cdot 10^6 - (1.1 \cdot 10^6 \cdot 1.95 + 1.6 \cdot 10^6 \cdot 0.71) = 44.0 \cdot 10^6 \text{ kg year}^{-1}$$

The mass flow out of the anaerobic digestion tank in mesophilic digestion is 1.4037 kg s⁻¹ and 1.3965 kg s⁻¹ in thermophilic digestion.

The simulation results from mesophilic digestion for the large plant are presented in Table 10 and Table 11. This configuration is the one presented in the process scheme of the plant, therefore not only yearly production is presented but also the produced biogas per hour has been calculated.

Table 10: Mesophilic digestion of the large plant

	Volume [m ³ year ⁻¹]	Volume [m ³ h ⁻¹]
Biogas	3.614 10 ⁶	413
CH ₄	2.071 10 ⁶	236
CO ₂	1.543 10 ⁶	176

Table 11: Production of biogas in storage for biomass (10% of production in fermentation tank)

	Volume [m ³ year ⁻¹]	Volume [m ³ h ⁻¹]
Biogas	0.36·10 ⁶	41.3
CH ₄	0.21·10 ⁶	23.6
CO ₂	0.15·10 ⁶	17.6

The mass flow from the anaerobic digestion tank will be the input substrate minus the biogas produced in the anaerobic digester:

$$m_{flow} = 120.0 \cdot 10^6 - (1.5 \cdot 10^6 \cdot 1.95 + 2.1 \cdot 10^6 \cdot 0.71) = 115.5 \cdot 10^6 \text{ kg year}^{-1}$$

The flow out of the tank per hour is $13.2 \cdot 10^3 \text{ kg h}^{-1}$ and if water density is assumed, the volume flow becomes $13.2 \text{ m}^3 \text{ h}^{-1}$. Since the yearly input of substrate is 120 000 tons, the flow into the system will be $13.7 \text{ m}^3 \text{ h}^{-1}$.

8.1.2 Heat exchangers

The two possible heat exchanger configurations generate different results. The results for the small plant with mesophilic temperature are presented in Table 12.

Table 12: The heat exchanger results for the small plant and mesophilic temperature

	Extra heat [kW]	Cold flow outlet of heat exchanger 2 in figure 8 resp. 10 [°C]	Cold flow outlet / hot flow inlet of heat exchanger 1 in figure 8 / figure 10 [°C]
Hygienization first	92.6	64.3	29.3
Fermentation first	91.5	64.0	41.0

The mass vaporized in the fermentation is 2944 tons year⁻¹ for the small plant at mesophilic temperature.

Table 13 presents the results from the same plant size as Table 12 but for thermophilic temperature.

Table 13: The heat exchanger results for the small plant and thermophilic temperature.

	Extra heat [kW]	Cold flow outlet of heat exchanger 2 in figure 8 resp. 10 [°C]	Cold flow outlet / hot flow inlet of heat exchanger 1 in figure 8 / figure 10 [°C]
Hygienization first	112.8	64.2	48.4
Fermentation first	100.9	63.1	61.9

The mass vaporized in the fermentation is 3281 tons year⁻¹ for the small plant at thermophilic temperature.

The configuration to be used in the process scheme is the large plant with mesophilic temperature and the simulation result from the heat exchanger function is presented in Table 14.

Table 14: The heat exchanger results for the large plant and mesophilic temperature

	Extra heat [kW]	Cold flow outlet of heat exchanger 2 in figure 8 resp. 10 [°C]	Cold flow outlet / hot flow inlet of heat exchanger 1 in figure 8 / figure 10 [°C]
Hygienization first	139.1	64.3	29.3
Fermentation first	137.3	64.0	41.0

The mass vaporized in the fermentation is 4479 tons year⁻¹ for the large plant at mesophilic temperature.

8.1.3 MCFC

The results from the Matlab function when all eleven points on the U/I-curve received from MTU are used are presented in Table 15. The outputs from this function are: all the flows in and out of the fuel cell, internal power consumption Q_{int} , the heat transferred to the fuel cell, Q_{transf} (negative value means that heat is transferred away from the fuel cell) and heat extracted from the depleted gas, Q_{ext} . Observe that these are the results when the HotModule generates an electrical power of 250 kW.

Table 15: Results from the fuel cell function for all the points on the polarization curve.

Point	CH _{4,in}	CO _{2,in}	H ₂ O _{in}	O _{2,out}	N _{2,out}	CO _{2,out}	H ₂ O _{out}	Q _{int}	Q _{transf}	Q _{ext}
1	0.49	0.36	0.98	0.06	1.15	0.85	1.71	42	35	143
2	0.49	0.37	0.99	0.06	1.16	0.86	1.73	43	33	144
3	0.50	0.37	1.00	0.06	1.18	0.87	1.75	43	30	146
4	0.51	0.38	1.03	0.06	1.21	0.89	1.80	44	25	149
5	0.52	0.39	1.05	0.07	1.23	0.91	1.83	45	20	153
6	0.54	0.40	1.07	0.07	1.26	0.93	1.87	46	15	156
7	0.55	0.41	1.09	0.07	1.29	0.95	1.92	47	10	159
8	0.56	0.42	1.12	0.07	1.31	0.98	1.96	48	4	163
9	0.58	0.43	1.15	0.07	1.35	1.00	2.01	49	-3	167
10	0.59	0.44	1.18	0.07	1.39	1.03	2.07	51	-10	172
11	0.60	0.45	1.20	0.08	1.41	1.05	2.10	52	-14	175

All flows are measured in mole s⁻¹ and the power is measured in kW.

Since it is important that the fuel cell produces enough heat to provide the rest of the plant with the needed process heat, simulations were made for different levels of the electrical power to determine the lower limit where the fuel cell system still can provide the rest of the process will the needed heat. Table 16 presents the resulting need of water, Q_{int} , Q_{transf} , Q_{ext} and the heat available for use in other parts of the process, Q_{out} . Table 15 presents the biogas needed to achieve the values in Table 16.

Table 16: Results from the fuel cell function for varying electrical effect.

P [kW]	H ₂ O _{in} [kg year ⁻¹]	Q _{int} [kW]	Q _{transf} [kW]	Q _{ext} [kW]	Q _{out} [kW]
50	1.36·10 ⁵	10.3	-2.8	35.0	27.5
100	2.73·10 ⁵	20.7	-5.6	70.0	54.9
150	4.09·10 ⁵	31.0	-8.4	105.0	82.4
200	5.45·10 ⁵	41.3	-11.2	140.0	109.9
250	6.82·10 ⁵	51.7	-13.9	174.9	137.1

Table 17: The amount of biogas used to achieve the corresponding electrical power.

P [kW]	Biogas [m ³ year ⁻¹]
50	148.9·10 ³
100	297.8·10 ³
150	446.8·10 ³
200	595.7·10 ³
250	744.6·10 ³

Table 18 and 19 presents the same results as Table 16 and 17 but for the larger HotModule. This means that the power is varied from 300 to 450 kW instead of 50 to 250 kW.

Table 18: The results for the larger HotModule

P [kW]	H ₂ O _{in} [kg year ⁻¹]	Q _{int} [kW]	Q _{transf} [kW]	Q _{ext} [kW]	Q _{out} [kW]
300	8.18·10 ⁵	62.2	-15.0	211.8	164.6
350	9.54·10 ⁵	72.5	-17.5	247.1	192.1
400	10.91·10 ⁵	82.9	-20.0	282.4	219.5
450	12.27·10 ⁵	93.3	-22.5	317.7	246.9

Table 19: The amount of biogas used to obtain the corresponding electrical power.

P [kW]	Biogas [m ³ year ⁻¹]
300	946.2·10 ³
350	1104.0·10 ³
400	1261.7·10 ³
450	1419.4·10 ³

The final configuration selected is the large anaerobic digestion process with hygienization before the fermentation. The selected fuel cell system is the large HotModule and a production of as much electrical power as possible (450 kW). The outputs from the fuel cell function for this simulation are presented in Table 20.

Table 20: Outputs of the fuel cell function

CH _{4,in}	CO _{2,in}	H ₂ O _{in}	O _{2,out}	N _{2,out}	CO _{2,out}	H ₂ O _{out}	Q _{int}	Q _{transf}	Q _{ext}	Q _{out}
87.7	74.4	0.14	10.9	205.1	161.1	305.3	93.3	-22.5	317.7	246.9

The unit of the flows is m³ h⁻¹ and for the power it is kW.

8.1.4 Greenhouse

The results from the final version of the larger plant proposal (inflow of 120 000 tons per year) make it possible to calculate the results for the greenhouse equations, which are presented in Table 21.

Table 21: Results from the greenhouse calculations

m _g	m _{H₂O}	T _{from fc}	T _{from gh}	Q _{to gh}
4,25 m ³ h ⁻¹	105 l h ⁻¹	372.0 °C	44.4 °C	116 kW

The amount of CO₂ that the fuel cell produces is shown in Section 6.1.4.2, this is given in m³ h⁻¹, but it is very interesting to see this result in kg h⁻¹. For gases it can be assumed that 0.0446 kmole m⁻³ and for carbon dioxide $M_{CO_2} = 44 \text{ kg kmole}^{-1}$, this means that

$$m_{CO_2} = 0.0446 \cdot 44 \cdot 161 = 316 \text{ kg h}^{-1}.$$

Now all the necessary information for making a process scheme is available and the process scheme for this process with all chosen configurations has been presented earlier in Figure 17. The scheme includes all flows, temperatures and power in different parts of the process.

8.1.5 Economy

Calculations have been made to calculate the pay back time and average annual profit of the HotModule investment. Those calculations show that the investment should be done since the average annual profit is positive. To maximize the profit, as much electricity as possible should be taken out of the HotModule. The pay back time will be 6.6 years.

9 RESULTS – CASE 2

To decrease the external energy demand, reusing the residual heat during the production of bioethanol is of great important. For example, the heat demand can be reduced by heating the distillation reboiler with the overhead vapour of the rectification column; this gives the largest reduction of heat demand. Surplus heat from stillage cooling and surplus heat from the distillation column 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 the fermentation step.

If the biogas generation, the fuel cell system and the greenhouse are taken into account, more opportunities of reusing the expelled heat will be available. For example, steam generation by the fuel cell system to partly satisfy the heat demand in the bioethanol production process; the heat from cooling the stream to the bioethanol fermentation tank and the heat from ethanol cooling can be used to heat up the greenhouse water.

Using process simulation carried out by Simulink, the simulation of the whole polygeneration system (including bioethanol production unit, biogas production unit, fuel cell, greenhouse and pellets systems) has been performed. Rough heat exchange and temperature of the main processes in the bioethanol plant are given in Figure 18. The heat exchanges are consistent with the values given in Table 22.

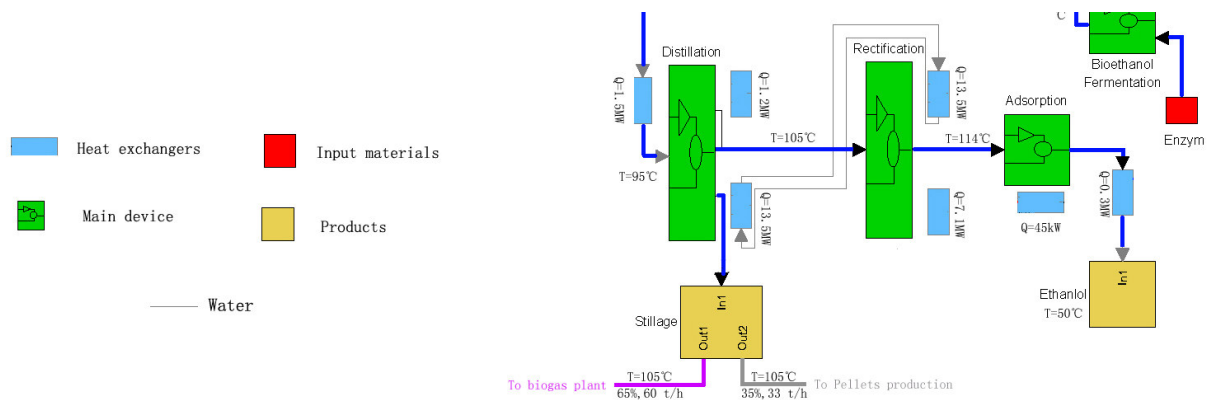


Figure 18. Some heat exchange values and temperatures of the main process in the bioethanol plant

The detailed energy and mass balances of the whole polygeneration plant are shown in Figure 19. Figure 19 illustrates the optimum configuration and their steady working states of the bioethanol based polygeneration plant. The flow rate, temperature and heat exchange in all parts of the process are cleared presented. The optimum configuration can ensure to generate as much electricity as possible (because electricity is high grade energy and easy to sell to the grid) and at the same time produce enough heat energy from both the fuel cell system and the pellets burning to satisfy the whole requirement of the plant.

Seen from the steady state values in Figure 19, around 65% of the stillage is used for biogas production, and all the biogas is consumed by the fuel cell system (5 sets of fuel cells have been chosen) to produce 6 MW electricity and 3.4 MW heat energy. A part of the heat energy produced by the fuel cell system is utilized to generate 10 bar saturated steam, and others are used to preheat the humidified biogas and then supplied to the greenhouse.

Simulation shows that heat generated by the fuel cell system is not enough to supply the entire plant with heat. Pellets production and combustion to generate steam are necessary. Therefore, the rest of the stillage is dried out to produce pellets, and then 10 bar saturated steam will be generated by burning pellets to satisfy the heat energy. The electricity produced by the fuel cell system (6 MW) is sufficient to provide the electrical power in the plant (totally 2.4 MW). Overproduction of electricity (3.6 MW) can be sold to the grid.

Table 22 summarizes the key parameters of the simulated results for the polygeneration plant.

Table 22: Performance summary of the modeled polygeneration plant

Key parameter	Performance
Raw material (wheat)	< 300 000 ton wheat/year
Rest product production	65% for biogas production, the rest to make pellets
Forest fertilizer	58.6 ton/h (TS is around 8.6%)
Fuel cell capacity	5 sets of DFC1500MA
Total heat supplied to greenhouse	3.4 MW
Total electricity usage	3.6 MW can be sold to the grid
Total steam usage	No outside steam is needed

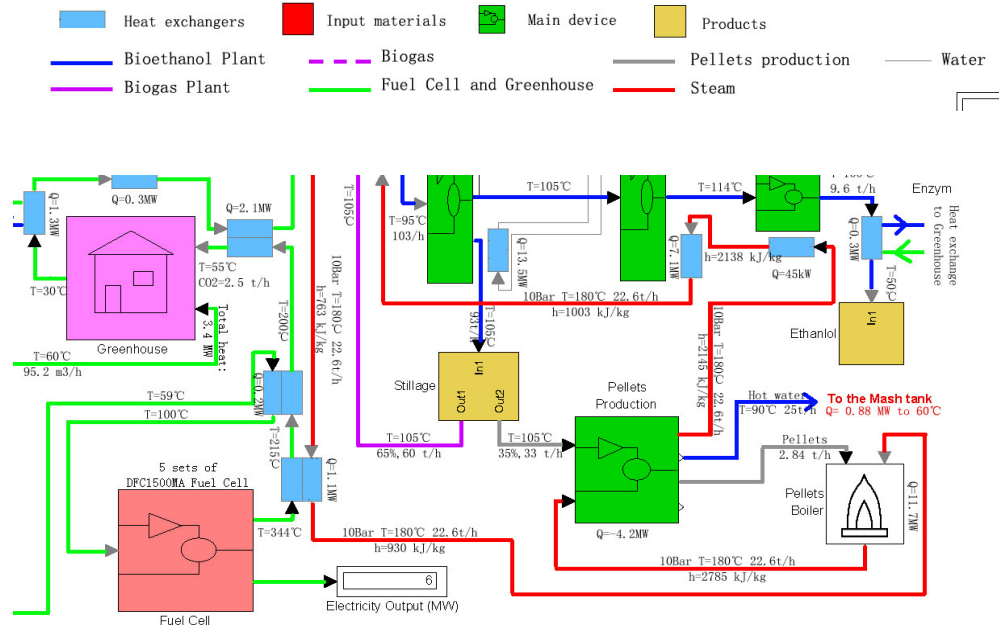


Figure 19. Part of the energy process scheme of the polygeneration plant.

Due to season variations, especially in winter time when more heat is needed in the greenhouse and the market of pellets is better, the percentage X% in Figure 5 can be decreased in order to get a maximum profit. Under such condition, working states of the polygeneration plant can be changed to generate as much pellet as possible and at the same time produce enough electricity from the fuel cell system to satisfy the whole requirements of the plant.

Figure 20 illustrates the changed working states of the bioethanol based polygeneration plant for the mentioned winter condition. The flow rate, temperature and heat exchange in all parts of the process are clearly presented. Seen from Figure 20, some extra steam production from burning the pellets are needed to heat up the stream out of the mash tank to reach the targeted temperature of 60°C in the liquefaction tank; the heat from cooling stillage is used to supply heat to the greenhouse; and the fuel cell units can be operated at a lower power output or 3 fuel cell units can be shut down (only 2 sets of fuel cell units are used in Figure 20).

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Kraftvärme från biogas/CHP from biogas.	01	49/56

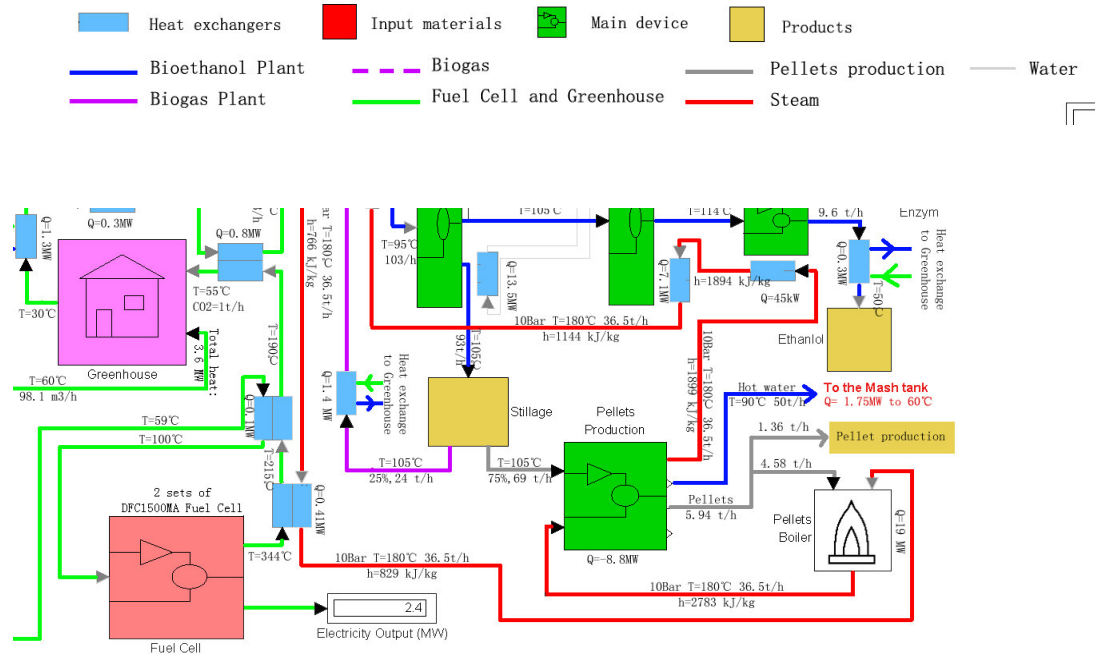


Figure 20. Part of the energy process scheme of the polygeneration plant for the mentioned winter condition

Table 23 summarizes the key parameters for the bioethanol based polygeneration plant under the mentioned winter condition.

Table 23: Plant performance summary for the mentioned winter condition

Key parameter	Performance
Raw material (wheat)	< 300 000 ton wheat/year
Rest product production	25% for biogas production, the rest to make pellets
Forest fertilizer	23.4 ton/h (TS is around 8.6%)
Fuel cell capacity	2 sets of DFC1500MA
Total heat supplied to greenhouse	3.6 MW
Total electricity usage	No outside electricity is needed
Total steam usage	No outside steam is needed

For the studied plant size, 65% of the stillage is used for biogas production, then by consuming the generated biogas, the 5 sets of fuel cell units can produce 6 MW electricity and 3.4 MW heat energy. The rest (35%) of the stillage is dried out and then burned to generate 10 bar saturated 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, 58.6 ton/h (TS is around 8.6%) of forest fertilizer are available from the biogas generation unit, and tomato producers can be supplied with heat and enough CO₂.

For the mentioned winter condition when more pellet productions are desired, one additional working state of the polygeneration plant has been designed to produce as much pellet as possible and at the same time produce enough electricity from the fuel cell system to satisfy the whole requirements of the plant. After covering the electricity demand of the whole plant, pellets can be sold to the market. Additionally forest fertilizer is available from the biogas generation unit, and the tomato producers can be supplied with heat and CO₂.

In this work, all the heat exchanger performance predictions are completely based on theoretical thermodynamics. No effort has been put in making a correct technical description of the heat exchangers.

10 DISCUSSION AND CONCLUSIONS

The discussion and conclusions from this work is summarized below. First the discussions and conclusions around Case 1 – Biogas Plant is discussed and secondly Case 2 – Combined Bioethanol and Biogas Plant. A section is also devoted to environmental considerations with the systems.

10.1 Case 1 – Biogas Plant

10.1.1 System configuration and economy

As already stated, the system configuration that will come in question is the mesophilic digestion, since not enough time has been put into investigating how to monitor the biogas production at thermophilic temperature. Regarding the heat exchangers there exist two configurations, one where the hygienization is first in the process and another where the fermentation is first. As shown the only advantage of putting the fermentation before the hygienization is an energy saving about 1.1 kW for the small plant and 1.8 kW for the large plant. Since the whole idea of using ammonia from the fermentation had to be dropped, this saving of 1.8 kW is not enough to motivate the extra precautions needed when the fermentation-first configuration is used. Therefore the configuration with the hygienization first and mesophilic digestion will be proposed.

After the work with the anaerobic digestion system for making a process scheme is finished the fuel cell system is added. When nothing else is stated, it is assumed that the smaller HotModule of 250 kW is used. It can be concluded that the higher up on the polarization curve, the more heat is produced in the fuel cell. For points 1 to 8, see chapter 8.1.3, the stack even needs heating to keep the working temperature. It is clear that the highest point on the polarization curve should be used and in all the following only this point will be considered.

It is desired that the fuel cell can deliver the extra heat needed in the system. With this demand in mind, Table 16 shows that the two last configurations are the only one that can come in question. When the internal need of heat in the fuel cell is satisfied, those will generate more energy than needed in the system.

From Table 13 and 16 it is clear that it is impossible to use the smaller HotModule when the biogas plant produces 22 GWh/year. The maximum heat delivered from the small HotModule is 137.1 kW. The extra heat needed in the biogas plant is 139.1 kW. The small HotModule does not live up to those demands, so if the biogas plant is to produce 22 GWh/year the big HotModule has to be used.

Since the process demand of heat is 139.1 kW for the bigger plant, all the configurations in Table 18 are technically possible. But it is also important to profit as much as possible. Since the biogas can be sold for 0.32 SEK/kWh, and the electricity for $0.38+0.18 = 0.56$ SEK/kWh, the economically best choice is to produce as much electricity as possible. Therefore the power 450 kW will be chosen for the fuel cell system. Thus 39% of the biogas produced in the digester tank will be used in the fuel cell.

10.1.2 Ammonia

Unfortunately, the original idea of maximizing the ammonia concentration in the biogas and use it as fuel in the molten carbonate fuel cell did not work. The reason for this was

that attempts to increase the free ammonia concentration led to a decrease in biogas production. Since the main fuel in the fuel cell is methane, and the purpose with the plant is to produce biogas, this was not a realistic approach. The result shows, however, that it can be suitable to not let the concentration of ammonia be too large.

10.2 Case 2 – Combined Bioethanol and Biogas Plant

Rest products of the bioethanol production plant have been investigated for biogas production and conversion to heat and electricity power to cover the energy demand in the whole plant. Carried out by MATLAB Simulink, the polygeneration was optimized to be heat energy self-satisfactory while with extra electricity output.

For the studied plant size 65% of the stillage is used for biogas production, then by consuming the generated, the 5 sets of fuel cell units can produce 6 MW electricity and 3.4 MW heat energy. The rest of the stillage is dried out and then burned to generate 10 bar saturated 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 forest fertilizer is available from the biogas generation unit, and tomato producers can be supplied with 3.4 MW heat and enough CO₂.

For the mentioned winter condition when more pellet productions are desired, one additional working state of the polygeneration plant has been designed to produce as much pellet as possible and at the same time produce enough electricity from the fuel cell system to satisfy the whole requirements of the plant. After covering the electricity demand of the whole plant, 1.36 ton/h pellets can be sold to the market. Additionally forest fertilizer is available from the biogas generation unit, and the tomato producers can be supplied with 3.6 MW heat and CO₂.

In this work, all the heat exchanger performance predictions are completely based on theoretical thermodynamics. No effort has been put in making a correct technical description of the heat exchangers.

10.3 Environmental considerations

There are numerous environmental advantages with the molten carbonate fuel cell when compared to conventional technology, e.g. gas engines:

- There are close to zero emissions of SO_x, NO_x and particulates, see figure 21
- Carbon dioxide emissions are lower than for conventional technologies, see figure 21-23
- Low (unburnt) HC and CO emissions
- As the efficiency is higher than for conventional technology, see figure 24, roughly around 50% electrical and 80-90% total efficiency (with heat), energy is saved which is a positive for the environment
- No net CO₂ to the atmosphere as the fuel (biogas) is renewable
- Other biofuels, as ethanol, bioethanol etc. can be used as fuel
- Low noise footprint

	NO_x (lb/MWh)	SO_x (lb/MWh)	CO₂ (lb/MWh)
Average US Fossil Fuel Plant	4.200	9.21	2,017
Microturbine (60 kW)	0.490	0	1,862
Small Gas Turbine (250 kW)	0.467	0	1,244
DFC Fuel Cell 47% efficiency	0.016	0	967
DFC Fuel Cell – CHP 80% efficiency	0.016	0	545

NO_x and SO_x are negligible compared to conventional technologies

Figure 21, NO_x, Sox and CO₂ emissions from MCFC/DFC vs. Average US Fossil Fuel Plant, Microturbine and small gas turbine. (Source FCE). (1 lb = 0.454 kg)

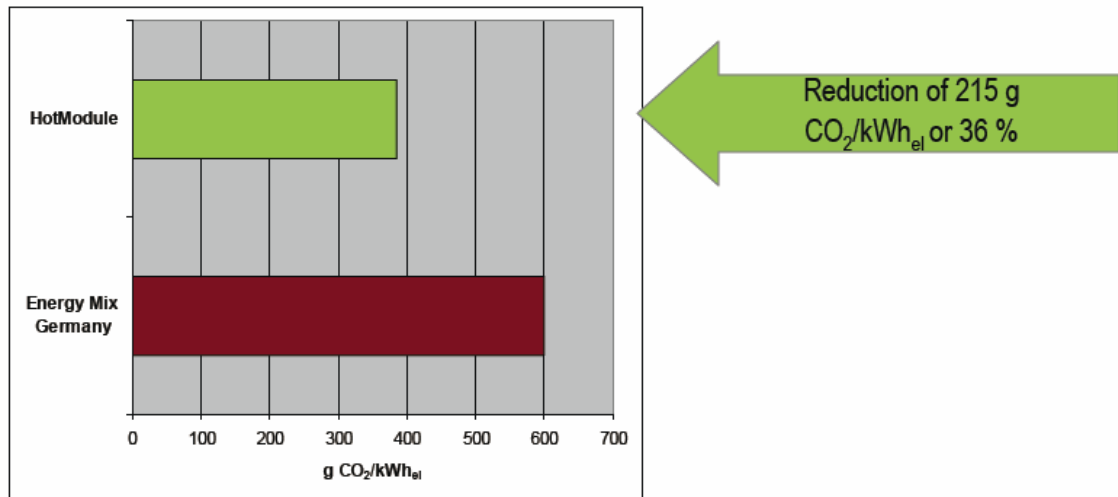


Figure 22. Reduction of CO₂ emission from HotModule (MCFC from CFC Solutions in Germany) vs. Energy Mix in Germany. (Source CFC Solutions).

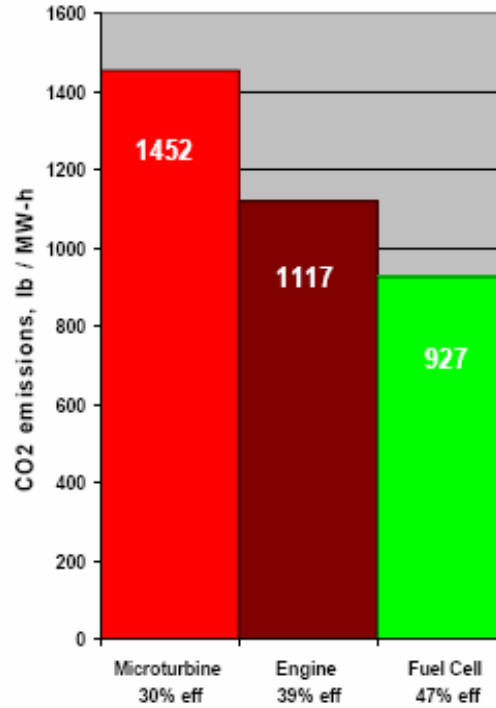


Figure 23. CO₂ emissions from Molten Carbonate Fuel Cell (MCFC) vs. Microturbine and Engine. (Source FCE).

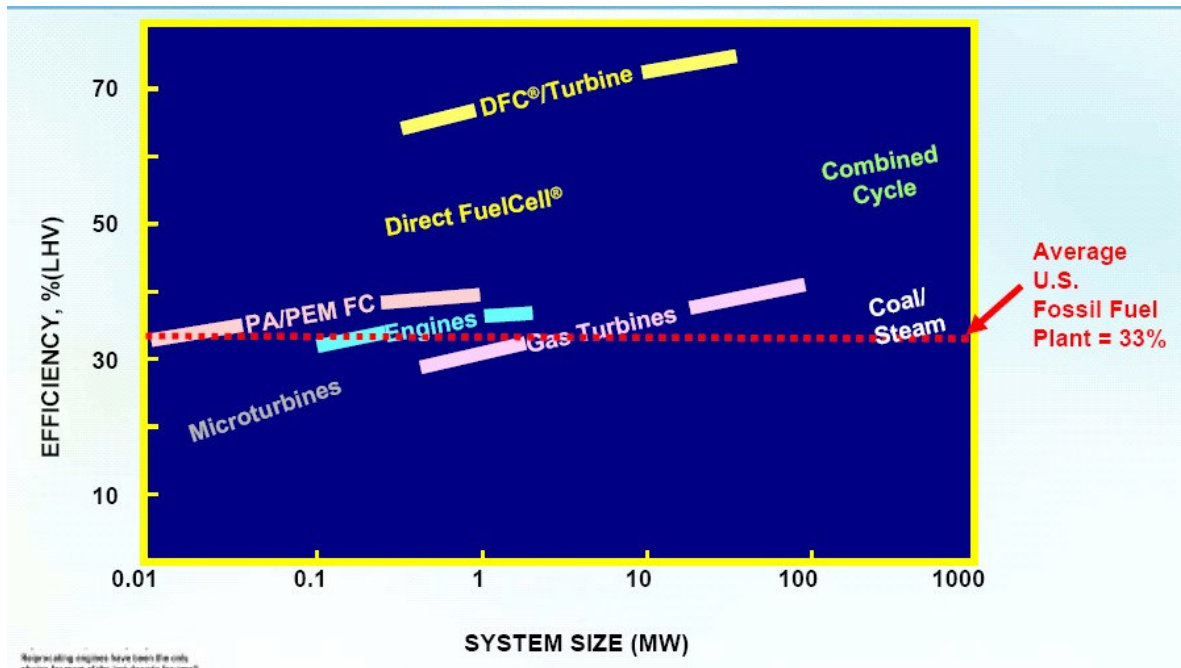


Figure 24. Electrical efficiency for MCFC (Direct FuelCell) vs. other conventional technologies.

From the above facts and figures it can be seen that the environmental advantages are substantial.

11 PROPOSED FUTURE WORK

ABB will continue the efforts in this field with the aim to install a CHP fuel cell system in a biofuel plant. The size of the CHP plant is preferably in the MW-range. There are some potential customers which ABB is in discussion with. As this would be a first installation in Sweden, and potentially in the world depending on the concept chosen, it is always difficult to get a first plant erected due to hesitation from the customer e.g. as there is no reference installation.

For Sweden, as an international leader in the biofuel area, this is an excellent possibility to build a world unique commercial plant. Something similar has not been built yet. Some parts of the total concept has been built in the US and in Germany.

The financing for the plants could come from the gas supplier/plant owner together with e.g. KLIMP subsidy. In the case where the biofuel based carbon dioxide is used in a greenhouse there are good possibilities that the plant can receive the status "Guldklimp".

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13 PRESENTATIONS

1. The concept was presented on the ”Elforsk”-day, in Stockholm, October 26, 2006.
2. The Case 2 study has been presented, both orally and as a poster, at a conference.