NTNU – Trondheim
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Biomass combined heat and power (CHP) for electricity and district heating

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Master's Thesis
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Norwegian University of Science and Technology
Department of Energy and Process Engineering

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MASTER THESIS

for

Stud.techn. Vladimir Novakovic

Spring 2013

Biomass combined heat and power (CHP) for electricity and district heating

Biomassebasert kogenerasjonsanlegg (CHP) for produksjon av elektrisitet og fjernvarme

Background and objective

Combined heat and power plants (co-generation plants) using biomass as fuel, can be an interesting alternative to the predominant electrical heating in Norway. The biomass-fuelled boiler provides heat for the steam cycle which in turn generate electricity from the generator connected to the steam turbine. In addition, heat from the process is supplied to a district heating system. The heat can be extracted from the system in a number of ways, for example, by using a back-pressure steam turbine, an extraction steam turbine, or by extracting heat directly from the boiler.

The objective of the thesis is the design, modelling, and simulation of such a CHP plant. The plant should be sized for providing electricity and heat for the NTNU Gløshaugen campus.

This assignment is realised as a part of the collaborative project "Sustainable Energy and Environment in Western Balkans" that aims to develop and establish five new internationally recognized MSc study programs for the field of "Sustainable Energy and Environment", one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2013.

The following tasks are to be considered:

1) Literature study on biomass CHP
2) Investigation into suitable biomass feedstock
3) Design a plant layout
4) Learn how to use a process simulation tool for modelling of plant
5) Simulate a CHP using the NTNU Gløshaugen campus as case study (electricity and heating needs)
6) Validate and analyse results

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

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The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 17. September 2013

Olav Bolland
Department Head

Vojislav Novakovic
Academic Supervisor

Research Advisors: Dr. Lars Olof Nord, NTNU
Prof. Aleksandar Jovovic, University of Belgrade

Preface

This report is a result of work conducted at the Norwegian University of Science and Technology, department of Energy and Process engineering during autumn 2013. It represents my master thesis which is as well presented and used at the University of Belgrade, Faculty of Mechanical Engineering.

After five years of education in engineering field and more than eight years of active social engagement in the environment protection field, renewable energy has become my main area of interest. I tried to use my knowledge and experience, investigate through the knowledge and experience of others and use the modern technologies to produce this report.

I want to thank my research advisor Dr. Lars Olof Nord for his help with my research work, my supervisor at the home University, Dr. Aleksandar Jovovic for his support and Prof. Dr. Vojislav Novakovic for the coordination. I would also like to thank to Ph.D. student Tymofii Tereshchenko for providing me important data and to my friend Luka Stefanovic for lecturing this document.

Without these people, this thesis would not have been possible.

Vladimir Novakovic

Belgrade, April of 2014

Abstract

Growing energy consumption requests development of the new energy sources and the application of new technologies in the energy sector. At the same time, the world is facing maybe the biggest challenge in human history – global warming. As the energy production sector is the most responsible for the greenhouse gases emissions which cause global warming, new technologies should be capable of decreasing these emissions.

Norway energy sector relies on oil and hydro power. More than 95% of Norway's electricity is produced in hydro power plants which puts this country in the world's top when it comes to the share of renewable energy in final consumption. However, most of the electricity comes from large hydro power plants and ends as the heat energy for residential heating due to theundeveloped district heating systems. As residential sector is also responsible for the greenhouse gasses emissions, we come to conclusion that energy system in Norway still needs to be developed.

One of the possible solutions is using combined heat and power (CHP) technology which is raising efficiency of the conventional electricity production by using the process waste heat. Waste heat can be used in district heating systems, which can decrease the need for the electricity in heating applications. If carbon neutral fuel, such as biomass is used to power CHP power plant, the problem with greenhouse gas emission could be solved. This paper focuses on designing CHP power plant sized to satisfy heat and electricity needs of Norwegian University of Science and Technology Gløshaugen campus and investigate the possibilities for biomass fuel application.

"This assignment is realized as a part of the collaborative project "Sustainable Energy and Environment in Western Balkans" that aims to develop and establish five new internationally recognized MSc study programs for the field of "Sustainable Energy and Environment", one at each of the five collaborating universities in three different WB countries. The project is funded through the Norwegian Programme in Higher Education, Research and Development in the Western Balkans, Programme 3: Energy Sector (HERD Energy) for the period 2011-2014."

Table of Contents

List of figures

List of tables

Abbreviations

AC	Alternate current
aM&T	Automatic Monitoring and Targeting
BEMS	Building and Energy Management System
CCA	Climate Change Adaptation
CHP	Combined Heat and Power
CI	Compression Ignition
DC	Direct current
DH	District Heating
EC	European Commission
EEA	European Economic Area
ERM	Energy Remote Monitoring
ESHA	European Small Hydropower Association
EU	European Union
IAPWS	International Association for the Properties of Water and Steam
LHV	Lower Heating Value
LMTD	Log Mean Temperature Difference
NOK	Norwegian Crown
NTNU	Norwegian University of Science and Technology (Norges teknisk-naturvitenskapelige universitet)
SI	Spark Ignition
SRK	Soave–Redlich–Kwong

Introduction

Background

The electrical energy sector in Norway predominantly relies on hydro power. In 2011, 95,2 % of total electrical energy production came from hydro power plants [1]. Although hydropower is considered to be a renewable energy source, only small hydro power plants are considered as environmentally friendly technologies. Large scale hydropower projects can be controversial because they affect water availability downstream, can endanger ecosystems, water accumulations, can cause tectonic movements, and sometimes, their construction may require relocation of populations. Even though there is no international consensus on definition of small hydro power plants, a capacity of maximum 10MW is generally accepted in Europe and supported by European Commission (EC) and the European Small Hydropower Association (ESHA). Taking that in consideration, by the available data from Statistic Norway from 2011, the share of installed power of small hydro power plants in total installed hydro power is around 5,5 % [2]. This figure indicates that current electrical energy production in Norway has quite high impact on environment.

Climate in Norway makes high energy demands for heating. Private households and agriculture make one third of general electricity consumption in Norway, and the biggest part of that electrical energy goes to heating needs[1]. The majority of the households in Norway use electric space and electric floor heaters (55 % by the available data from 2009[2]), which shows that the predominant source of energy for heating in Norway is electrical energy. District heating share shows constant growth in the last years, and the largest share of district heating production comes from waste incineration and accounted for 42,3 % in 2012, while the biofuel comes second (Statistic Norway). Biomass combustion is considered as carbon neutral technology since the amount of CO_2 that is produced in combustion process has been already consumed by the plants. Development of district heating network and raising its capacities is supported by Norwegian government trough Enova subsidy program. Since there is only a limited amount of waste that can be incinerated, especially in the winter when the heat demand is at its peak, biofuel and biomass can become the most important energy sources for district heating in the future.

Directive on the promotion of cogeneration based on useful heat demand in the internal energy market and amending Directive 92/62/EEC, officially 2004/8/EC, or better known as CHP (Combined Heat and Power) Directive, was made to promote cogeneration in order to increase the energy efficiency and improve secure energy supply. Although this Directive stands for all the CHP, the recommendation is that carbon neutral fuels are used, and one of those is definitely biomass. Like every European Commission Directive, this one is mandatory only for EU28 member states, but it definitely made an impact on the whole Europe and its CHP development. Biomass powered CHP is interesting solution for the electricity and heat production in Norway, especially having in mind current electricity production and heating energy sources as well as Norway's ability to track the following trends in EU.

Scope of work

As stated above, Norway still has to improve its electricity production sector and district heating systems. One of the possible solutions is to invest in small and medium size biomass fuelled CHPs. In order to reduce carbon footprint and pollution, raise security of energy supply and make the national energy system more reliable, energy production needs to be decentralized as much as possible. That is why it is better to invest in smaller scale CHPs than in those that have large capacity.

The aim of this work is to investigate the possibilities for using biomass powered CHPs in Norway. For that purpose, a case study is going to be done and a suitable steam cycle CHP plant will be designed to satisfy the needs of NTNU Gløshaugen campus. For the design and simulation needs, PRO/II software package is going to be used.

Based on the CHP's input heating value, several possible biomass feedstocks will be considered. Availability, price, lower heating value and sustainability will be considered when making a selection, but as well in the discussion and comparative analysis.

Limitations and sources of error

Even though all the work is done in a way that all the data match realistic conditions as much as possible, there are some limitations and sources of error that follow this work.

The design of CHP is planned to be simple and without all the equipment that is usually used in this kind of plants. Also, the heat to power ratio will be adjusted to match the values of heat and electricity load of Gløshaugen campus. These are the two things that can affect the plant performance and decrease the overall efficiency.

Input data for the design of CHP is considered to be static in time, and it is taken as peak load for the year 2011, which means that for the most of the time, either plant will produce more heat and electrical energy than needed or it would run at partial load capacity. For the needs of this work, it will be considered that the plant is working at full capacity, while the energy excess is used in a different place.

Water and steam properties calculation method that is recommended in PRO/II for calculating working fluid properties in steam power generating loops is Soave–Redlich–Kwong (SRK) equation of state modified for water properties application. This method is very popular in petroleum industry and gives very good results, especially for the high pressure and temperature values, but it can be a source of minor errors in these kinds of applications.

Although these assumptions can definitely affect the result of CHP plant calculation, deviations are not that large to affect the final result. Improvement of all of the above mentioned faults can only cause improvement of efficiency of the plant which means lower heat input. That brings to conclusion that discussed condition of the plant is the worst case scenario, and any improvement would lead to higher feasibility and cost effectiveness of the project.

Combined Heat and Power (CHP) technology

Overview

Combined heat and power production or cogeneration is the generation of multiple forms of useful energy (usually electric and heat) in a single integrated system. Type of CHP system is usually identified by the type of equipment that drives the overall system (primary mover). It can be internal combustion engine, combustion or gas turbine, steam turbine, micro turbines or the fuel cell. These components are using heat from the combustion of fuel to generate mechanical power which is usually used to generate electricity, but it can be also used to drive rotating equipment such as compressors, pumps and fans. Thermal energy from the process can be used in direct process applications or to produce steam, hot water, hot air, or chilled water for the adsorption cooling process. [3]

Combined heat and power production processes have much higher efficiency than the separate production of heat and power. Next figure shows this comparison taking natural gas combustion CHP into consideration. It also incorporates the electricity distribution losses and assumes United States national average efficiencies for heat and electricity generation.

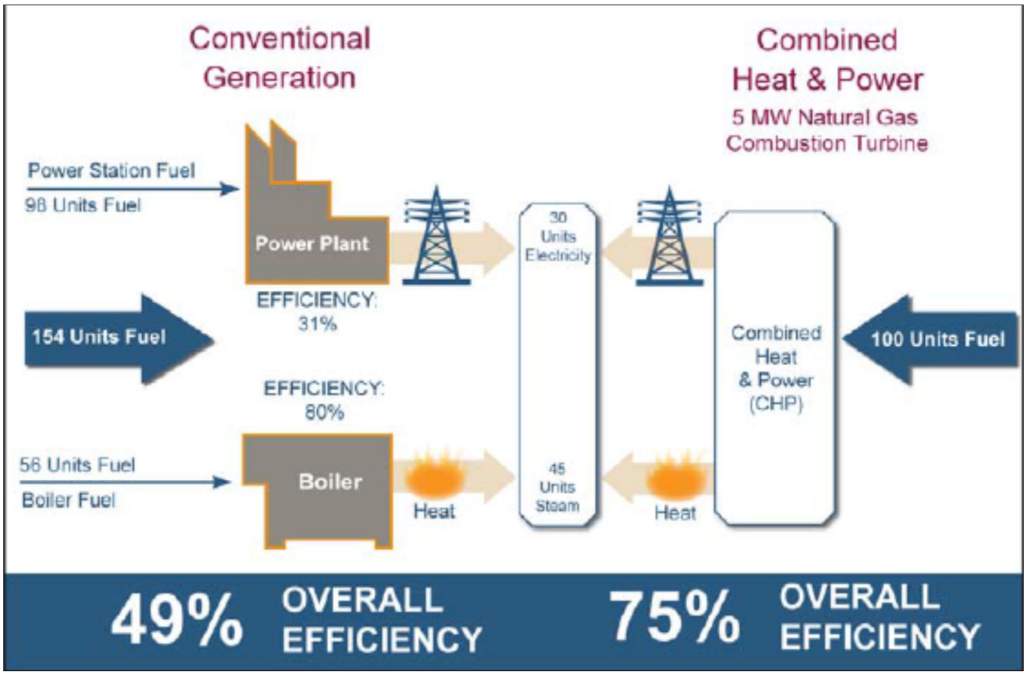

Figure 1 - Combined versus separate heat and electricity production

Although the general principle of functioning had been known for a long period of time, cogeneration technologies started their wide application in developed countries in the late 70's. Over the last few decades, the interest in cogeneration technologies has grown among energy customers, developers, regulators and legislators as consumers and providers seek for the energy cost reduction and energy supply stability.

CHP plants found their application in industry and building sector. Industries suitable for cogeneration are those that use heat in the production process such as chemical and pharmaceutical industry, paper and wood industry, textile industry, etc., while in building sector, CHP technology is suitable for buildings of any kind.

Benefits of cogeneration systems are following [4]:

1. ***Mitigation of high energy prices problem***. Cogeneration reduces the energy prices by doubling or tripling the efficiency of fuel use.
2. ***Reducing of harmful substances emission***. Every energy transformation is causing pollution. At the same way it reduces the energy price, cogeneration technology reduces the emission by using two or three times less fuel.
3. ***Increasing of electro systems reliability***. Reliability of current electro systems is low, and system breakdowns cause high economic damage, especially in highly computerized systems. CHP eliminates possibilities for breakdowns that happen in the public distribution systems.
4. ***Disburdening of electro-distributing grid capacities.*** CHP technology introduces new electricity production which reduces the need for new investments in public distribution network and electricity production units and also reduces electricity distribution losses.
5. ***Ensuring autonomous energy supply.*** Energy market is still highly monopolized. A lot of different stakeholders participate in CHP projects which makes potential for competing with traditional energy suppliers.
6. ***Positive impact on environment.*** Large power plants make significant impact on environment, while cogeneration plants are usually small and placed between existing buildings.
7. ***Fast compensation of the lack of electricity.*** Building of large power plants requires years. CHP plants become operational in less than two years, while for the smaller plants (less than 2 MW) it takes six months.
8. ***Increasing of the state security.*** Energy systems are a vulnerable target of attack. CHP systems are distributed in long distances. Unlike CHP systems, big power plants are easy to spot while damaging them can cause a huge problem in country's energy stability.

These aspects should be taken into consideration when making a decision to invest in the cogeneration technologies. Many governments and international institutions have recognized the significance of CHP technologies and introduced legal framework to support its development trough subsidies and incentive schemes.

CHP technologies

As mentioned before, type of CHP is determined by the type of equipment that drives overall system. In the table below is given a basic overview of CHP technologies, advantages and disadvantages of each, including available sizes [3].

Table 1 - Summary of CHP technologies

CHP system	Advantages	Disadvantages	Available sizes
Gas turbine	High reliability Low emissions High grade heat available No cooling required	Require high pressure gas or in-house gas compressor Poor efficiency at low loading Output falls as ambient temperature rises	
Microturbine	Small number of moving parts Compact size and light weight Low emissions No cooling required	High cost Relatively low mechanical efficiency Limited to lower temperature cogeneration applications	30 KW to 250 KW
Internal combustion engines	High power efficiency with part-load operational flexibility Fast start-up Relatively low investment cost Can be used in island mode[1] and have good load following capability[2] Can be overhauled on site Operate on low pressure gas	High maintenance costs Limited to lower temperature cogeneration applications Relatively high air emissions Must be cooled even if recovered heat is not used High level of low frequency noise	< 5 MW in distributed generation High speed (1200 RPM) ≤ 4 MW Low speed (102-517 RPM) 4-75 MW
Steam turbine	High overall efficiency Any type of fuel can be used Ability to meet more than one site heat grade requirement Long working life and high reliability Power to heat ratio can be varied	Slow start up Low power to heat ratio	50 KW to 250 MW
Fuel cells	Low emission and low noise High efficiency over load range Modular design	High cost Low durability and power density Fuels requiring process	5 KW to 2 MW

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[1] Operation in isolation from national and local electricity distribution network

[2] Capability to adjust its output power according to electricity demands

Gas turbine technology

Gas turbines are the most used technology in CHP systems, but it can also be used in power-only generation. They produce high-quality exhaust heat that can be used in CHP systems to reach overall efficiency of 70 to 80%. The most efficient technology for power-only production is gas turbine-steam turbine combined-cycle plant where efficiency can go up to 60% of the fuel LHV[3], while simple-cycle gas turbines for power-only production can reach 40% of the fuel LHV.

Gas turbines are considered to be one of the cleanest ways to produce electricity. Because of their high efficiency and natural gas as primary fuel, this technology emits less carbon dioxide per generated kilowatt-hour than any other fossil technology in commercial use.

This technology found wide application in oil and gas industry where gas turbine is used to drive pumps and compressors. In process industries they are used to drive compressors or other large mechanical equipment, while many other industries use turbines to generate electricity on site. When used for this purpose, gas turbines are usually used in CHP mode where energy in exhaust gases provides the thermal energy.

Gas turbine systems operate on the thermodynamic cycle called Brayton cycle. In this cycle, air is compressed in a compressor, heated in the combustion chamber and then expanded in the turbine. Part of the power produced by turbine is used for the compressor. Ideal Brayton cycle is showed in the following figure.

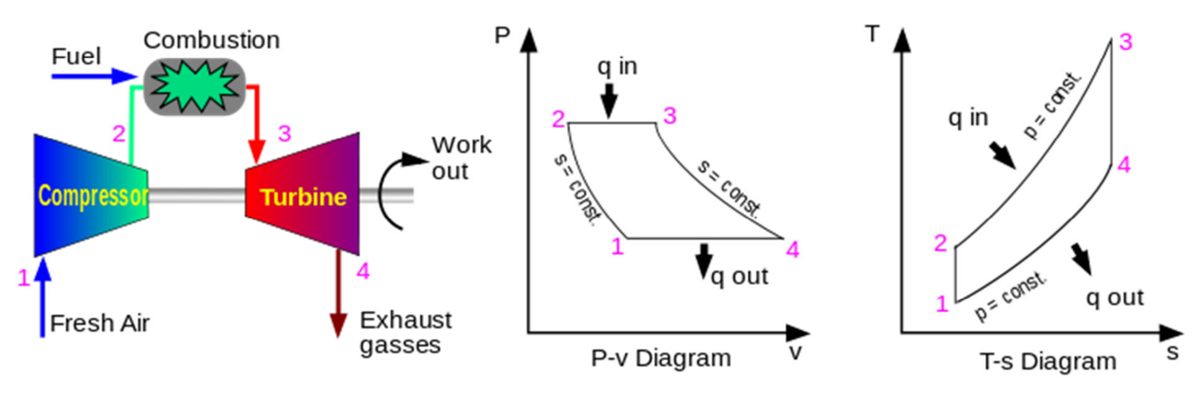

Figure 2 - Ideal Brayton cycle in gas turbine

The following figure shows simplified illustration of a gas turbine in cogeneration process. Compressed air is going through the combustion chamber after which it goes to the

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[3] Lower Heating Value – energy of the fuel in J/kg

turbine. Turbine shaft is connected to the compressor and the generator at the same time. In the outlet stream there is a supplementary firing chamber where exhaust gas temperature is raised to process requirements. Heat recovery boiler uses the heat from the exhaust gas to produce steam or hot water which is later used in district heating system or some other industrial process.

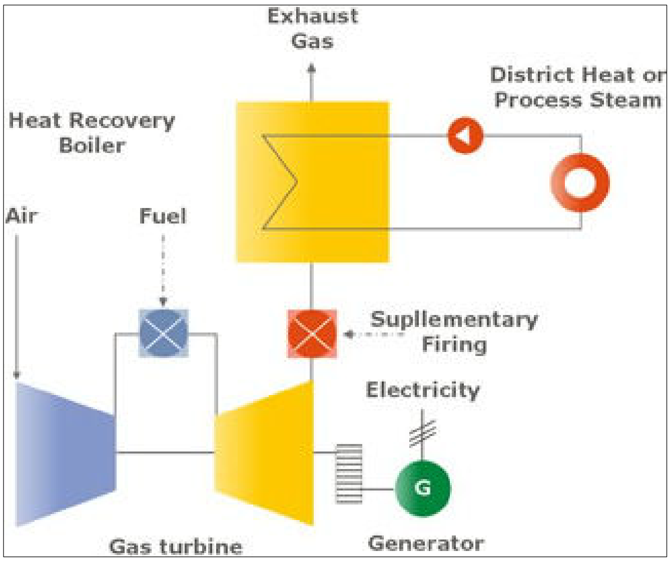

Figure 3 - Gas turbine CHP

Microturbine technology

Microturbines are small electricity generators that use fuel to produce high speed rotation which is transformed to electricity in a generator. They use a variety of gaseous and liquid fuels. It is a relatively new technology which started to be commercially used in 2000. Origins of this technology can be found in automotive industry in 1950's when turbochargers and turbo compressors started to be used in automobile engines.

This technology is able to provide a stable and reliable power supply with low emissions. It is ideal for distributed generation because of microturbine's flexibility in connection methods and ability to be connected parallel in order to give higher output power. Microturbines are used in financial services sector, data processing and telecommunication, hotels and restaurants, residential buildings, office buildings and in other commercial sectors. Because of the wide range and low quality of fuels that can be used in this technology, microturbines are used in resource recovering operations in oil and gas industry, coal mines and landfill operation where they use by-product gas.

When used in cogeneration, waste heat from microturbines is used for the water heating, building space heating or to drive ventilation system of the building.

Microturbines operate on the same principle gas turbines do as they basically are small gas turbines, so they use Brayton thermodynamic cycle. Most of them have internal heat exchanger that is used to preheat compressed air, which are called recuperators. Centrifugal compressor compresses the inlet air which later goes to the recuperator. After that, preheated air is mixed with the fuel in the combustor and hot combustion gas expands through turbines. There is one-shaft model that has a generator, compressor and turbine on the same shaft, and two-shaft models which have one turbine that drives the compressor, and the second to drive the generator. As the generator shaft is rotating at high rotation-per-second, high frequency generator produces AC electricity which is rectified to DC and then inverted back to AC with the frequency of 60 HZ for the U.S. market or 50 HZ for European market. Following figure shows a scheme of single shaft microturbine CHP system.

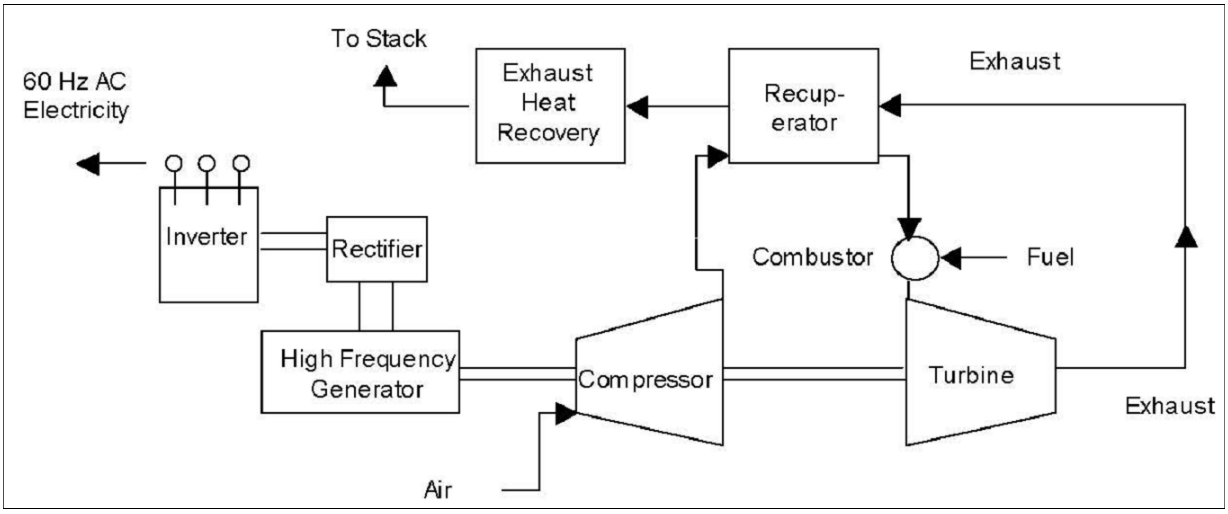

Figure 4 - Single shaft microturbine CHP system

Steam turbine technology

Steam turbine technology has been in use for more than 100 years since it replaced less efficient piston steam engines. Today, the most of the world’s electricity comes from the conventional steam turbine power plants. Steam turbines are widely used in CHP technologies as steam and hot water, which can easily be produced in these kind of plants and have many applications in industry and buildings.

Unlike the other technologies used in CHP systems, steam turbines are independent from the type of fuel because they do not use the fuel directly. Chemical energy of the fuel is transferred to heat energy in steam boilers in combustion process, after which is used to heat water and turn it to a high temperature steam. Steam is then expanded through the steam turbine where its pressure and temperature drop, while steam energy is transferred to mechanical energy on the steam turbine shaft. After the steam turbine, low pressure and temperature steam goes to condenser where the heat is taken away and steam is turned into liquid. From the condenser water goes to pump which raises its pressure to the turbine's inlet pressure. Steam boiler firstly heats the water to the bubbling point, then evaporates it to the steam phase line, and then heats the steam to the steam turbine inlet temperature. These three phases are done in the steam boiler components that are called economiser, evaporator and superheater. Thermodynamic cycle which is used in the steam turbine plants is called Rankine cycle.

Even though steam turbine price is competitive with other prime movers, the whole system which includes a steam boiler and other equipment has quite a high price per installed unit of power. This is why steam turbine CHPs are well suited for medium and large-scale applications, especially if there are inexpensive fuels available, such as biomass, various solid waste and by-products, refinery oil and gas.

In CHP systems, heat can be extracted and used in many different ways. One is using a back pressure turbine where the expansion is interrupted at some point, other is using an extraction-condensing turbine where one part of the steam is extracted and then used, and there is possibility to produce steam and hot water for the heat directly in the steam boiler. Next figure shows systems with the back pressure turbine and the extraction-condensing turbine.

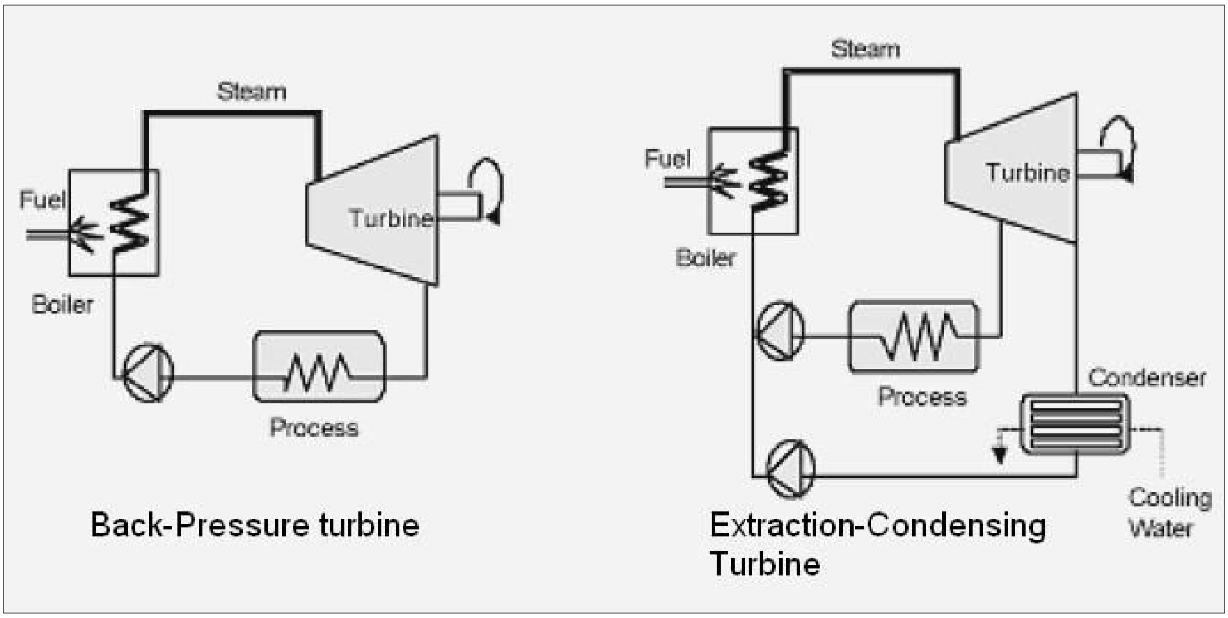

Figure 5 - Back-pressure and extraction-condensing turbines CHP systems

Internal combustion engines

Internal combustion engines are a well-known and widely used technology, especially in the transportation sector. They are as well used for power generation, usually for the stand-by and emergency power, peaking service, intermediate and baseload, and for combined power and heat generation.

There are two types of internal combustion engines: spark ignition (SI) and compression ignition engines (CI). Spark ignition engines used for power generation usually run on natural gas, but they can also use gasoline, propane or the landfill gas. Compression ignition engines, also known as diesel engines, use diesel or heavy oil fuel. They were very popular in power generation, but nowadays they have very limited application because of the emission concerns.

Internal combustion engines are very well suited to a variety of distributed generation applications. They have a good partial load efficiency, high reliability, and they start quickly. If we also consider the fact that this technology is relatively low priced and it is very easy for maintaining and operating, there is no wonder why it is used worldwide.

Internal combustion engines operate on Otto and Diesel thermodynamic cycles. The main difference between these two cycles is in ignition, so in Otto cycle engines, there is a device that makes the ignition spark, while in Diesel cycle engines, the fuel ignites when compressed. Mechanically, these two engines are quite similar: Fuel is ignited and combusted in the cylinder with the piston which is connected to the crankshaft which is transforming linear movement of the piston to rotation.

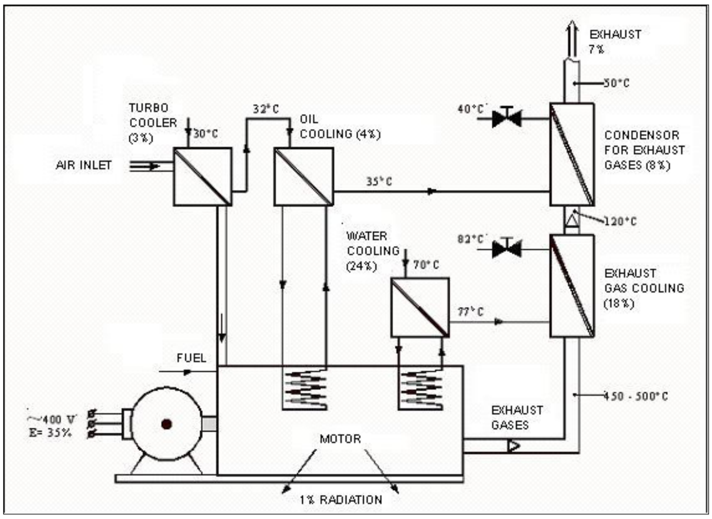

Figure 6 - Internal combustion engine in CHP technology

In CHP applications, the internal combustion engine waste heat can be used from four different sources: exhaust gas, engine jacket cooling water, lube oil cooling water and turbocharger cooling. This heat recovered from internal combustion engines is suitable for the low temperature processes, space heating, portable water heating, or for driving absorption cooling systems. *Figure 6* shows how waste heat can be used in the internal combustion engines.

Fuel cells technology

Fuel cells technology has a totally different approach to energy production then the other prime movers mentioned above. Like the batteries, fuel cells produce direct current electricity (DC) trough electrochemical processes without the direct combustion of fuel. Two electrodes, a cathode and anode, pass the charged ions to electrolyte to generate electricity and heat.

This technology offers a clean, quiet and efficient power generation. Since there is no combustion, there are no direct emissions associated with this technology. Fast development of this technology started 40 years ago as the fuel of the future and currently, some fuel cell systems are already available for the commercial use. However, these systems face competition problems such as low energy density, expensive materials in use for their production, system complexity and unproven durability and reliability. Because of these problems, it is very hard to ensure funds for their development and production, but as this technology is proven to be environmentally friendly and high efficient, there are many incentive programs that can help mitigate their cost level.

Fuel cells use hydrogen as the most common fuel. Hydrogen is usually derived from hydrocarbons such as natural gas and then used in the fuel cells. Most of the fuel cell systems have three main subsystems:

1) The fuel cell that generates direct current electricity
2) The fuel processor that converts natural gas to hydrogen
3) The power conditioner that process electrical energy into AC or regulated DC

As the production cost of the fuel cell technology is high, they are often used in CHP systems in order to achieve higher efficiency. Waste energy is usually used for the district heating applications. Following figure shows the scheme of one fuel cell CHP plant.

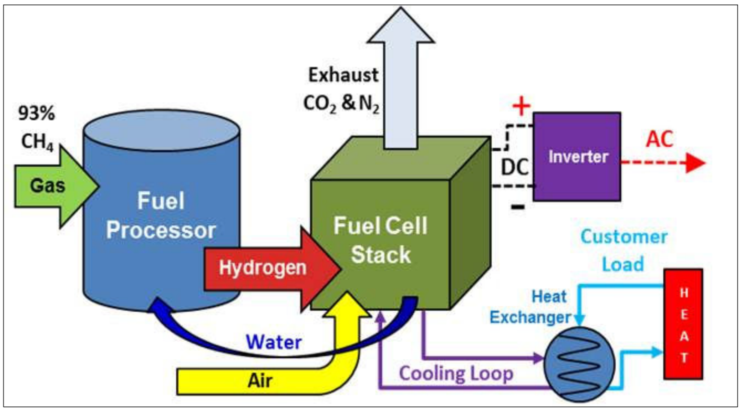

Figure 7 - Fuel cell CHP plant

Biomass

Overview

Through the history, biomass has been the most important source of energy satisfying energy demands of a variety of consumers: from households to large industries including transportation applications. Nowadays, biomass is perceived as a renewable source of energy that can be used as a replacement for fossil fuel in production of heat and electrical energy which puts biomass among main energy sources in foreseeable future. It most often refers to plant or plant-based materials which store energy in the process of photosynthesis in which plants convert the energy of light, normally from the sun, into chemical energy. Chemical energy is stored in carbohydrate molecules such as sugars, which are synthesized from water and carbon dioxide. Additional value of this process is realising of oxygen which is crucial for the life processes on Earth.

Biomass is considered to be a renewable but limited energy source. It is renewable for the same reason solar energy is: the sunlight is an inexhaustible source of energy. Unlike the wind, solar or hydro energy, biomass needs a long period of time to be generated. Sometimes that time can be measured in years, so usage of biomass requires careful and long-term planning. It is considered to be limited source because it requires land for the plants to grow. Growing world population makes growing demand for the food production, so occupying the land for growing high energy biomass crops can sometimes be opposed to growing food crops. The other difference of biomass from other renewable energy sources is that it cannot be used onsite. Biomass needs to be transformed to heat energy, while the others can be transformed to mechanical or even directly to electrical energy.

According to Rosillo Calle, [5], biomass includes a wide range of products and by-products from forestry and agriculture as well as municipal and industrial waste streams. It specifically includes:

- Trees
- Arable crops
- Algae
- Agricultural and forest residues
- Effluents
- Sewage sludge
- Manure
- Industrial by-products
- Organic fraction of municipal solid waste

Biomass can be directly combusted in order to get heat energy, fermented into fuels on alcohol basis, or transformed to high energy gas. The way biomass energy is produced or consumed depends on many different factors among which conversation technologies, specific chemical and physical properties of biomass and energy demands are available.

For the heat and electricity production through direct biomass combustion, any biomass feedstock could be effectively used. However, wood based biomass is traditionally used for these kind of applications. From the other hand, in transportation appliances, solid biomass needs to be transformed by the refining process to liquid or gas fuel, also known as biofuel.

The following figure shows different ways to get energy from biomass. It can also be seen that production, conversation, and transport of biomass requires additional process energy which very often origins from fossil fuels. This means that less energy required for the production of energy from biomass means more energy for the final consumers (higher net-energy value) and less greenhouse gases emission.

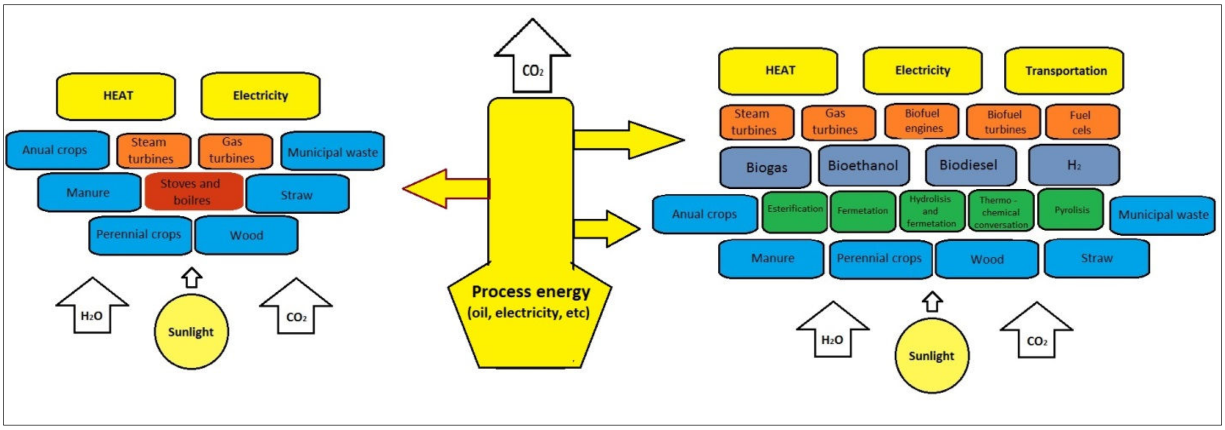

Figure 8 - Biomass to energy conversation

In general, liquid biofuels have low net-energy value, while direct combustion of solid biomass ensures the highest net-energy value. From the other hand, liquid and gas biofuels have other advantages such as easier distribution and consumption, especially in conventional engines used in the transportation sector. Having this in mind, biomass efficiency can be extended from net-energy value to aspects such as available technologies, biomass availability, economic factors as well as culture and lifestyle.

Starting point of bioenergy systems are the main elements of biomass production: sunlight, wind, rain, soil and human work. In order to be competitive, bioenergy systems must be effective. Sustainable bioenergy systems can be defined in different ways, therefore different models for sustainability measuring has been developed. According to Börjesson [6], standard model for bioenergy systems is comprised of four aspects: resource, energy, environmental and cost efficiency.

As illustrated in the *figure 9* [7], bioenergy systems link many individual aspects such as technical, economic, institutional, social and environmental. In order to plan bioenergy systems, it is important to have all this aspects in mind. Political decision to support bioenergy systems has to be made and implemented on many levels and it is one of the prerequisites for the bioenergy systems developments, especially in the developing countries.

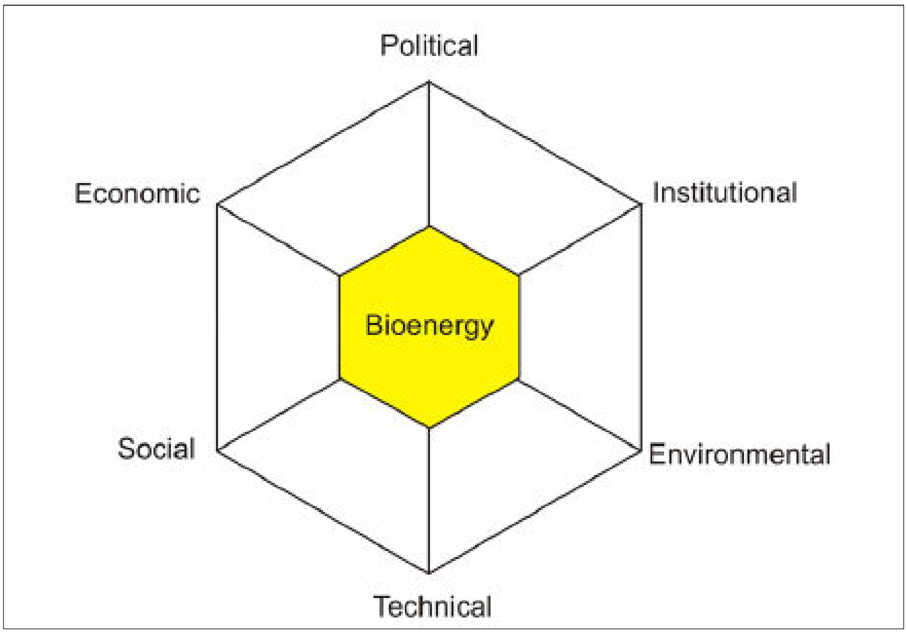

Figure 9 - Bioenergy system aspects

Bioenergy systems change as the other aspects change over time, but they are, as well, acting as a driving force for socio-economic change. All the aspects of bioenergy systems are interconnected as shown in the figure above, but not all have the same significance, even though it is presented that way. Which aspect will have more significance, changes with time and location, and it cannot be defined which aspect will be predominant where. For example, in the last years, biodiesel and use of biofuels in transportation sector became very popular, which made a huge impact on developing that branch of biomass production. New technical solutions for biomass conversion and for the usage of biofuels have been developed, decision makers were forced to change policies in this field, new investments came in this branch and new work places opened up, and last but not the least, greenhouse gasses emissions have been decreased. The most probable cause for blooming of this sector in Europe could be the pressure of environmental lobbies to decision makers to subsidize production and consumption of biofuels which led to further sequence of events, but somewhere else other factors could be predominant. For example, in South America, specifically in Brazil, agriculture development and rapeseed price initiated the development of this sector.

The model presented by J. Domac, K. Richards and S. Ristovic [8] illustrates the complexity of bioenergy systems by identifying socio-economic benefits associated with local bioenergy production. The model divides the benefits in four dimensions: Social aspect, Macro Level, Supply side and Demand Side.

Social aspects are divided into two categories: Increased standard of living and Social cohesion and stability. The first one refers to each household income in economic terms, but since there are some factors that influence living standard which have no immediate economic value such as health, environment and education, those have been added separately. Introducing bioenergy production could help dealing with social problems that many countries have (high level of unemployment, rural depopulation, etc.). Deploying bioenergy plant would first have influence on direct employment, and then to employment in related industries such as agriculture.

Table 2 - Benefits associated with local bioenergy production [8]

Dimension	Benefit
Social Aspects	• Increased Standard of Living - Environment - Health - Education • Social Cohesion and Stability - Migration effects (mitigating rural depopulation) - Regional development - Rural diversification
Macro Level	• Security of Supply / Risk Diversification • Regional Growth • Reduced Regional Trade Balance • Export potential
Supply Side	• Increased Productivity • Enhanced Competitiveness • Labour and Population Mobility (induced effects) • Improved Infrastructure
Demand Side	• Employment • Income and Wealth Creation • Induced Investment • Support of Related Industries

On macro level, bioenergy contributes to all important elements of development: economic growth through business expansion and employment, substitution for energy import, and secure energy supply trough diversification of energy sources [8].

The supply side effects are more subjective to regional development and they are based on increasing region’s competitiveness through bioenergy production. It presumes that the investment in bioenergy system will bring other investments and develop other industries in the region.

The demand side refers to the extent and direction of capital flow to employment and regional income. It can be categorized into direct, indirect, induced and displacement effects. [8]

Biomass resource potential of Norway

Norway is Scandinavian country that lies in the western part of the peninsula. It is a relatively large country and its area of 385178 km² puts Norway on the 6th place of the Europe's largest countries. Because of its strong climate, Norway has a population of only 5136700 and one of the lowest population densities of 15, 5/ km². [2]

Energy in Norway is characterized by a low electricity price, abundance of hydro power and large oil and gas reserves. Contribution of renewable energy in final energy consumption in Norway is among the highest in Europe and it counts to 58 %. This is mostly thanks to high hydro-energy usage from which 98% of electricity is produced. Bioenergy contributes with only 6% in Norway final energy consumption, but this sector has high developing potentials.[2] In 2007 Norway established a national target of 14 TWh of additional bioenergy by 2020 which is close to doubling current bioenergy production. This will probably increase net import of biomass to Norway as mobilization of domestic resources seems challenging at this moment.[9]

The European Union (EU) has set very ambitious targets for 2020. EU directive 2009/28/EC which was brought in order to promote renewable energy sources, aims to increase the renewable energy use in final energy consumption by 20% and by 10% in transportation in EU member states by 2020. European Environmental Agency expects bioenergy to ensure 14% of energy mix and about 236 Mtoe[4] by 2020 and 293,3 Mtoe by 2030 in EU [10]. Norway is a part of European Economy Area (EEA) which allows it to participate in the European Market. Directive 2009/28/EC is EEA relevant, but no targets are set for Norway so far, although it is expected to be similar as for the other EU member states. It would mean that Norway should reach 72% share of renewables in final energy consumption by 2020.

Norwegian parliament adopted the first White paper on Climate Change Adaptation (CCA) in 2013 outlining national policies and guidance for their adaptation in Norway. The White paper represents the Norwegian national strategy for CCA. By this White paper, the aim of Norway is to become carbon neutral by 2030. One of the goals set is to reach 2,4 Mtoe of bioenergy by 2020. Strategy outlines measures, including CO_2 emission credits as well as CO_2 taxation. Action plan of this strategy supports switching from fossil fuels to renewables, and one the measures is a ban on oil heating in large public and commercial buildings.[7]

The small incentives and low energy prices did not favour the production of electricity from biomass in Norway. However, there are investment subsidies and support programmes that can be provided for heating network and the development of bioenergy. Investment subsidies for heating network go from 20 – 40% of investment cost.[11]

---

[4] Mtoe – Million tonnes of oil equivalent

Estimated potential of biomass in Norway is 140 PJ[5], from which 30 % is currently used. Economic potential of biomass is estimated to be below 5 €/GJ. Despite that, Norway is a net importer of biomass mainly in the form of indirect trade through the forest industries. The net wood import in the forest industries is 20 – 30 % of the wood consumption. Reason for these high numbers could be found in stable/non increasing wood harvest. The consumption of firewood in Norway was 1,235 million tons of which 7 % was imported. The import of firewood is more than doubled from 1999 to 2009. [9]

Forest biomass is a major source of bioenergy in Norway, followed by municipal waste used in district heating systems. Forests cover 12 million hectares which is 37 % of the land area with a growth stock of 910 million m^3. From an annual growth of about 25 million cubic meters, less than a half is harvested every year. [12] The most important biomass feedstock's in Norway are firewood, wood chips, logging residues, thinning residues and stumps from clear cutting. Agriculture resources and energy crops play no significant role in biomass production in Norway as only 3, 5 % of land is used for agriculture. [2]

In the following table biomass potentials of Nordic countries in forest industry, agriculture, and high energy crops are presented. As mentioned before, the highest potential of Norway, but of the other Nordic countries as well lays in forest industry, especially in firewood and wood residues.

Table 1 - Estimation of the range of biomass potential in Nordic countries [PJ] [11]

	Denmark	Finland	Norway	Sweden
Forest sector	**37-40**	**158-325**	**88-124**	**457-530**
Black liquor		144-161		142-162
Wood residues	6,5	80-140	37-84	48-150
Logging residues	5-37	108	14-30	72-250
Firewood	19	50	37-84	44-72
Agriculture	**55-87**	**23-29**	**9-19,8**	**4-28**
Agri-residues	6,6-31	4-9	9-16	4-14
Energy crops	48-56	19-29	3,5-11	4-14
Waste	**22-30**	**8-10**	**11,9**	**15-35**
Industrial waste			2,9	9-15
Municipal waste	30		9	9-25
Biogas	**22-40**	**8-10**	**8-15**	
Biomass potential	***147-165***	***359-460***	***104-167***	***554-583***

For the use in designed biomass powered CHP, biomass from the forest sector will be considered and analysed. Forest fuel based on the set of raw materials including harvesting residues, low quality trees, thinnings[6] and hardwoods[7] will be analysed in following chapters.

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[5] 1 PJ (Petajoule)=10^{15} J

[6] Trees removed from the forest in order to make room for the other trees

[7] Wood from angiosperm (flowering plants) trees

Case study – Gløshaugen campus

Gløshaugen is the main and the largest campus of Norwegian University of Science and Technology (NTNU) in Trondheim. The campus is the home of following faculties: Faculties of Engineering science and technology, Information technology, Mathematics and Electrical Engineering, Architecture and fine arts, and one department of Faculty of Social Sciences and Technology Management (SVT). It is located in an area approximately 2 km southeast of Trondheim city centre, and occupies the area of more than 100 hectares[8]. Campus has 35 buildings with a total area of 313 000 m², among which is the largest building in Trondheim Realfagbygget with approximately 60 000 m². Buildings are being used for different purposes: offices, educational, laboratory workshops and sport facilities. This variety makes Gløshaugen "a town within a town", and therefore it is very interesting to analyse the energy use for this campus.

Heat and electricity needs of Gløshaugen campus

Gløshaugen campus is connected to district heating network and to local electricity grid. Building and Energy Management System (BEMS) and web-based Energy Monitoring System (Energy Remote Monitoring – ERM) are available at NTNU. Access to building systems data and operational data are available via BEMS client installed on computers in University Library.

The Schneider Energy Remote Monitoring (ERM) system is an Automatic Monitoring and Targeting (aM&T) system with advanced analysis features which receive data from 46 heating and 79 electricity meters from all over the campus. It provides system energy reporting, alarming, monitoring and analysis, so the heat and electricity consumption can be read online, hour by hour.

Following figure shows the campus district heating network. The main heat exchanger is in the old electric building which is also showed.

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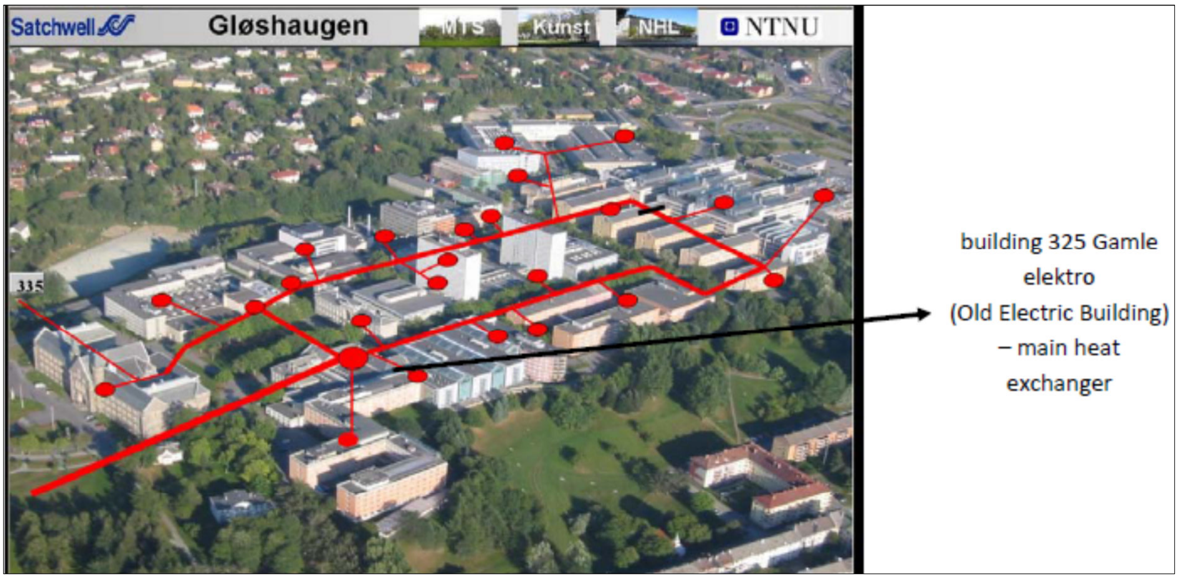
[8] Source: Google maps



building 325 Gamle elektro (Old Electric Building) – main heat exchanger

Figure 10 - District heating network

For the purpose of design of power plant, peak values of heat and electricity were used. The data from 2011 show that the maximum heat demand was about 14MW and maximum electricity demand was at 11MW. The figure below shows the heat and electricity load of the campus through 2011. It can be seen that the peak values, especially for the heat, significantly deviate from the average load. One of the solutions that should be taken into consideration is designing a smaller scale plant, and then using additional energy sources to satisfy the peak load. However, this work is focused on the worst case scenario and the maximum load of the plant so this idea will be in the list of possibilities for the future work.

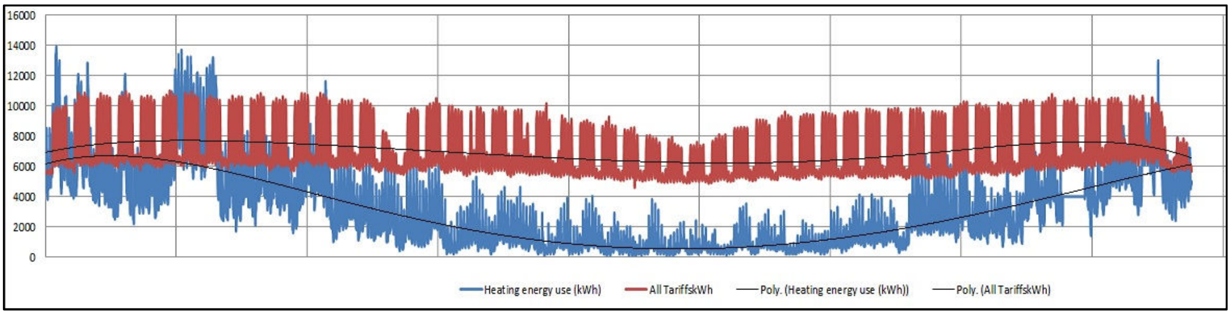


Figure 11- heat and electricity demands for the Gløshaugen campus in 2011

CHP design

PRO/II process simulation software was used for designing this plant. It is the software designed to perform heat and material balance calculations for a wide range of chemical processes. In this case, the software was used to design plant parts and simulate its work.

Total output power of around 25MW puts this plant in a medium size CHP. For this purpose, chosen design of the plant is CHP with Rankine steam cycle and back pressure turbine and reheating and double expansion. High power to heat ratio requires high energy stream for the heating needs, so the backpressure turbine was the logical solution.

The first step in the sequence leading to the construction of a power plant and its use is the conception of a process. The concept of a process is embodied in the form of a "flowsheet". The following picture is extracted from the process simulation software and represents the design of the plant. In further text, when explaining the process, next to descriptive name of all of the components will be the name of the component in the flowsheet in brackets.

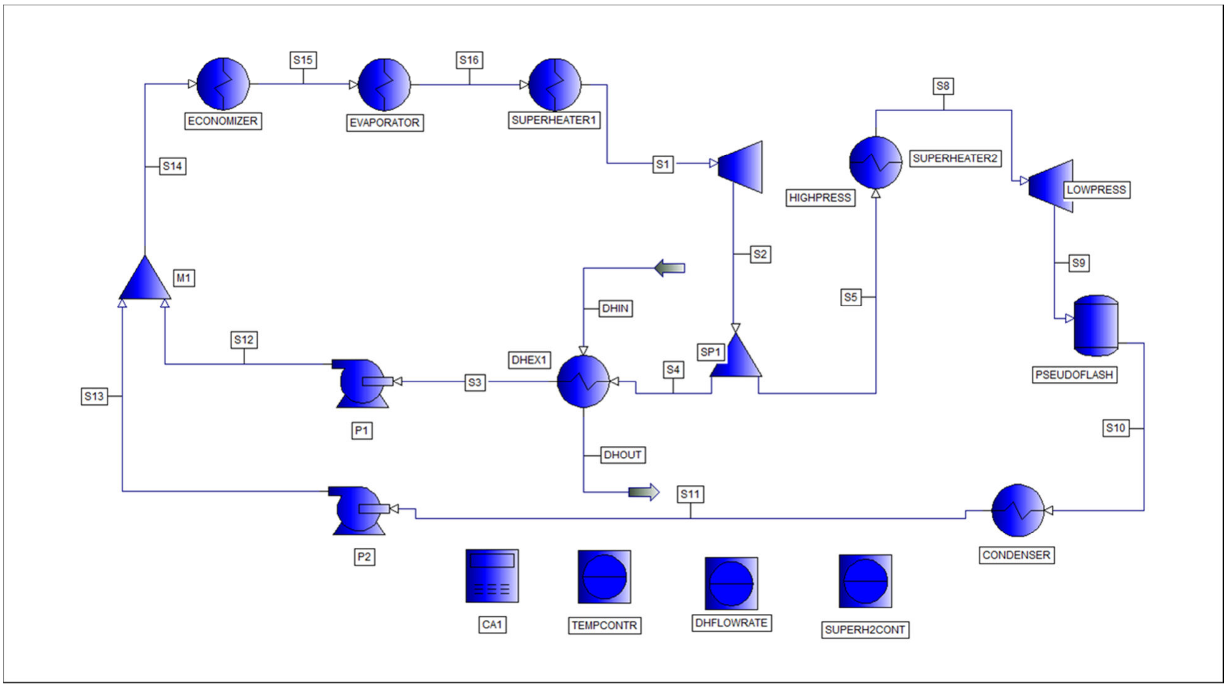
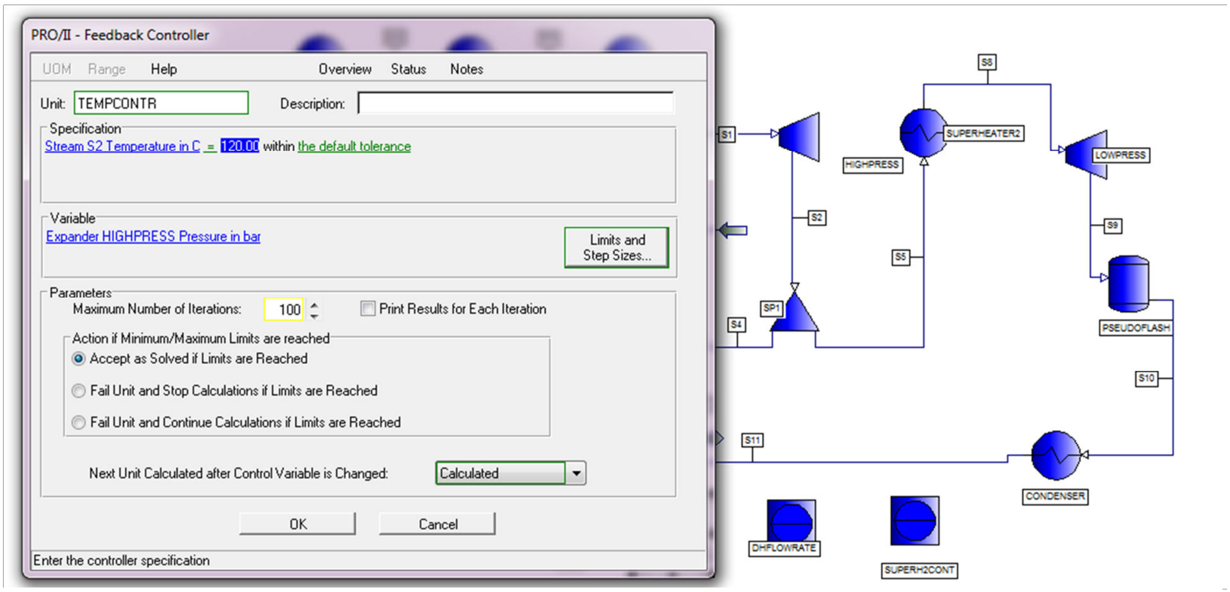


Figure 12 - CHP flowsheet

The starting point for design of the plant was satisfying district heating demands. Based on the recommendation that in order to avoid corrosion, water temperature of return line should be higher than 70 ºC, and that the temperature drop should not exceed 45 ºC [13], temperatures of return line and discharge temperature of hot water are chosen to be 75 ºC and 115 ºC respectively.



Unit: TEMPCONTR

Description:

Specification

Stream S2 Temperature in C = 120.00 within the default tolerance

Variable

Expander HIGHPRESS Pressure in bar

Parameters

Maximum Number of Iterations: 100

☐ Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached

● Accept as Solved if Limits are Reached

○ Fail Unit and Stop Calculations if Limits are Reached

○ Fail Unit and Continue Calculations if Limits are Reached

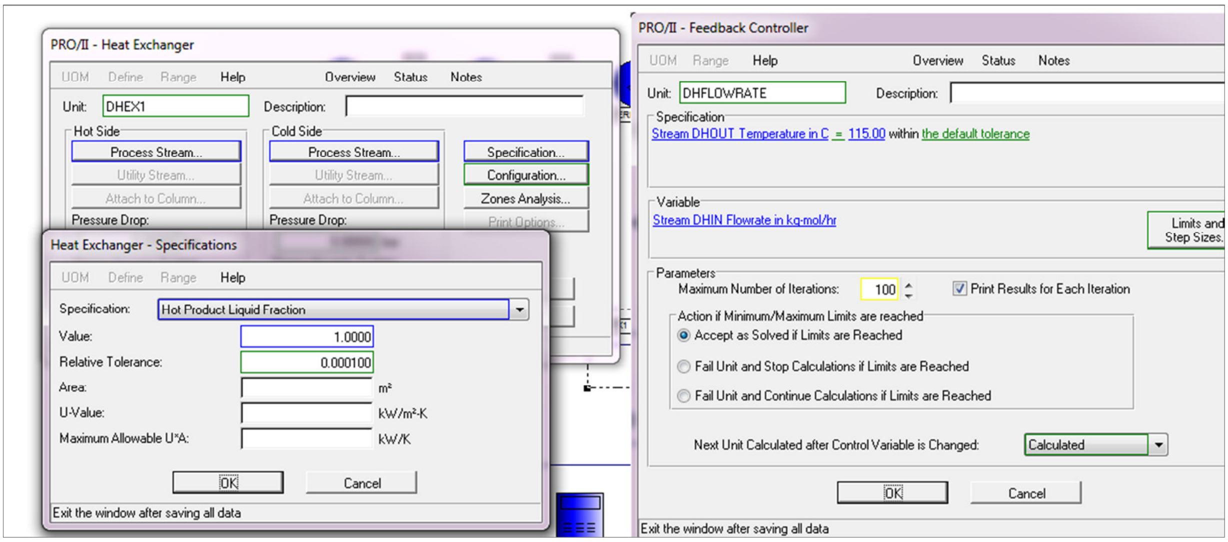
Next Unit Calculated after Control Variable is Changed: Calculated

Enter the controller specification

Figure 13 – High pressure expander control

Hot side of heat exchanger (DHEX1) made for heating up the district heating return line is the steam from the high pressure expander (HIGHPRESS). The expander is set to stop its expansion when the temperature of the steam reaches 120 ºC, so it would be high enough to transfer the heat to the district heating water stream. It is regulated by the controller named TEMPCONTR. It changes the high pressure expander outlet pressure and when the outlet temperature reaches 120 ºC, controller stops the expansion.

Heat exchanger (DHEX1) is chosen to have counter-current flow and it is set to change the phase from vapour in inlet stream to liquid in outlet stream. Phase change has the highest heating potential and the water in liquid state can be pressurised to the high pressure turbine inlet pressure. At the same time, the flowrate of district heating line (cold side of heat exchanger) has variable flowrate which is controlled by the controller DHFLOWRATE until it reaches the outlet temperature of 115 ºC. Flowrate of the heat exchanger DHEX1 hot side inlet stream is calculated manually and controlled at the splitter. The programme settings are shown in the picture below.



PRO/II - Heat Exchanger

Unit: DHEX1

Description:

Hot Side

Pressure Drop:

Cold Side

Pressure Drop:

Heat Exchanger - Specifications

Specification: Hot Product Liquid Fraction

Value: 1.0000

Relative Tolerance: 0.000100

Area: m²

U-Value: kW/m²-K

Maximum Allowable U*A: kW/K

Exit the window after saving all data

PRO/II - Feedback Controller

Unit: DHFLOWRATE

Description:

Specification

Stream DHOUT Temperature in C = 115.00 within the default tolerance

Variable

Stream DHIN Flowrate in kg-mol/hr

Parameters

Maximum Number of Iterations: 100

☑ Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached

● Accept as Solved if Limits are Reached

○ Fail Unit and Stop Calculations if Limits are Reached

○ Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed: Calculated

Exit the window after saving all data

Figure 14 - District heating heat exchanger control

Expander adiabatic efficiency is set to 80% for the high pressure turbine and to 70% for the low pressure turbine as suggested by the ICF International [14] based on the expander output power.

Stream that comes out from the high pressure turbine is split into two streams which go to a district heating heat exchanger and a low pressure expander. Splitter which is used for this operation can regulate the distribution of flowrate between these two streams, and it is the main tool for changing heat to power ratio of the plant. In the initial design, the splitter was set to maintain the ratio of flowrates of the district heating and second level expansion streams at 0,48 in order to maintain the heat to power ratio of the plant at 1,24 (14 MW of heat demand and 11 MW of electricity demand). Since electricity can be distributed through network to other users outside of the campus area, this can be one of solutions for dealing with partial load of the plant. In other words, if the heat demand is lower than 14 MW, stream energy can be redirected to electricity production and vice versa. Power-to-heat ratio is also affecting overall efficiency of the plant. The following illustrative curves display how the overall efficiency might change under alternate power-to-heat ratios for a separate power and heat production system and a CHP system (for illustrative purposes, the CHP system is assumed to use 5 percent less fuel than its separate heat and power plant with the same level of electrical and thermal output). It is assumed that the electric generation is 40% efficient, and the heat generation is 80% efficient [3].

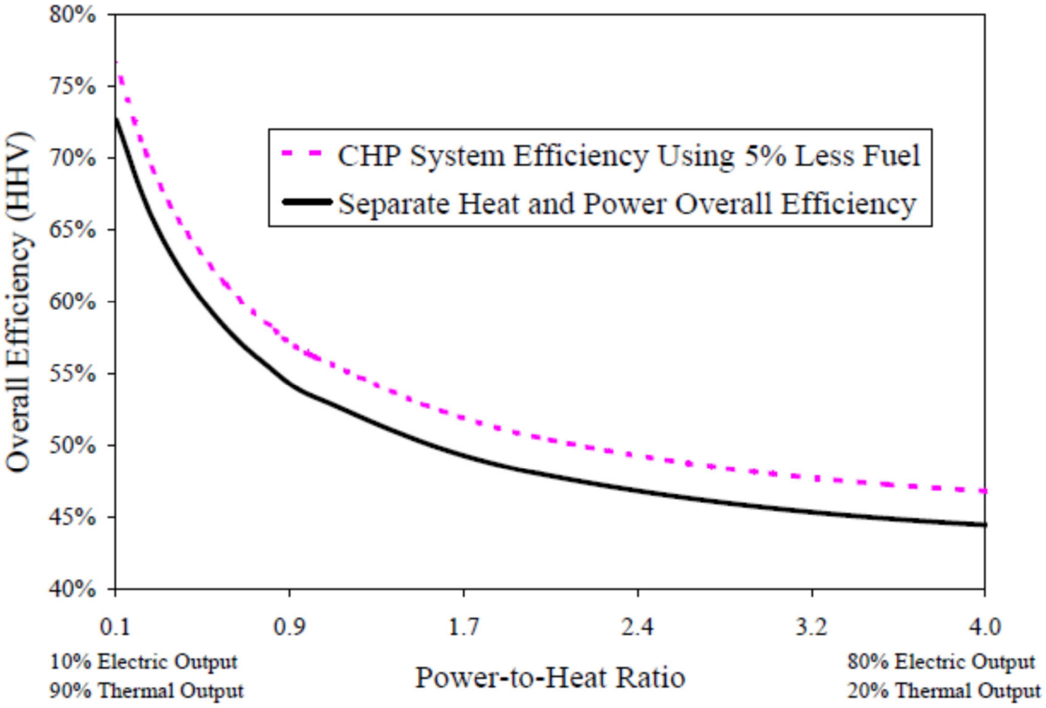
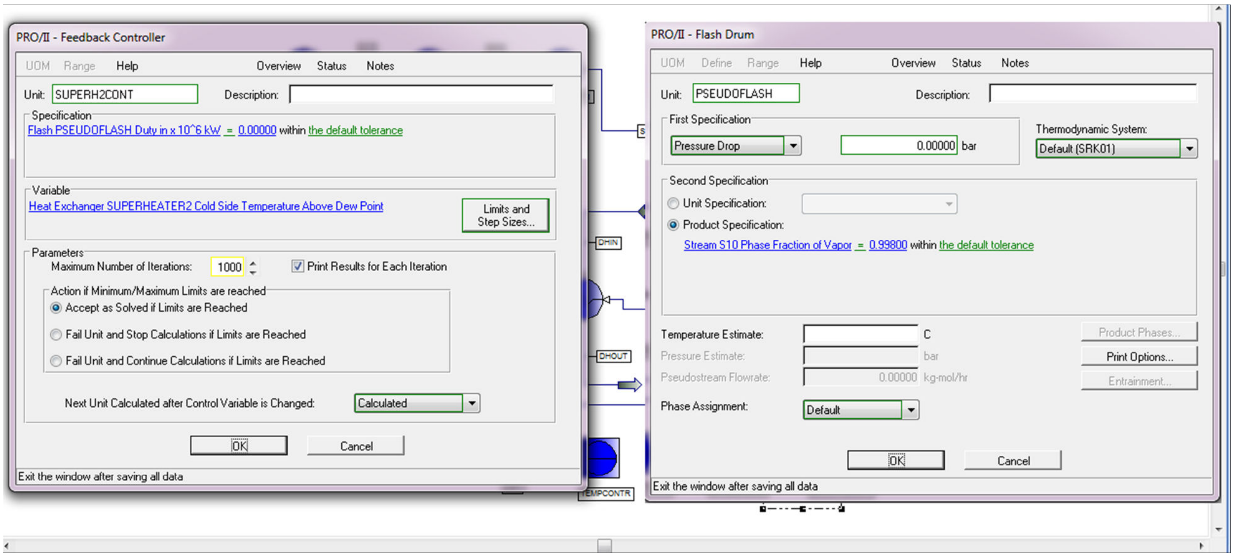


Figure 15 - Equivalent Separate Heat and Power Efficiency

After splitting the outlet high pressure expander stream, one part of it is expanded again in the low pressure expander (LOWPRESS). In order to use the heat of the steam in the most efficient way, it is reheated in the heat exchanger named SUPERHEATERII (as stated above, high pressure outlet temperature is set to be 120 ºC), and expanded all the way to the saturated vapour line. To achieve this in the process simulation environment, pseudo flesh and controller were added in the loop. Pseudo flesh (in the flowsheet named PSEUDOFLESH) is installed after the low pressure expander, and it is set to have no pressure drop so it does not affect the flow. Also, fraction of vapour in the outlet stream is set at 99,8%. This condition guaranties that the end of expansion process is at the saturated vapour line. SUPERHEATERII outlet temperature is controlled using a controlling unit named SUPERH2CONTR. It automatically adjusts outlet temperature using the condition that pseudo flesh duty is equal to 0. It means that there is no heat exchange in the pseudo flesh so it does not affect heat balance. SUPERH2CONTR makes closed loop between SUPERHEATERII, and low pressure expander, using pseudo flesh as a measuring point. The software makes iterations until those conditions are satisfied or until it reaches maximum number of iterations. The number of iterations in this case is set to 1000, as the default number of iterations which was set to 10 was not enough for the software to solve the problem.



PRO/II - Feedback Controller

Unit: SUPERH2CONT

Description:

Specification

Flash PSEUDOFLASH Duty in x 10^6 kW = 0.00000 within the default tolerance

Variable

Heat Exchanger SUPERHEATER2 Cold Side Temperature Above Dew Point

Parameters

Maximum Number of Iterations: 1000

☑ Print Results for Each Iteration

Action if Minimum/Maximum Limits are reached

● Accept as Solved if Limits are Reached

○ Fail Unit and Stop Calculations if Limits are Reached

○ Fail Unit and Continue Calculations if Limits are Reached

Next Unit Calculated after Control Variable is Changed: Calculated

Exit the window after saving all data

PRO/II - Flash Drum

Unit: PSEUDOFLASH

Description:

First Specification

Pressure Drop 0.00000 bar

Thermodynamic System: Default (SRK01)

Second Specification

○ Unit Specification:

● Product Specification:

Stream S10 Phase Fraction of Vapor = 0.99800 within the default tolerance

Temperature Estimate: C

Pressure Estimate: bar

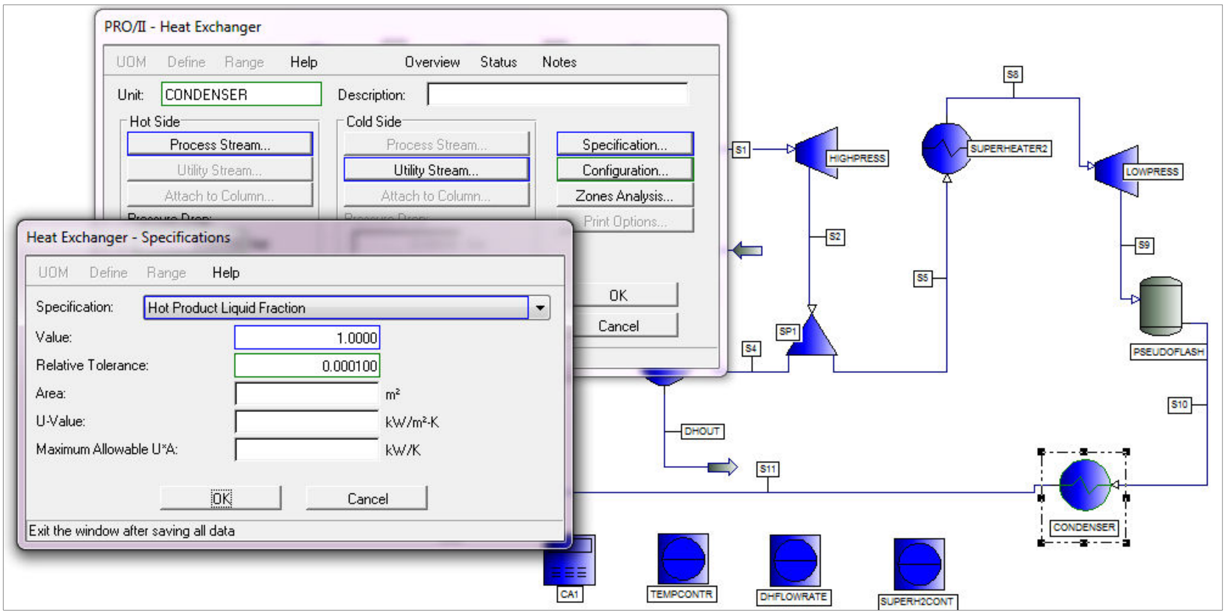
Pseudostream Flowrate: 0.00000 kg-mol/hr

Phase Assignment: Default

Exit the window after saving all data

Figure 16 - Superheater 2 Control

After second level expansion in low pressure expander, the outline stream goes to condenser (CONDENSER). It takes away the heat from the steam until all become liquid. It is achieved by setting the hot product liquid fraction of condenser to 100% as shown in the picture below.



PRO/II - Heat Exchanger

Unit: CONDENSER

Description:

Heat Exchanger - Specifications

Specification: Hot Product Liquid Fraction

Value: 1.0000

Relative Tolerance: 0.000100

Area: m²

U-Value: kW/m²-K

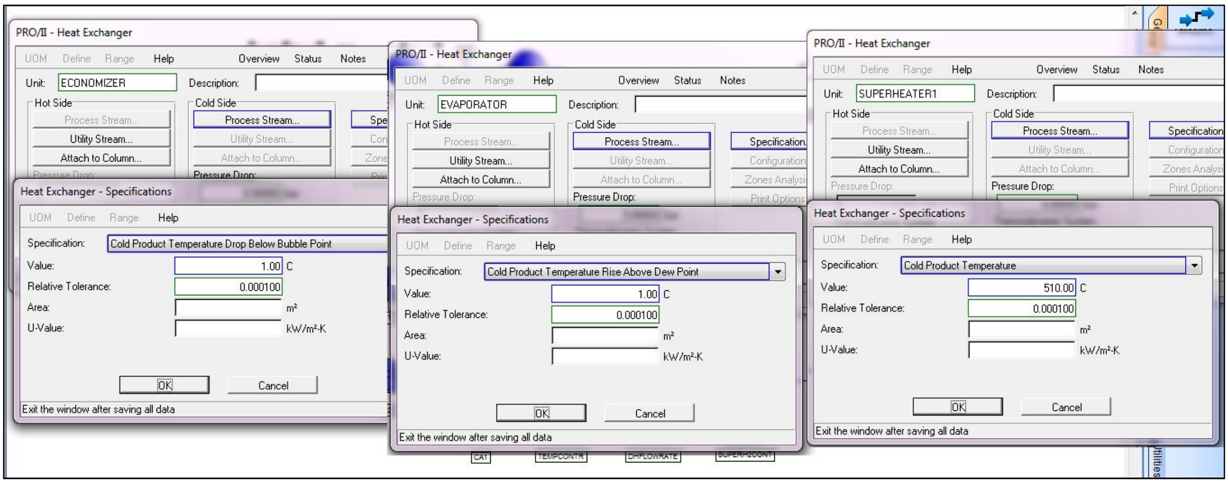
Maximum Allowable U*A: kW/K

Exit the window after saving all data

Figure 17 - Condenser Settings

After condensing the steam that comes out of the low pressure expander (LOWPRESS) in the condenser, and the steam that is used for district heating in district heating heat exchanger, those two streams in liquid state go to pumps (P1 and P2) where the water is pressurized to 60 bar pressure, as suggested by Sha Sha and Markku Hurme [15] for the similar biomass powered CHP.

Economizer, evaporator and superheaters (SUPERHEATER1 and SUPERHEATER2) are set to have only cold product side as they represent steam boiler. Economizer is set to reach bubble point, evaporator is set to finish bubbling and change phase to vapour, and the superheater (SUPERHEATER1) is heating steam to 510 ºC [15]. Settings for those three heat exchangers are shown below.


PRO/II - Heat Exchanger
Unit: ECONOMIZER
Heat Exchanger - Specifications
Specification: Cold Product Temperature Drop Below Bubble Point
Value: 1.00 C
Relative Tolerance: 0.000100
Area: m²
U-Value: kW/m²-K
Exit the window after saving all data

PRO/II - Heat Exchanger
Unit: EVAPORATOR
Heat Exchanger - Specifications
Specification: Cold Product Temperature Rise Above Dew Point
Value: 1.00 C
Relative Tolerance: 0.000100
Area: m²
U-Value: kW/m²-K
Exit the window after saving all data

PRO/II - Heat Exchanger
Unit: SUPERHEATER1
Heat Exchanger - Specifications
Specification: Cold Product Temperature
Value: 510.00 C
Relative Tolerance: 0.000100
Area: m²
U-Value: kW/m²-K
Exit the window after saving all data

Figure 18- Steam boiler settings

By defining these three heat exchangers, the heat and electricity production loop is closed. All it's left to define is mass flowrate of the steam, which was done by a method of trial and error. Mass flowrate was manually changed until the plant was giving satisfying output power. At the end, steam mass flowrate is calculated to be 46200 kg/h.

Next graph shows the process in T-S diagram which also enables reading values of enthalpy and pressure. Number 1 to number 2 is expanding in the high pressure turbine (HIGHPRESS). At number two, stream is split in two. One part goes to district heating heat exchanger (DHEX1) where it is condensed and that is the process from 2 to 5, while the other part is reheated in the second superheater (SUPERHEATER2), then expanded through the low pressure turbine (LOWPRESS) and then condensed in the condenser (CONDENSER) in processes 3 and 4. Those two part of streams are mixed again at number 5 after pressurizing in pumps (P1 and P2), after which they are heated in a steam boiler (ECONOMISER, EVAPORATOR, SUPERHEATER1) all the way to number 1 again.

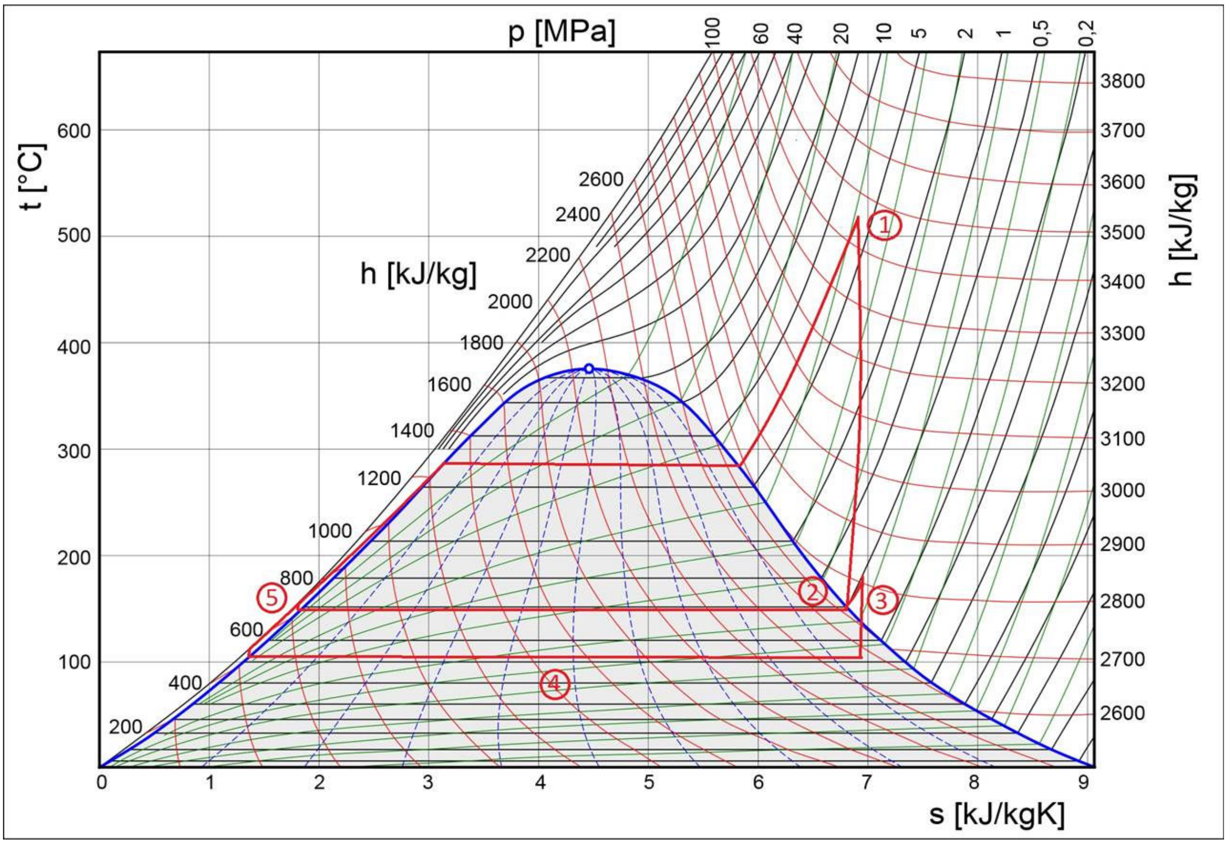


Figure 19 - Thermodynamic cycle of CHP

Calculation methods

As the main goal of designing a CHP was to find the input power to achieve heat and electricity demands, material and energy balance calculations in PROII software package were reliable enough for the further work. As stated above, one of possible sources of error is the Soave–Redlich–Kwong calculation method which is default calculation method in PRO/II. It is because the PRO/II software package is designed for process industry and this method gives very good results when used in petroleum industry. When used for the calculation of steam cycles, this method gives satisfying results, but in order to minimize possible errors, this method was modified using IAPWS – IF97 tables.

In 1997 the International Association for the Properties of Water and Steam (IAPWS) released the “IAPWS Industrial Formulation for the Thermodynamic Properties of Water and Steam (IAPWS-IF97)”. It replaced the industrial standard IFC-67, which had been valid until 1967.

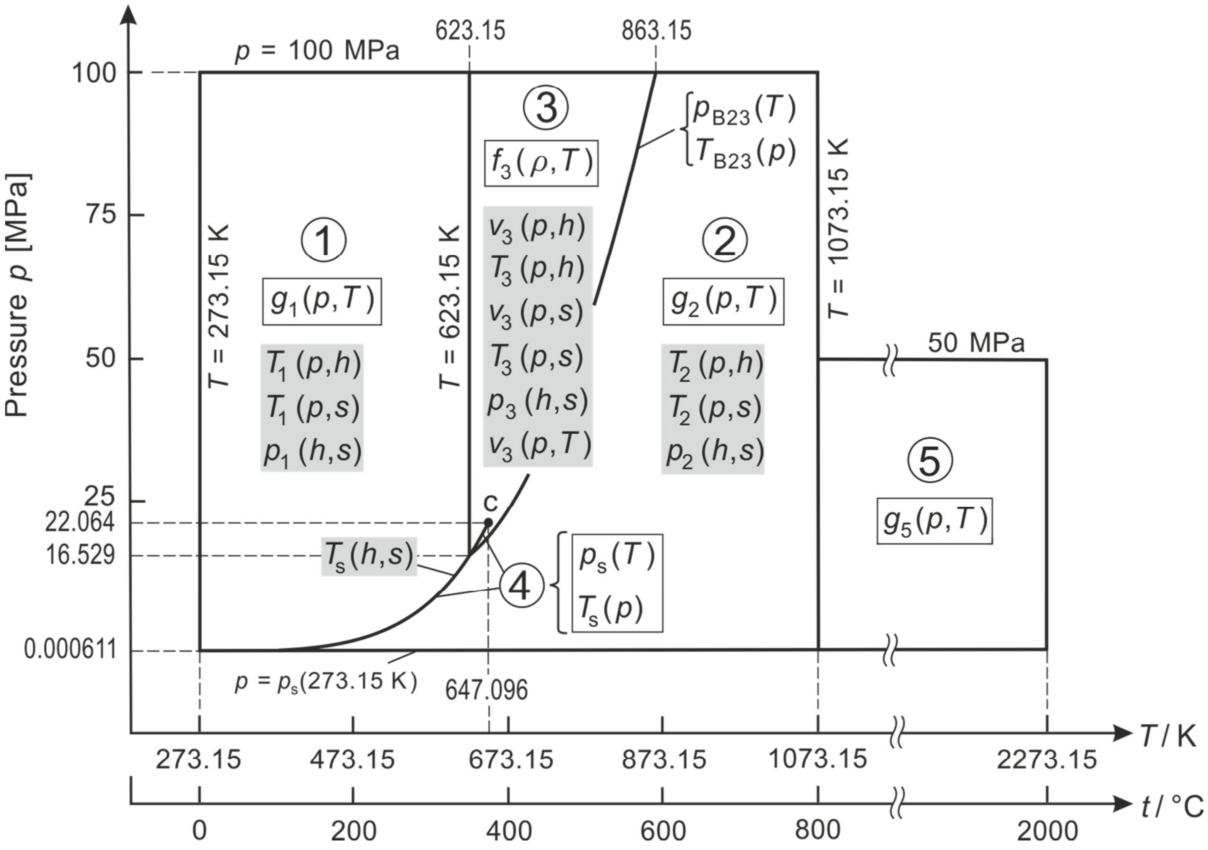


Figure 20 - Structure and regions of IAPWS-IF97

The IAPWS – IF97 consists of a set of equations for different regions, which cover the following range of validity:

$0\ °C \le t \le 800\ °C,\ p \le 1000$ bar

$800\ °C < t \le 2000\ °C,\ p \le 100$ bar

The *figure 9* shows the five regions into which range of validity of IAPWS – IF97 is divided. All the boundaries of the regions can be directly taken from the figure except for the boundary between regions 2 and 3. This boundary corresponds approximately to the isentropic line $s = 5.047$ kJ kg^{-1} K^{-1}, and is defined by a corresponding auxiliary equation. Fundamental equation for the specific Gibbs free energy $g(p,T)$ is used for the regions 1 and 2, region 3 is covered by a fundamental equation for the specific Helmholtz free energy $f(\rho,T)$, and the region 4, corresponding to the saturation curve, is covered by a saturation-pressure equation $p_S(T)$. Region 5, which is high-temperature region, is also covered by a $g(p,T)$ equation. These five equations which are shown in rectangular boxes in the *figure 9* are so-called basic equations.

The use of modified Soave–Redlich–Kwong equations in PRO/II is done by changing the input settings of thermodynamic data. When the modification is done, software is using Soave–Redlich–Kwong equations for calculation, but it also uses IAPWS – IF97 tables to correct the results.

Analysis of results

When all the components are connected and all the parameters defined, system simulation can be done. If calculation for all the components is performed and equations are solved, they turn blue. Otherwise they turn red which means that either some parameter remained undefined, or there is a problem with connections or number of iterations. Program then generates the report which can be active (it changes if some parameters are changed and simulation is ran) or in excel file form.

Additional component on the flowchart which helps the analysis of results is the calculator. Calculator can solve equations which connect different component's simulation results. In this case, calculator is used for finding the input energy and for calculating overall efficiency. As the analysis of combustion and calculation of the boiler was not done, boiler efficiency is taken from the references and incorporated in calculator equations. Depending on biomass type, boiler size and other construction parameters, the efficiency of biomass boilers is in the range between 0,87 and 0,92. For this calculation, the efficiency coefficient of the boiler was set to 0,9. The results are presented in a generic report.

Table 3 - expanders

Expander (Summary)	UOM	HIGHPRESS	LOWPRESS
Name		HIGHPRESS	LOWPRESS
Feed Streams		S1	S8
Product Streams		S2	S9
Product Stream Phases			
S9		N/A	Mixed
S2		Vapor	N/A
Outlet Temperature	C	119,9681234	45,8075482
Outlet Pressure	bar	1,158024135	0,1
Pressure Drop	bar	58,84197586	1,058024135
Adiabatic Efficiency (%)		80	70
Work - Actual	kW	9391,381627	1803,54213

In the *Table 1*, results of expander calculations are presented. The most important result is the actual work of the expanders which is the mechanical work of the turbine shaft. It slightly goes over 11MW when summed up for both of the expanders (11,195 MW), but there is a generator efficiency which is around 98 % which has not been calculated. High pressure expander has much higher pressure drop, and that is why it produces much more energy. It also has higher adiabatic efficiency as suggested by ICF International [14].

Table 4- pumps

Pump (Summary)	UOM	P1	P2
Name		P1	P2
Description		P1	P2
Thermodynamic System		SRK01	SRK01
Feed Streams		S3	S11
Product Streams		S12	S13
Product Stream Phases			
S13		N/A	Water
S12		Water	N/A
Outlet Pressure	bar	60	60
Pressure Rise	bar	58,84197586	59,9
Work	kW	54,18521664	57,69025319
Head	m	628,3072431	617,4923632
Efficiency %		70	70
Outlet Temperature	C	104,8102516	46,6302376

The table above shows calculation of the pumps that are pressurising the water before it goes to steam boiler. They pressurise water to 60 bar pressure, as it is the working pressure in the boiler. Their adiabatic efficiency is 70 %, and the power they use to achieve the needed pressure is more than 110 KW in total. One interesting result that is calculated and shown here is the head of the pump which is the maximum height to which water could be pumped.

Table 5 - heat exhangers

Hx (Summary)	UOM	CONDENSER	DHEX1
HX Name		CONDENSER	DHEX1
Hot Side Thermo Method		SRK01	SRK01
Cold Side Thermo Method		SRK01	SRK01
Hot Side Feed Stream(s)		S10	S4
Hot Side Product Stream(s)		S11	S3
Cold Side Feed Stream(s)		N/A	DHIN
Cold Side Product Stream(s)		N/A	DHOUT
Duty	KW	15931,091	14044,284
LMTD	C	32,55194891	13,55178639
U*A	kW/K	489,405146	10363419,49
Hot Product Temperature	C	45,8075482	103,7595007
Hot Product Liquid Fraction	fraction	1	1
Cold Product Temperature	C	45,8075482	114,9973615
Cold Product Liquid Fraction	fraction	N/A	1

This table shows calculation results for the district heating heat exchanger (DHEX1) and for the condenser (CONDENSER). It can be seen that district heating receives a bit more than 14 MW of heat, and almost 16 MW of heat power is wasted in the condenser. By the 2nd law of thermodynamics, this is an inevitable loss, and it cannot be used in process anyhow because of the low temperature. However, there are some ways to use at least some parts of this heat, for example, in green houses.

Software is able to calculate some parameters of heat exchanger such as LMTD. LMTD stands for Log Mean Temperature Difference, and it is used to determine the temperature driving force for heat transfer in heat exchangers. Mathematically, it is a logarithmic average of the temperature difference between the hot and cold streams at each end of the exchanger. The larger the LMTD, the more heat is transferred.

$$LMTD = \frac{\Delta T_A - \Delta T_B}{\ln(\frac{\Delta T_A}{\Delta T_B})}$$

Where ΔT_A is the temperature difference of a cold and hot stream at the end A of the heat exchanger, and ΔT_B is the same difference at the other end of a heat exchanger called end B. With this definition, it is possible to calculate heat exchanger duty using the following formulae:

$$Q = U * A * LMTD$$

Where Q is the exchanged heat duty, U is a heat transfer coefficient, and A is the exchanger area. Since there was no heat exchanger area defined, software was only able to calculate $U*A$.

Next table shows the calculation results for the heat exchangers that represent steam boiler.

Table 6 - steam boiler

Hx (Summary)	UOM	ECONOMIZER	EVAPORATOR	SUPERHEATER1	SUPERHEATER2
HX Name		ECONOMIZER	EVAPORATOR	SUPERHEATER1	SUPERHEATER2
Hot Side Thermo Method		SRK01	SRK01	SRK01	SRK01
Cold Side Thermo Method		SRK01	SRK01	SRK01	SRK01
Cold Side Feed Stream(s)		S14	S15	S16	S5
Cold Side Product Stream(s)		S15	S16	S1	S8
Product Stream Phases					
S8		N/A	N/A	N/A	Vapor
S1		N/A	N/A	Vapor	N/A
S16		N/A	Vapor	N/A	N/A
S15		Water	N/A	N/A	N/A
Duty	KW	11438,16	20287,57	8435,42	454,02
Cold Product Temperature	C	274,5864108	276,5864108	510	153,759656
Cold Product Liquid Fraction	fraction	1	0	0	0

Economizer, evaporator and superheater are parts of every steam boiler. They heat water in different phases, and it can be seen in the table above. The overall duty of the boiler is **40615,12 KW**, which is the amount of heat that should be transferred to steam in order to get 11 MW of electrical and 14 MW of heat energy. Efficiency of the boiler is not calculated, but since it goes around 90 % for a boiler this size, that is the efficiency used for the calculation of the mass flow of fuel and for the overall efficiency of the plant. Those figures are obtained with the calculator, and the results are shown in the following table.

Table 7 - calculator results

Calculator (Summary)	UOM	CA1
Name		CA1
Results		
RESULT1 - overall boiler duty	KW	40615,1255
RESULT2 - overall efficiency	/	0,563070858

Overall efficiency of the boiler is higher than in a conventional thermal power plant, but still lower than a CHP plant can achieve. The reasons lay in high power-to-heat ratio as well as in the low temperature range because of biomass usage. More detailed design and partial load calculations would most likely increase the overall efficiency of the plant.

CHP energy demand

In the previous chapters, we have shown that a CHP plant sized for Gløshaugen campus heat and energy demands requires nearly 40, 5 MW input power. Annually, the plant requires around 350 000 MWh or 0, 35 TWh of fuel power. In petajules, the amount of fuel power for the plant is 1, 26 which is around 1% of Norway's bioenergy potential.

As defined in the scope of work, this specific CHP should be powered by biomass. Overview of Norway's biomass potentials shows that biomass from the forest sector has the highest energy potential of all. Although current production of bioenergy in Norway is at the lowest level of all the Nordic countries, this sector shows constant growth over time most of all thanks to government subsidies. [2] Forest fuel came as a choice, not only because forest sector has the highest bioenergy potential, but also because of the low price and available detailed study of forest fuel supply for Nord Trøndelang land which is the region north from Trondheim city [16].

Next table shows different biofuel heat value.[17] Having in mind the energy consumption of the plant, it is easy to calculate the fuel mass flow.

Table 8 - different biofuel heat value and fuel mass flow

Type of biofuel	Lower heating value (GJ/t)	Fuel mass flow (t/h)
Logging residues	8,30	17,32
Demolition wood	13,70	10,49
Forest industry residues	13,70	10,49
Bark	8,30	17,32
Briquettes	16,90	8,51
Pellets	17,30	8,31

It is obvious that higher the heating value of biofuel is, the mass flow of fuel is lower and therefore transportation and storage costs are lower. However, high energy fuels have higher cost per unit of energy which makes them non-competitive for the plants of this size.

As forest fuel is based on forest industry residues, it means that the most probable mass flow of fuel in the plant will be around 10,5 t/h. Taking in consideration that predominant tree species in this region is spruce which has energy content of 1900 kWh/m^3 with a moisture content of 30%, we come to a volume flow of fuel at about 21 m^3/h or 504 m^3/day. It is around 6,7 lorries of fuel per day[9], which makes quite big transportation and logistical challenge.

Economic analysis

Forest fuels are considered to be by-products of traditional forestry where tops and branches together with low quality trees are harvested at the same time with high quality wood. In addition the fuel resources also include hardwood and thinnings. In the model developed for economic analysis for forest fuel production in Nord Trøndelang land, biomass comprised of those four sources is harvested, collected, dried to uniform water content, chipped and transported to the specified terminal site [16].

Variables that determine costs of forestry production, and thus also the production of forest fuels have been divided into three groups: Technology, biology and geography. Technology includes harvesting technology, in-forest transportation, drying (storage), chipping technology, and road transportation technology. Biology variable represents variation of trees that are harvested, their transportation and energy calculation. The last one, geography, includes site specific characteristics such as terrain layout, distance to terminal site, etc.

Forest fuel cost is determined by marginal costs, or the additional costs to traditional forestry. Marginal costs are calculated for each of the production stages (harvesting, collecting, drying, chipping and transportation). Variables (technology, biology and geography) influence the biomass sources processing (residues, low quality trees, hardwood and thinnings), and thus influence marginal costs.

Price and availability are the final results that are calculated by this model. Price of the forest wood is given in NOK/kWh[10], and the market price for Nord Trøndelang is at about 0,105 NOK/kWh. Having this information, we can calculate operational costs of the plant, which are 100600 NOK/day or 12550 €/day which is compared to pellets (200 – 220 €/ton) [17] more than 3 times less.

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[9] It is calculated with standard lorry dimensions of 12x2,5x2,5 (LxWxH)

[10] NOK – Norwegian crown, national currency of Norway, 1€ is approximately 8 NOK

Availability analysis

Trondheim city is an administrative centre of Trøndelag region, which consist of Sør Trøndelag and Nord Trøndelag, two countries of approximately same size. As it can be seen on the map bellow, Trondheim city lies on the border between two countries. This region, like the rest of Norway, does not have a well developed road infrastructure which may cause problems in biomass transportation. However, available boat transportation can compensate land transportation faults.

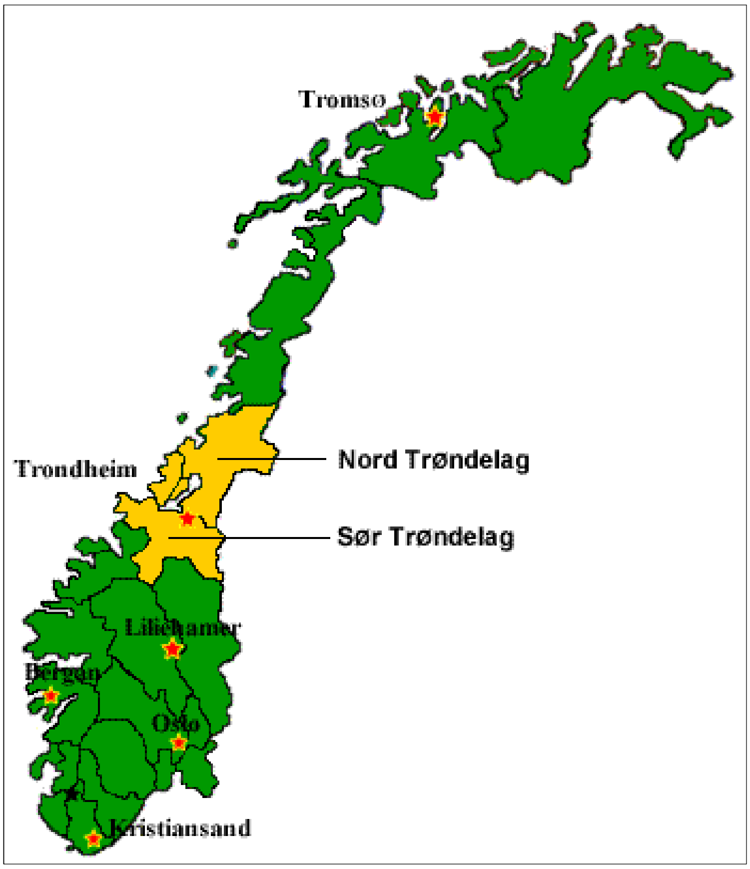

Figure 21 - Trøndelag region

Nord Trøndelag country has close to 0,5 TWh of total annual amount of forest fuel with current rate of traditional forestry. If we assume that Sør Trøndelag country has the same annual amount of forest fuel, it makes almost 1 TWh of bioenergy only as forest fuel. Designed CHP plant has annual demands of 0,35 TWh which makes about one third of Trøndelag region forest fuel potential.

Having in mind that forest fuel is not exploited in this region and that amount projected is for the current forestry level which could be increased if the demand increase, we come to a conclusion that this project could be feasible, at least from the biomass supply side.

Concluding remarks

Climate change is the biggest challenge humanity has ever faced. Fossil fuel reserves are running out, and although our generation did not make decision to have fossil fuel based economy, we enjoyed all the benefits it brought. Our grandchildren will probably be unaware of fossil fuels, but they will definitely be aware of the consequences those left on the planet. Maybe we cannot stop climate change from happening, but it is our duty to give our best and to mitigate the consequences as much as possible.

Developing bioenergy systems and following technologies is one of the possible answers to the challenges we have been faced with. In the short term period it might look unprofitable, but the price we will pay if we give up on that could be much higher. Combined heat and power technology helps us increase energy efficiency and satisfy energy demands in the best possible way. Many governments have recognised the potential of biomass and especially CHP technologies and Norwegian government is one of them. Unfortunately, Norway is one of the world's largest oil producers, and even though environmental awareness in Norway is at the very high level, at this moment there is no economic interest to invest in this technology. One of the possible solutions for Norwegian government would be to invest in CHP technologies in developing countries with more biomass potential.

Future work

There are two significant issues with this specific CHP plant that have been mentioned before, and those are efficiency and partial load analysis. Although calculation for this work had a purpose to estimate input power, optimization of the process and its efficiency is something that needs to be improved.

As shown before, maximum load of the plant occurs in a very short period of time. This plant is designed and analysed to run at maximum load with the assumption that all the heat and electricity will be used. When it comes to electricity, the possible solution is that it can be distributed to public electricity distribution system. Heat load, from the other hand, especially when used in district heating varies a lot and it is technically challenging to distribute hot water to longer distances. One of the solutions mentioned before is changing power to heat ratio. Technical solution of this plant leaves that possibility open, but no additional analysis and influence of this change has not been done. The other solution is running the plant at the partial load. These two solutions should be carefully analysed and implemented in the economic feasibility study of this plant.

One of the aspects that have not been mentioned before is the environmental impact of this plant. It is very important issue, especially as this plant is supposed to operate in the urban environment. Using CHP plants, especially those running on biomass, is environmentally friendly if we consider greenhouse gases emissions, but the combustion of biomass generally produce huge amounts of ash and polluters in the exhaust gases. This is something that needs to be considered and analysed.

And finally, this work considered only one possible fuel and that is the forest residues. Although it is shown that this fuel is available and probably the most suitable for this plant, other fuels that can be even imported should be taken into consideration. One of the biomass feedstocks that were initially considered was algae biomass, but as the weather conditions in Norway are not convenient for growing algae, this idea was rejected. However, there is a possibility for importing this fuel, and that is something that can be considered.

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