

Rational bioenergy utilisation in energy systems and impacts on CO₂ emissions

Bertil Wahlund



Doctoral thesis

Department of Chemical Engineering and Technology
Energy Processes
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Contact information:
Royal Institute of Technology
Dept. of Chemical Engineering and Technology/Energy Processes
SE-100 44 Stockholm
Sweden

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This thesis is based in part on work conducted within the interdisciplinary graduate school Energy Systems. The national Energy Systems Programme aims at creating competence in solving complex energy problems by combining technical and social sciences. The research programme analyses processes for the conversion, transmission and utilisation of energy, combined together in order to fulfil specific needs.



The research groups that participate in the Energy Systems Programme are the Division of Solid State Physics at Uppsala University, the Division of Energy Systems at Linköping Institute of Technology, the Department of Technology and Social Change at Linköping University, the Department of Heat and Power Technology at Chalmers Institute of Technology in Göteborg as well as the Division of Energy Processes and the Department of Industrial Information and Control Systems at the Royal Institute of Technology in Stockholm.

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Bertil Wahlund

Dept. of Chemical Engineering and Technology/Energy Processes
Royal Institute of Technology, Stockholm, Sweden

Abstract

The increased concentration of greenhouse gases in the atmosphere, in particular CO₂, is changing the Earth's climate. According to the Kyoto protocol, where the international community agreed on binding emission targets, developed countries are committed to reduce their greenhouse gas emissions. The increased use of biomass in energy systems is an important strategy to reduce CO₂ emissions. The purpose of this thesis has been to analyse the opportunities for Sweden to further reduce CO₂ emissions in the energy system, by rationally utilising woody biomass energy.

The characteristics of current commercially operating biofuel-based CHP plants in Sweden are surveyed and systematically presented. A consistent and transparent comprehensive reference base for system comparisons is given. Furthermore, the fuel effectiveness and contribution to CO₂ reduction is calculated. The governmental subsidies of the CHP plants' investment, expressed as cost of specific CO₂ reduction, appears to be low.

The competitiveness of biomass-fuelled energy production in relation to fossil-based production with carbon capture is analysed, showing that the biomass-fuelled systems provide a competitive option, in terms of cost of electricity and efficiencies.

The remaining Swedish woody biofuel potential of at least 100 PJ/yr is principally available in regions with a biomass surplus. Transportation is therefore required to enable its utilisation in a further national and international market. Refining the biofuel feedstock to pellets, or even further refining to motor fuels (DME, methanol or ethanol) or power, could facilitate this transport. Different options for fuel refining are studied and compared. The entire fuel chain, from fuel feedstock to end users, is considered and CO₂ emissions are quantified. Substituting fuel pellets for coal appears to be the most cost-effective alternative and shows the largest CO₂ reduction per energy unit biofuel. Motor fuels appear more costly and give about half the CO₂ reduction. Transportation of the upgraded biofuel pellets is highly feasible from CO₂ emissions point of view and does not constitute a hindrance for further utilisation, i.e. the pellets can be transported over long distances efficiently with only limited emissions of CO₂.

Bioenergy utilisation has additional features for environmental improvement, apart from the CO₂ aspect. Waste heat from biofuel-based CHP can be cost-effectively used in conjunction with sewage treatment. The incoming sewage water to the nitrification process can be preheated with the waste heat, and thereby substantially enhance the nitrification and the reduction of ammonium nitrogen during the winter season.

Language: English

Keywords: CO₂ reduction, energy system, biofuel, CHP, refining, fuel pellets, ethanol, methanol, DME, fuel substitution, sewage water, nitrification.

List of appended papers

This thesis is based on the following papers, referred to by Roman numerals I-VI.

- I Comparative assessment of biofuel-based combined heat and power generation plants in Sweden**
Wahlund B, Yan J, Westermark M.
In Proceedings of 1st World Conference on Biomass for Energy and Industry, Volume II, p 1852-1855, Seville, Spain, 2000.
- II Comparisons of CO₂ reducing alternatives for heat and power generation: CO₂ capture and fuel shift to biomass**
Wahlund B, Yan J, Westermark M.
In Proceedings of GHGT-5, The Fifth International Conference on Greenhouse Gas Control Technologies, p 229-234, Cairns, Australia, 2000.
- III Värmning av avloppsvatten med spillvärme för att förbättra kvävereningen – En förstudie**
Wahlund B, Westermark M.
Elforsk rapport 00:32, November, 2000
- IV Exergy analysis of a tri-generations plant: A case study of the existing plant in Skellefteå**
Minciuc E, Wahlund B, Yan J.
In Proceedings of ECOS 2002, 15th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Aspects of Energy Systems, Volume II, p 917-925, Berlin, Germany, 2002.
- V A total energy system of fuel upgrading by drying biomass feedstock for cogeneration: A case study of Skellefteå bioenergy combine**
Wahlund B, Yan J, Westermark M.
Biomass and Bioenergy, 23(4), 2002, p 271-281.
- VI Increasing biomass utilisation in regional energy systems: A comparative study of CO₂ reduction and cost for different bioenergy processing options**
Wahlund B, Yan J, Westermark M.
Manuscript submitted for publication, 2002.

The papers are appended at the end of the thesis.

Related publications not included in this thesis

**Study of total energy system of fuel upgrading by drying biomass
feedstock for combined heat and power production: A case study of
Skellefteå bioenergy combine**

Wahlund B, Yan J, Westermark M.

In Proceedings of World Clean Air & Environment Congress
(IUAPPA01), Seoul, Korea, 2001.

**Efficient and Flexible Utilization of Renewable Biomass Energy and
its Environmental Aspects Part I: Status and Future of Biomass
Based Power and Heat Generation**

Wahlund B, Yan J.

China International Environment, Renewables and Energy Efficiency
Exhibition and Conference, CERE 2000, Beijing, China, 2000.

**Energi- och exergiflödeskartläggning över Borlänge kommuns
energisystem**

Wahlund B.

In P. Gyberg, J. Palm, J. Sjödin och B. Wahlund, "Borlänges energisystem
– påverkan och förändring", Program Energisystem, Report no 3, 1999.
(in Swedish)

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1 Thesis outline

This thesis consists of a summary built on six research papers and is laid out as follows:

Chapter 2 contains an introduction, familiarising the reader with the background of this work. Additionally, the scope of this work is presented.

Chapter 3 treats the methodologies used. Theoretical models which calculate CO₂ reductions and the cost of these reductions are presented. Furthermore, the general methodologies for the papers are summarised.

Chapter 4 examines biofuel-based combined heat and power from different aspects. The competitiveness of biofuel-based systems for CO₂ lean energy production¹ is also reviewed and compared to carbon capture with fossil-based systems. The material summarised is based on papers I & II.

Chapter 5 summarises an alternative way to enhance the environmental performance of biomass-fuelled CHP through the use of waste heat in a sewage treatment works for ammonium nitrogen removal. The material is based on paper III.

Chapter 6 presents the results of an energy combine that produces fuel pellets, which is based on paper IV & V. The energy combine's CO₂ implications and the possibilities to transport the pellets, as well as the exergy efficiency, are discussed.

Chapter 7 addresses how to further use biomass in the regional energy system with the goal to achieve the largest possible CO₂ reduction. Different options are studied and compared. The material is taken from Paper VI.

Chapter 8 summarises the conclusions found during the course of this thesis. Additionally, suggestions for further research are presented.

¹ The expression "energy production" is sometimes used in the thesis and refer to the production of energy products, such as heat, power, fuel pellets and motor fuels, that are consumed by a user, and does not mean any violation of the first law of thermodynamics.

2 Introduction

The increased concentration of greenhouse gases observed in the atmosphere, in particular carbon dioxide (CO₂), is changing the Earth's climate. Greenhouse gases reduce the efficiency of the Earth's surface radiation to space and thereby increases the Earth's temperature. It is evident that human activity in the modern industrialised world has contributed to this increase.

In 1992, the United Nations Framework Convention on Climate Change took an important step by putting climate change and the possibility of global warming firmly on the international political agenda. The next important step was taken in 1997 at the Conference of the Parties in Kyoto, where the international community agreed on binding emission targets in the so called Kyoto protocol. Countries included in Annex B of the Protocol (most OECD countries and countries with economies in transition) agreed to reduce their anthropogenic greenhouse gas emissions by at least 5 % below 1990 levels in the commitment period 2008 to 2012. Sweden is, despite this, allowed to increase its emissions of CO₂ by 4 % as a result of negotiations under the "burden sharing" agreement within EU. Recent analysis shows, however, that the global anthropogenic emissions is required to drop below 1990 levels within a few decades to stabilise the CO₂ concentration levels in the atmosphere (IPCC, 2001). Furthermore, Swedish emission figures indicate that Sweden will have to reduce its emissions eventually in order to reach the emission targets by 2012.

Most CO₂ emissions are energy related, which implies that the sustainable design of the energy systems is a crucial factor for emissions development. Two of the largest sources of CO₂ emission are power generation and transportation using fossil fuels. In many European countries, for example in Great Britain, Germany, Poland and The Netherlands, power generation is based on conventional thermal power, where coal is the main fuel (Swedish Energy Agency, SEA, 2000). The power sector contributes thereby substantially to the total CO₂ emissions. If the global reduction target is to be fulfilled, great reductions, through changes in the energy system to achieve CO₂ lean energy production, are necessary.

One way to move towards fulfilling the emission targets would be to use biofuels instead of fossil fuels. The purpose of this thesis is to analyse and identify the opportunities for Sweden to reduce CO₂ emissions in energy systems by the rational use of indigenous solid biofuel to supply energy.

2.1 Options for CO₂ mitigation

There are several options available for CO₂ mitigation, which can be grouped into three principle groups.

The first group consist of **CO₂ removal or capture** options, which are generally discussed for removing CO₂ from fossil systems. It can, however, also be applied on bioenergy systems, giving negative CO₂ emissions. The use of CO₂ capture results in an efficiency penalty and increased costs for the energy products. Furthermore, the removed CO₂ must be stored securely, which at present does not have any obvious solutions. The CO₂ capture options are further discussed in section 4.2.1.

The second group is **energy savings** or **efficiency improvement** in energy conversion, resulting in reduced fuel consumption, and thereby reduced CO₂ emissions.

Fuel shift, the third option, constitutes a promising option for large reductions. Switching from carbon-rich fuels, such as coal, to fuels with less CO₂ emissions per MJ of fuel reduces the CO₂ emissions. However, a more substantial reduction can be achieved if the carbon-rich fuel is shifted to CO₂-neutral fuels like biofuels. Switching from fossil fuels to renewable biomass fuel is accordingly a powerful way to reduce anthropogenic CO₂ emissions.

2.2 History, current state and future trends of solid biofuel utilisation in Sweden

Biofuels are fuels of biological origin. It is a diverse fuel and may be in many forms, such as wood and forestry residues, energy crops and industrial by-products (such as black liquor). If properly grown and managed, biomass does not contribute to climatic change through emissions of CO₂ to the atmosphere because it absorbs the same amount of carbon in growing as it releases when consumed as fuel, see Figure 1 for the carbon cycle of principle (Yan et al, 1997).

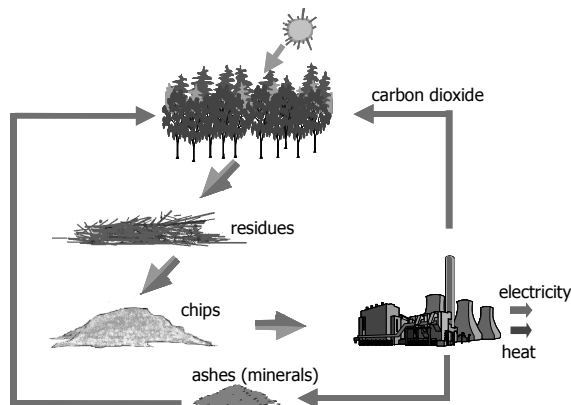


Figure 1. Biomass energy conversion and the carbon and mineral cycle (Yan et al, 1997).

In Sweden, the biomass share of the total energy supply has since 1970 increased from 8 % to the current level of 16 % (totally 342 PJ/yr², excluding peat), which is exceptionally high for industrialised countries (Hall, 1991). Despite the last decades of increase and the current high utilisation, Sweden has still a large wood fuel potential of at least 108 PJ annually, due to Sweden's unique biomass resources (Lönner et al, 1998; Ekström et al, 2002).

There are several reasons why biofuel utilisation has increased during the last decades. Two important reasons are the oil crisis in 1970s and today's climate change issue. The oil crisis led to the expansion of district heating networks and the erection of boilers for biofuels and other solid fuels in order to decrease national dependence on non-indigenous energy carriers like oil and hence increase the security of energy supply. Other reasons were trade and labour policies and measures to stimulate the production of domestic fuels. The early governmental incentives, luckily, were compatible with current taxes, subsidies and fees aimed at reducing CO₂ emissions by increasing the use of renewable energy.

The expansion of indigenous biofuels has been most pronounced in the district heating sector, where a dramatic increase took place from almost nothing in 1980 to 108 PJ/yr in 2001, see Figure 2. The increased amount of biofuels has greatly curbed oil and coal use, thereby reducing CO₂ emissions considerably. Not much oil and coal remains in the district heating sector to be substituted. With the assumption that these 108 PJ have substituted oil, the CO₂ reduction have amounted to 8200 Gg/yr, which is 15 % relative to 1990 total CO₂ emission in Sweden. An increase in the use of wood fuel, from only 1 PJ in 1980 to 67 PJ in 2001, represents the core of this expansion in biofuel utilisation. Additionally, biofuel use in the industry sector, mainly in the pulp industry, has also increased over the years. The district heating network has also been extended during the period of time. (SEA, 2002:c & d)

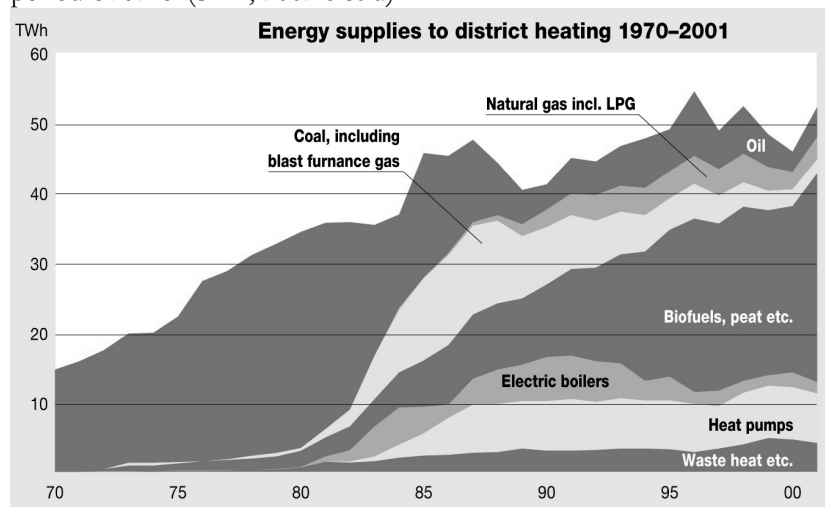


Figure 2. Use of biofuels, peat etc in district heating sector (SEA; 2002:c).

² Multiples of the SI unit J is used in the thesis, conversion factor 1 Wh = 3600 J.

In 1996, the dramatic increase of district heating and biofuel utilisation subsided. Most of the suitable and profitable fuel switches were already made and already large district heating networks were expanded to their profitable limits. Capacity limitations of district heating networks are therefore an obstacle for further expanding the energy efficient co-generation of heat and power (CHP). Hence, the potential for additional CHP is generally low in sparsely populated forestry regions with a surplus of biomass. For a further substantial expansion and to realise its potential, biofuel must find new markets and areas for utilisation. Thus, biofuel must be efficiently transported over long distances to regions with unsaturated markets, which is usually problematic with unrefined biofuels. Refined fuels are more suitable for long transportation and seasonal storage.

Nonetheless, a wide spectrum of measures is available to substitute fossil fuels with upgraded biofuel in the form of fuel pellets in areas where district heating is not possible. Pellets open up new possibilities and may provide for further biofuel implementation. Some 90 PJ electricity and 280 PJ oil is still used for heating in the residential and service sector and can partly be substituted (SEA, 2002:c). Most of it is small-scaled, however, and therefore difficult and probably not cost-effective for fuel conversion. It is reasonable to assume that is the reason why it has not taken place yet. Larger scale possibilities exist abroad, which probably give more cost-effective CO₂ reductions, mainly due to a lower capital cost of fuel conversion and longer operating hours. Moreover, it is also possible to produce biofuel-based motor fuels aimed at substituting some of the 290 PJ of petrol and diesel used in the transportation sector. The markets for bioenergy are thus greater than the supply. Therefore, we may choose the best options to utilise the biofuel, to attain the largest and cost-effective CO₂ reduction.

Hence, to further utilise Swedish biofuel rationally, the biofuel market should become increasingly international, necessitating processing (without generating large quantities of heat) and transportation to domestic and international markets for coal and oil substitutions. As the Swedish biofuel potential is small compared to European demand, globalisation would change a national surplus to an international deficit. More extensive fuel substitutions of coal with biofuel may be achieved in European countries like Germany, Poland, Great Britain and the Netherlands, than can be done in Sweden alone.

2.3 Scope of this work

In this thesis, some aspects of the possibility to develop a more sustainable Swedish energy system through an increased and efficient bioenergy utilisation (wood fuel) are analysed. The parts of the energy system studied includes the energy sector (power, heat also incl. motor fuels). The following central issues are hence addressed:

- The CO₂ benefits with an expansion of existing biofuel-based CHP
- The competitiveness of biomass-fuelled systems for CHP and power generation compared to fossil generation with carbon capture
- The CO₂ efficiency for upgrading biofuel to pellets
- Is transportation an obstacle for utilisation of Sweden's biofuel potential
- How should Sweden utilise its woody biofuel potential in a CO₂ and cost-effective way
- Can the utilisation of waste heat for ammonium nitrogen removal from municipal sewage water be a realistic option

2.4 Previous studies

Some previous studies have been carried out to evaluate the potential for CO₂ reductions in the Swedish energy system by utilising the surplus of biofuels. Studies which encompass the broad array of the available and relevant options for bioenergy conversion and utilisation, such as production of power, heat, fuel pellets, motor fuels or their combinations, are limited. A good example of such study is performed by Ekström et al (2002). This report extensively covers several technologies for biofuel utilisation, including for instance power production, a large number of possibilities for heating in residential, commercial and service sector and the production of biofuel-based motor fuels. It also includes bioenergy utilisation in the pulp and paper industry. With the reports assumption of domestic biofuel utilisation but an international power market, the results are in essence that the most cost-effective and largest CO₂ reduction may be attained if biofuel for heating substitutes coal-based power (assumed as marginal power production). This study concludes, furthermore, that the production of motor fuels for replacement of petrol and diesel give much higher cost of reduction and less reduction potential for CO₂ reduction. The assumption of domestic biofuel usage is limiting, however, and excludes the possibility of exporting refined biofuels for fossil-fuel substitution in other European countries.

Studies by Börjesson (1998) focussed on biomass cultivation and production, though in one study having a wide approach and investigating the possibility for biomass to substitute fossil fuels. Some of Börjesson's important findings in short are that the energy input, including transportation, per unit biomass produced is

about 4-5 % for forestry residues and that the resulting CO₂ emissions corresponds to 2-3 % of those from a complete coal fuel-cycle. Börjesson does not include the possibility of exporting the biofuels in any form either.

Most studies have been focussed on one type of energy production without having a wide system approach, e.g., motor fuels or one type of conversion technology, e.g., biomass-based CHP. Ahlvik and Brandberg (2001) is an excellent example of such a study. They have thoroughly and systematic studied several technologies for the production of motor fuels, but not included economic aspects or a cost analysis. Some of their findings are that dimethyl ether (DME) and methanol are identified as fuels that provide the best efficiency when produced both from natural gas and from biomass, provided that the best powertrains are used. Other examples of similar studies are Winell and Svedberg (1997) and Elam et al (1994).

Publications presenting the current situation and characteristics of Swedish biomass-fuelled CHP are lacking. Studies by Atterhem (2001:a) and Mazur (1997) discuss the new concept of the bioenergy combine for simultaneous production of fuel pellets, heat and power. Mazur presents an overview, including technical configurations and nominal data. The study by Atterhem is a more in-depth study, giving an extensive evaluation of the first years of operation. However, both lack a system approach and the neglect the bioenergy combine's impacts on the energy system, such as CO₂ emissions.

From previous studies, we could find that a systematic study with considerations of the whole chain of biomass conversion and utilisation from biomass feedstock to final users, is important to reveal the CO₂ reduction potential in all parts of the system and compare the results using a common method.

The topic carbon capture and sequestration is at present under constant investigation. There are several technologies under development, although much further work is required. In the longer term, the IPCC (2001:b) estimates that physical carbon removal and storage from fossil fuels and biomass, followed by sequestration, could potentially become viable options. Lindeberg (1999) analyses the possibilities to dispose CO₂ underground and concludes the most attractive option for storage is underground disposal in aquifers and exhausted oil and gas reservoirs. Examples of studies presenting and examining several options for carbon capture and disposal is Göttlicher and Pruschek (1997), Audus and Riemer (1994), Herzog and Vukmirovic (1999), Lindeberg (1999), David and Herzog (2000) and IPCC (1996 & 2001:a).

3 Methodology

In this chapter the general methodologies for each paper are summarised and presented briefly. Furthermore, the methods are also presented for estimating the CO₂ reductions and cost used in the majority of the papers. Other methodologies are presented in respective section or paper.

3.1 General methodologies for respective paper

Input data in the majority papers involves real operating data collected through inquiries at the respective station (paper I, II, III, IV & V). In paper II and V, the data is also collected from literature, while in paper VI, compiled data from literature is the major basis for the analysis. For compilations and calculations, excel spreadsheets were created in paper I, III, V & VI. In paper IV, Aspen Plus were used to simulate the process modifications. Interviews were conducted in paper V to identify non-technical factors influencing the realisation of the energy combine.

It is important to point out that data for all papers have been treated consistently. The input data from the reference sources are based on different assumptions and these inconsistencies have been considered. In paper VI, it is judged that in this kind of study the conclusions are robust and clear, and can therefore stand the possible uncertainties arising from such inconsistencies.

3.2 Model for estimation of CO₂ reduction

Central in this thesis is the method for estimating the CO₂ emission reduction associated with a process (method used in paper I, II, V and VI). When adding an energy product to the energy system, another is replaced. To calculate the CO₂ reduction achieved in the energy system when adding a renewable energy carrier, the following methods have been used, based on the current and future energy utilisation of Sweden:

- For the **electricity**, two different approaches, taking into account the time scale, have been used to quantify the reduction of CO₂ emissions achieved when electricity generated with biomass is added to the Nordic power grid. The first approach considers short-term effects, where coal-based power with an electrical efficiency of 38 % is the marginal production during the entire year (Bejgrowicz et al, 1999; SEA, 1998 and 2002:a). Ekström et al, (2002) considers that even if the power grid is regarded as partly closed with bottlenecks in the transmission between the Nordic countries and Northern Europe, coal power

on the margin may be true for a limited amount of electricity, approximately 36 PJ annually, if produced in Southern Sweden (due to national bottlenecks). The second approach considers long-term effects, where natural gas combined cycles (NGCCs) with an electrical efficiency of 60 % are assumed to constitute the production capacity of additional electricity to the Nordic grid (SEA, 2002:a).

- **District heating** (biomass based) replaces heat generated with oil in a district heating plant with an energy conversion efficiency of 90 %.
- **Refined motor fuels** (biomass-based methanol, DME and ethanol) replace fossil diesel oil, resulting in a 2 % increase in consumption as LHV compared to diesel (Ekström et al, 2002; Ahlvik and Brandberg, 1999).
- Produced **biofuel pellets** replaces coal with the ratio of 1:1, as LHV.

The indirect emissions for all energy carriers, mainly due to transportation and extraction, have also been taken into account. Table 1 shows the direct (i.e. combustion of the fuel itself) and indirect (i.e. mining, transport, etc) emission factors for the energy carriers included in this thesis. For further discussion regarding the estimated emissions, refer to paper VI. (Based on Uppenberg et al, 2001; SEA, 1998; Börjesson, 1996; Wahlund et al, 2002; Börjesson and Gustavsson, 1996; Ahlvik and Brandberg, 2001; Byman and Sjödin, 1999; Frank and Berntsson, 1999.)

Table 1. Direct and indirect CO₂ emission factors for different energy carriers.

Energy carrier	Direct emission kg CO ₂ /GJ	Indirect emission kg CO ₂ /GJ
Diesel	74	3.5
District heating, oil based ^a	84	6.6
Electricity, coal based ^b	239	8.4
Electricity, natural gas based ^c	93	7.2
Coal	91	3.2
Unrefined biofuel	0	2.9 ^d
Fuel pellets, biofuel based	0	1.2 ^e
Methanol, biofuel based	0	1.6 ^f
DME, biofuel based	0	1.6 ^f
Ethanol, biofuel based	0	1.2 ^f

^a Energy conversion efficiency 0.9, oil-fired boilers

^b Electrical efficiency 0.38, coal condensing power

^c Electrical efficiency 0.6, NGCC

^d For cutting, etc and transport by lorry of forestry residues 50 km

^e Lorry 15 km+boat 800 km, which is the distance from the bioenergy combine in Skellefteå to the Hässelby CHP plant

^f For domestically produced methanol 2 % and for ethanol 1.5 % of the fuels energy content is used in transportation. It assumed that the energy used for DME is equivalent to methanol.

3.3 Model for estimation of specific CO₂ reduction cost

The methods for calculating the cost per unit reduced CO₂ are presented in papers V and VI, and reviewed in this section. Two different approaches have been applied on two different cases.

The first approach, presented in paper V, is a simplified model that gives the local cost of fuel substitution for the Hässelby CHP plant when replacing coal with biomass fuel pellets. The second approach, explained in paper VI, gives a system cost of the replacement of fossil fuels. Identical for both approaches is that the fuel cost will increase when the fossil fuels are replaced by renewables (excl. taxes and fees).

In the first approach, the capital cost to retrofit the CHP plant to fire biomass, has been added to the increased fuel price. The capital cost has been annualised with an interest rate of 6 % and a pay back time of 15 years. With the emission factor of 91 kg CO₂/GJ_{fuel}, the increased cost has then been re-calculated and expressed as a corresponding CO₂ reduction cost in US\$/Mg avoided CO₂ (here, the indirect emissions were not considered as local costs were calculated).

The second approach makes it possible to deal with systems producing several renewable energy products as it takes into account the CO₂ reductions from all products as well as end use. It addresses the additional specific cost for CO₂ reduction when introducing a renewable energy carrier that replaces a fossil fuels. This cost is calculated as, starting with the increased cost for biofuel introduction:

$$\text{Increased cost} = \text{the prod cost renewable product} - \text{cost replaced fossil product} \quad (3-1)$$

The production cost for the main renewable energy product includes cost for distribution. The costs used in the calculations of replaced fossil energy carriers are presented in Table 2. The cost per specific reduced CO₂ can then, when the secondary products (by-products) are credited for, be calculated as following:

$$\frac{\text{US\$}}{\text{Mg CO}_2} = \frac{(\text{Increased cost}) \cdot \eta_{mp}}{R_{mp}^{CO_2} \cdot \eta_{mp} + R_2^{CO_2} \cdot \eta_2 + R_3^{CO_2} \cdot \eta_3 + \dots} \quad (3-2)$$

where R refers to the replaced energy carriers' total CO₂ emissions in kg/GJ according to Table 1, the subscript mp denotes the main product, 2 and 3 the secondary or by-products, respectively, and η is the efficiency (energy yield) corresponding to the specified product according to Table 8.

Table 2. Cost for fossil energy carriers.

Fossil energy carrier	Cost, US\$/GJ	Based on reference
Diesel	10.88 ^a	Preem, 2002
Electricity, coal based	9.65	Bärring et al, 2000
Electricity, natural gas based	8.04	Bärring et al, 2000
Coal	1.26 ^a	SEA, 2001

^a The price that the customer pays, including transportation cost but without taxes and any quantity discounts.

4 Biofuel-based combined heat and power generation

CO₂ emissions from power and heat generation will have to be greatly reduced to meet environmental constraints and agreed commitments. CO₂ lean energy production through the combustion of a solid fuel may either be achieved with CO₂ capture from fossil fuel systems or by increasing the use of biofuels.

This chapter summarises paper I & II. Paper I considers existing biofuel-based CHP plants in Sweden, presented in section 4.1. Paper II, reviewed in section 4.2, deals with how and if existing and emerging biomass-based energy production can compete with fossil-based generation applying carbon capture.

4.1 Performance of existing biofuel-based CHP plants in Sweden

Due to the cold winters Sweden is suitable for district heating using efficient CHP to reduce fuel consumption. CHP plants require, however, a sufficiently large heat demand, and this demand is the key factor in determining the size of a CHP plant. The heat demand is often the limiting factor for the expansion of CHP, as district heating networks of adequate size need to be found. This, along with the dependence upon the district heating load, limits the annual operating time.

There are currently debates whether new or emerging energy systems are better or more efficient than existing plants for CHP. This is caused by the lack of a common reference base for system comparisons. This section summarises paper I, which attempts to create a consistent and transparent comprehensive reference base that can be used by engineers and scientists to compare the performance of new plants with existing systems. CHP is generally considered as energy efficient, but the question is how efficient they are? This section shows the energy effectiveness of the existing CHP plants. Furthermore, Swedish government has subsidised biofuel-based co-generation of heat and power, aiming at increasing the renewable power production. The question here is how successful and cost-effective these subsidies have been in terms of CO₂ reduction.

4.1.1 Fuel savings and energy effectiveness

The CHP plants are evaluated through how energy efficient they are by comparing their fuel consumption with a reference case where the same amount of heat and electricity are produced separately. The fuel attributed for heat production in a CHP plant, $F_{dh,ref}$, is calculated by:

$$F_{dh,ref} = \frac{Q_{dh}}{\eta_{ref,dh}} \quad (4-1)$$

where Q_{dh} is the heat generated in the CHP plant and the efficiency, $\eta_{ref,dh}$, is 110 % (based on LHV). An LHV-based efficiency of 110 % is possible to achieve if the boiler is equipped with flue gas condensing (Aleberg et al, 1995). The fuel attributed for electricity production, $F_{e,CHP}$, is then calculated through:

$$F_{e,CHP} = F_{CHP} - F_{dh,ref} \quad (4-2)$$

where F_{CHP} is the total fuel consumed in CHP. The amount of fuel to generate the electricity in the reference case, is calculated as:

$$F_{e,ref} = \frac{W_e}{\eta_{e,ref}} \quad (4-3)$$

where W_e is the power produced in CHP. The amount of fuel that is saved through co-generation, F_{saved} , can then be calculated by:

$$F_{saved} = F_{dh,ref} + F_{e,ref} - F_{CHP} \quad (4-4)$$

In Figure 3 $F_{e,CHP}$ is plotted versus the power output, together with the reference case, a future advanced power plant, with an assumed electrical efficiency of 42 %. The vertical distance in between the reference line, 0.42, and the plants gives the saved fuel, F_{saved} , through co-generation compared to the reference case of separate production of heat and power shown in Table 3.

As can be seen in Figure 3, the three plants with flue gas condensation in two steps need the least amount of extra fuel to generate the electricity. This is because these three plants generate proportionally more heat per unit power, compared to the others, and have a high total efficiency. The six plants without flue gas condensation need the most fuel to generate electricity. All co-generation plants, except one, perform better than the reference.

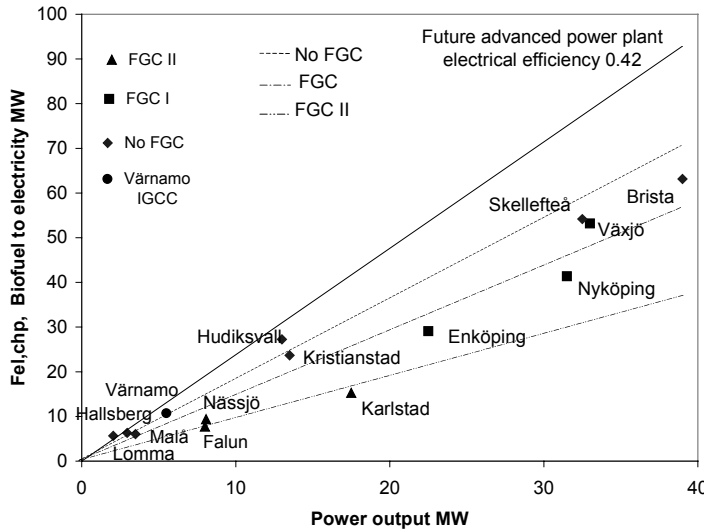


Figure 3. Power output versus the fuel needed for electricity production in CHP.

To complement the size-dependent F_{saved} , a dimensionless factor, κ , called the cogeneration effectiveness, was used to evaluate and compare the biofuel-based CHP plants regardless of size. The factor, which is based on fuel consumption, is defined as the extra fuel required for the separate production of heat and power divided by the fuel consumption in the CHP plant for generation of the same amount of heat and power (Anheden, 2000):

$$\kappa = \frac{F_{saved}}{F_{CHP}} \quad (4-1)$$

κ is actually the saved fuel per fuel input, and its value for each CHP plant is shown in Table 3. For the most fuel efficient units, κ is in the range 0.3-0.323 and for the worst units it is even negative, -0.05-0.06.

4.1.2 Characteristics of existing commercially operating CHP plants

For generating heat and power from solid biofuels, a steam turbine cycle is the conventional technology in commercial use at present. The biofuel boiler may be of Circulating Fluidised Bed, Bubbling Fluidised Bed, Fluidised Bed, Multitubed Combustion or grate-fired type, and the cycle may be equipped with flue gas condensation (FGC). An advanced cycle may be of Biomass Integrated Gasification Combined Cycle (BIGCC) type. The system configurations are shown in paper I.

The compiled characteristics of existing and commercially operating CHP plants in Sweden are presented in Table 3. Data are collected from respective operators.

Rational bioenergy utilisation in energy systems and impacts on CO₂ emissions

Table 3. Compiled characteristics of the existing and recently built and commercially operating biofuel-based CHP plants in Sweden.

Plant	Brista	Enköping	Falun	Hallsberg	Hudiksvall	Kaartstad	Kristianstad	Lomma	Mälå	Nyköping	Nässjö	Skellefteå	Värnamo	Väsjö
Start up year	97	95	93	87	92	92	94	95	91	94	90	96	94	97
Boiler/furnace ^a	CFB	Grate	FB	MBC	Grate	CFB	BFB	CFB	FB	BFB	CFB	CFB	BIG-CC	CFB
FGC no of stages ^b	0	I	II	0	0	II	0	0	0	I	II	0	0	I
Fuel	Wood	Wood	Wood	Wood	50 wood 50 peat	Wood	Wood	Wood	Wood	85 wood 15 coal	Wood	80 wood 20 peat	Wood	80 wood 20 peat
Fuel input, MW	132.6	80	35	14.1	60	88	55.5	18.3	16.3	105	33	106	18.5	111
Power output, MW	39	22.5	8	2.05	13	17.5	13.5	3.5	2.95	31.5	8.07	32.5	5.5	33
Electrical efficiency ^c	0.29	0.28	0.23	0.14	0.22	0.2	0.24	0.19	0.18	0.3	0.24	0.31	0.3	0.3
Total efficiency ^b	0.87	0.98	1.09	0.80	0.82	1.11	0.87	0.93	0.85	0.96	1.03	0.84	0.76	0.87
Fuel saved, MW ^E	29.7	24.36	11.32	-0.76	3.86	26.4	8.46	2.31	0.61	33.0	9.85	23.2	2.37	25.39
Co-gen effectiveness, κ ^E	0.224	0.305	0.323	-0.054	0.064	0.3	0.152	0.126	0.038	0.314	0.299	0.219	0.128	0.229
Steam turbine	ABB-Stal	ABB-Stal	ABB-Stal	ABB-Stal	PBS	ABB-Stal	ABB-Stal	Skoda (ABB)	-	ABB-Stal	ABB-Stal	ABB-Stal	ECE (ST) EGT (GT)	ABB-Stal
Steam pressure, bar	Vax	Vax	IG	65	axial	radial	Vax			Vax	TIGB	Vax		Vax
Steam temp, °C	140	100	63	67	67	66.7	65	60	41	140	85	140	40	142
Steam flow, kg/s	540	540	490	500	475	500	510	510	480	540	490	540	455	540
Investment, MSEK	50	27	10.2	4	18	29	17.5	5.7	4.4	40	12	37	-	41
Subsidiary, MSEK	680	320	160	67	120	650	280	150	63	340	150	295	-	445
Investment, SEK/RW _e	125.4	90.0	32.8	0	0	26.1	56.8	15.8	3.9	136.8	0	95.2	-	112.1
Oper hours per year	17436	14222	20000	32683	9231	37143	20741	42857	21356	1079	20074	90776	-	13485
SO _x , mg/MJ fuel	5500	5400	6500	4500-5000	5500 ^F	5000	6500	6500	-	5760	5500	6000-6500	-	5000
NO _x , mg/MJ fuel	-	18	30	0	59	8	-	-	-	12	0	20	-	1
N ₂ O, mg/MJ fuel	19	42	59	55	94	48	70	95	-	40	60	50	-	44
Particulates, mg/Nm ³	7-8	1	-	-	5	5	-	-	-	20	-	-	-	10
	4-6	15	15-20	-	8	3	<5 ^G	2%	-	<35	1-2 ^G	35	-	0.3

^A CFB is Circulated Fluidised Bed, BFB is Bubble Fluidised Bed,

^B FB is Fluidised bed, MBC is Multibed Combustion,

^C BIG-CC is Biomass Integrated Gasification Combined Cycle

^D FGC I is flue gas condensation in one step,

^E FGC II is flue gas condensation in two steps

^F Defined as the net power output/fuel input (LHV)

^D Defined as (net power output+district heating output)/fuel input (LHV)

^E Defined in chapter 3.1

^F electricity 5500 hours/year, heat 6500 hours/year

^G mg/MJ fuel

- Data not available

4.1.3 Technical performance

The plant capacity appears to have great influence on the electrical efficiency, which probably is due to the fact that an increased size enables increased steam temperatures and pressures, leading to higher electrical efficiencies. The existing conventional biofuel-based CHP plants have electrical efficiencies between 20-30 %. A few have even lower, below 20 %, which is due to their small size.

The total efficiency appears to be dependent on system configurations instead and is between 80-110 %. Flue gas condensation gives higher total efficiency – highest with flue gas condensation in two stages. Up to 111 % is obtained in the Karlstad CHP plant, which is optimised for heat production, however.

The existing CHP plants' electrical efficiencies are rather low compared to emerging technologies for power generation, whose efficiency is estimated by US Department of energy and EPRI to reach 42-45 % in the future (EPRI, 1997). Albeit these plants have high electrical efficiency, they use the fuel inefficiently as opposed to the existing CHP systems, as their total efficiency equals the electrical.

4.1.4 The governmental cost for CO₂ reduction by CHP

In order to promote power production from biofuel during the 1990s, the Swedish government subsidised the conversion of old heating plants to CHP plants (by installing a steam turbine) as well as the construction of entirely new CHP plants, with subsidies in the range of US\$ 326-435³ per kW_e installed (Governmental proposition, 1997). Ten of the studied biofuel-based CHP plants received subsidies to the total amount MUS\$ 75.5, indicated in Table 3. The subsidies have, hence, been successful as they resulted in an installed capacity of approximately 224 MW_e for the considered plants.

To evaluate these subsidies from a CO₂ mitigation perspective, the plants' reduction may be calculated according to the methodology presented in chapter 3 together with annual operating hours. The ten CHP plants have, thus, reduced CO₂ emissions by about 980 Gg annually in the short term. This is equivalent of 8.8 % of Sweden's fossil CO₂ emissions from the electricity and district heating sector in 1999 (or 1.7 % of 1990/2000's total CO₂ emissions). With 15 % rates of return per year of the subsidies, it gives the low cost of reduction of 11.6 US\$/Mg CO₂. Distributed on the plants entire technical lifetime the cost of reduction will be even lower. The subsidies thus give CO₂ reductions at a low governmental cost for the already constructed plants. Future identical subsidies may not show the same result.

Other governmental CO₂ incentives should, in its evaluation, be compared with this result. This is subjected to further research.

³ Throughout the thesis the exchange rate US\$ 1 = SEK 9.2 have been used, valid nov 2002.

4.2 Competitiveness for biofuel-based systems compared to fossil-based systems with carbon capture for CO₂ mitigation

There is a challenge for new biofuel-based power and heat generation technologies to be better and cheaper than already existing biofuel-based plants, and how they successfully can compete with fossil-fuelled plants with CO₂ capture systems. In this section, based on paper II, two options for CO₂ reductions – fuel shift from fossil fuels to biofuel and CO₂ capture of fossil systems – are compared and analysed. The efficiency and cost of electricity are compared.

CO₂ capture may penalise fossil fuel energy systems severely. With CO₂ capture, its cost increases and efficiencies drop, resulting in an increased cost of electricity and an increased fuel utilisation for the same amount of energy products. The biomass systems of today show poor electrical efficiencies, compared to fossil-fuelled systems. Furthermore, the electricity generated with biomass is currently more expensive than the electricity generated with fossil fuels. The question is if biofuel-based generation can be competitive compared to fossil-based generation with CO₂ capture applied? Furthermore, what can we expect from emerging and advanced biomass technologies – how good are these?

4.2.1 Fossil-fuelled systems with CO₂ capture

Carbon capture or removal can be applied to fossil fuel energy systems in order to reduce CO₂ emissions. The major CO₂ removal options under development include three process families: (i) pre-combustion processes where a synthesis gas produced from the fossil fuel undergoes a carbon monoxide (CO) shift prior to hydrogen (H₂)/CO₂ separation and CO₂ removal, (ii) processes where the fuel is combusted in a oxygen rich atmosphere mixed with recycled CO₂ or steam and (iii) end-of-pipe solution where CO₂ is removed (captured) from the flue gases. The removal processes may include chemical or physical absorption, physical adsorption, cryogenic methods and selective membranes (Desideri and Corbelli, 1998; Audus and Reimer, 1994; Göttlicher G and Pruschek R, 1997). The use of CO₂ capture, however, results in a efficiency penalty and an increased cost of the electricity produced. Typical figures are shown in Table 4. Moreover, the CO₂ captured must be disposed securely, which would penalise the efficiencies and cost even further. According to Lindeberg (1999) the most attractive option for storage is underground disposal in aquifers and exhausted oil and gas reservoirs.

It should be noticed that it is not economical for all the CO₂ to be removed from the flue gas. Only up to about 90 % may be removed economically by the above mentioned methods. This means that about 0.05-0.1 kg CO₂/kWh_e still will be emitted to the atmosphere, even when capture is applied (Audus and Riemer, 1994; Herzog, 1999). It can be found that the energy penalty is expected to be between 9-37 percent, depending on type of power plant, capture technologies, fuel and assumed time horizon. The cost of electricity (COE) is expected to increase about 1.1-3.1 c/kWh_e, which is 16-44 %. For most cases, the cost of CO₂

removal is in the range of 30-50 US\$/Gg CO₂ avoided (not including the cost of disposal, which would increase the cost by approximately 5-10 US\$/Mg CO₂).

Table 4. Typical system characteristics of large scale fossil-fuelled power plants: electrical efficiencies, estimated COE and expected energy penalties and increased COE, due to CO₂ capture systems, and estimated cost for CO₂ avoided.

Technology ^A (reference)	Electrical efficiency ^B	Energy Penalty %		COE c/kWh	Incremental CO ₂ avoided	
		Today	Future		COE c/kWh	US\$/Mg
PC (Herzog, 1999)	40-44	27-37	15	7-8	2.3-3.1	39-45
IGCC (Herzog,1999)	38-46	13-17	9	6-7	1.1-1.7	18-27
NGCC (Herzog,1999)	52-60	15-24	10-11	5-6	1.9-2.1	53-77
PC (Audus,1994)	40	28	-	7.4	1.5	35
IGCC (Audus,1994)	42	14	-	7.8	2.5	23
NGCC (Audus,1994)	52	19	-	5.3	1.8	55

^A PC - Pulverised Coal, IGCC - Integrated Gasification Combined Cycle, NGCC - Natural Gas Combined Cycle

^B Based on Lower Heating Value (LHV)

4.2.2 Biomass-based systems for reducing CO₂ emissions

Fuel shift from fossil fuel to biomass fuel for heat and power generation is a powerful way for CO₂ mitigation. In Sweden, the potential for using more biofuel is large (at least 108 PJ annually) due to the fact that a considerable part of the forestry residues are left in the forest. Advanced cycles are considered to play an increasing role in the future, due to their expected high electrical efficiencies (however with reduced total efficiency compared to conventional CHP). The biomass systems included in the comparison are shown in Table 3 (today's technologies) and Table 5 (potential future technologies).

Table 5. System characteristics of typical potential technologies, for both CHP (upper part of table) and power (lower part).

Technology ^A (reference)	Fuel input MW ^B	Electrical output MW	Heat output MW	Electrical efficiency % _B	Total efficiency % _B	COE c/kWh
BEFGT (Anheden, 2000)	8	3	5.8	0.33	1.06	5.2
BEFGT (Eidensten et al, 1996)	100	30	47	0.3	0.77	-
BIGCC (Sydkraft, 2001)	18.5	5.5	8.6	0.3	0.76	-
BIGCC (Aronsson, 1991)	140	61	65	0.44	0.90	-
BIGCC (Barring et al, 2000)	-	-	-	-	-	5.2-7
Steam turb (Barring et al, 2000)	-	-	-	-	-	5.1-5.7
BEvGT (Eidensten et al, 1994)	15	6	0	0.4	0.4	-
Steam turb (EPRI, 1997)	294-540	100-184	0	0.34	0.34	3.9-4.7
BIGCC (Arbre, 2000)	25.8	8	0	0.31	0.31	-
BIGCC (Craig, 1996)	330	132	0	0.4 ^C	0.4 ^B	6.5-8.2
BIGCC (EPRI, 1997)	244	110	0	0.45	0.45	3.6-3.1

^A BEFGT - Biomass Externally Fired Gas Turbine, BIGCC - Biomass Integrated Gasification Combined Cycle, BEvGT - Biomass Evaporative Gas Turbine; ^B Based on (LHV); ^C Higher Heating Value; - Data not available

4.2.3 Comparison of biomass- and fossil-fuelled systems

Comparing the two alternatives to reduce CO₂, the fossil-fuelled power systems not using CO₂ capture show higher electrical efficiency than the biomass-fuelled ones (Figure 4). Although the existing biomass systems are characterised by rather low electrical efficiencies, mainly due to the small size of most facilities and the fuel characteristics, they perform well when compared to fossil systems applying CO₂ capture. With the development of future technologies, there is a great potential to improve the electrical efficiency. The efficiency penalty to fossil fuel systems with CO₂ reduction will provide an opportunity for biomass-based systems to be a more competitive alternative for the reduction of CO₂ emissions from heat and power generation. The higher fuel cost for biofuel is balanced by the cost of CO₂ capture, transportation and storage for fossil fuels.

The comparison of the total efficiency is somewhat halting, as the fossil technologies included here only generates power, while many of the biomass-fuelled systems are CHP plants.

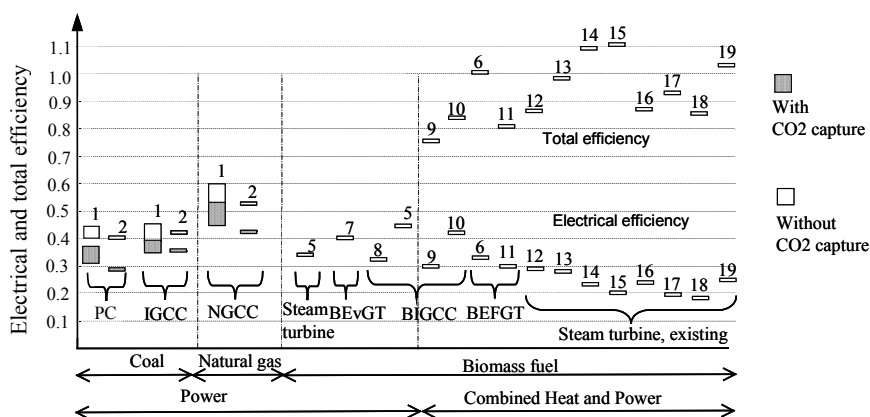


Figure 4. Power output versus electrical and total efficiency for existing and future bio-fuelled systems, and fossil-based systems with and without CO₂ capture.

Refs: 1 Herzog and Vukmirovic (1999), 2 Audus and Riemer (1994), 3 Craig and Mann (1996), 4 Barring et al (2000), 5 DOE (1997), 6 Anheden (2000), 7 Eidensten et al (1994), 8 Arbre (2000), 9 Sydkraft (2001), 10 Aronsson (1991), 11 Eidensten et al (1996), 12-19 Wahlund et al (2000).

(Existing plants: 12 Brista, 13 Enköping, 14 Falun, 15 Karlstad, 16 Kristianstad, 17 Lomma, 18 Malå, 19 Nässjö)

The cost of electricity for biofuel systems and fossil fuel systems with CO₂ capture are about the same (paper II). This indicates that with the development of both technologies, the biomass-fuelled systems may be more competitive than fossil-based systems with CO₂ capture for CO₂ lean heat and power production. However, the technologies for CO₂ capture are also under development, which may also reduce the costs quickly in the future.

In practice the two methods for CO₂ mitigation described in this section are complementary and both must be used. If future CO₂ emissions should be reduced considerably the extraction potential of biofuels is too small to replace sufficient amounts of fossil fuels. The use of CO₂ capture is more applicable to large-scale power stations, whereas biofuel is more suitable for small-scale utilisation.

4.3 Results

The existing and commercially operating biofuel-based CHP plants are characterised by rather low electrical efficiencies but high total efficiencies, thus high fuel effectiveness. The best plants have an electrical efficiency of 30 %, while the majority have an electrical efficiency between 18-25 %. The poorest has an efficiency as low as 14 %. The size appears to have a great impact on the electrical efficiency, where increased size leads to higher efficiency. The total efficiency, which appears to be influenced by the system configurations, lay between 80-111 %. It is highest for plants with flue gas condensation in two stages, giving total efficiencies of 105-111%.

Large amounts of CO₂ are continuously avoided, about 980 Gg CO₂ annually, through the biofuel-based generation of heat and power in the CHP plants. The construction of these plants has been subsidised with the total sum of MUS\$ 75.5 by the Swedish government. If annualising these subsidies with 15 % rates of return per year, the cost of specific reduction amount to low US\$ 11.6/Mg CO₂.

The co-generation of heat and power has saved substantial amounts of biofuel compared to separate production of the same energy products. The saved biofuel could then be used elsewhere in the energy system to achieve further fossil fuel substitution and connected CO₂ reductions.

The high efficiencies associated with fossil fuel energy production are severely penalised if carbon capture and sequestration is applied. Therefore, for CO₂ lean energy production, biomass-fuelled systems may constitute a more competitive option compared to fossil fuel generation using carbon capture. The best of the biofuel-based CHP plants perform well, despite the small size of most facilities, compared to the coal systems with CO₂ capture. The development of emerging biofuel technologies may provide a further improvement in their competitiveness for CO₂ lean generation.

4.4 Discussion

CHP is energy effective but a problem for biomass-based CHP using unrefined wet wood chips is to find sufficiently large heat demands near the fuel resource. A great extent of the district heating demand suitable for CHP has already been utilised, implying that any further expansions in CHP will be increasingly difficult. Unrefined biofuel is difficult to transport any great distance. However, if the biofuel could be efficiently transported biofuel-based CHP plants could be geographically independent of the biofuel's origin, opening new markets and applications

The more advanced cycles, such as BIGCC, have been under development for many years, yet they have not been commercialised. A fair guess is that we still have to wait several years until they come commercially available. Conventional biomass-based CHP technology, based on steam cycles, constitute at present an efficient and realistic option that has been integrated in energy systems for many years and reduced large amounts of CO₂ emissions.

5 The use of heat from biofuel-based CHP in sewage treatment works

The R&D focus regarding energy production usually only addresses high efficiencies, emissions and economics – all this to increase the profitability and reduce the environmental impact of energy systems. Other means to improve their environmental performance may be found if one seeks alternative uses, outside the plant site, for the low grade (waste) heat produced in biofuel-based plants. An example of such a means is to use the low grade heat to improve the biological nitrogen treatment (nitrification) of sewage water, giving a better environmental performance within the same region. This is examined in Paper III and summarised in this chapter.

In Sweden and other Nordic countries, municipal sewage water have such a low temperature during the winter that the sewage treatment works' biological nitrogen treatment of sewage water is inhibited by the slow growth of the nitrification bacteria. The fact of the matter is that the nitrification process in most existing sewage treatment works ceases to work in the wintertime. However, through warming the sewage water to a temperature where the biological nitrogen treatment functions well (approximately 15-17°C), a good nitrification level would be maintained throughout the entire year.

Heating sewage water in order to improve the nitrification during the winter is most justified and interesting with large effluent flows, i.e. large cities, and at sensitive recipients. These cities generally have district heating networks and CHP, which makes it possible with efficient heating of sewage water.

Two example of sources for the low grade heat are (a) the end condensation of the wet flue gases from biofuel-based CHP plants and (b) district heating networks with biofuel-based CHP where either the heat can be utilised when the ordinary demand is low to maintain full electricity production or cool the return of the district heating water to attain further flue gas condensation. The main issue addressed here is if this further heat utilisation, on a temperature level with no other competing areas, for increasing the environmental performance constitute a feasible option.

5.1 The Case Ekeby sewage treatment works

The study was performed as a case study on a average sized sewage treatment works with nitrogen purification, the Ekeby sewage treatment works located in Eskilstuna with some 80 000 inhabitants. The municipal's extensive district heating network, whose heat is mainly supplied by a biofuel-based CHP plant equipped with flue gas condensation, is located nearby. A detailed process scheme can be found in appendix I of paper III.

Eskilstuna produces approximately 500 kg/s sewage water. In simplification, the nitrogen content is constant over the year, and is composed mainly of ammonium nitrogen (NH₄⁺) and organic nitrogen (org-N), but also a smaller share nitrite and nitrate (NO₂⁻ and NO₃⁻), see Figure 5. The influx of ammonium nitrogen is approximately 710 kg/day. The municipal sewage treatment works has today a poor ammonium nitrogen reduction of 40 percent on an annual basis due to the low temperature of the sewage water during the period December to April, when nitrification literally ceases to work. The current purification is shown in Figure 6.

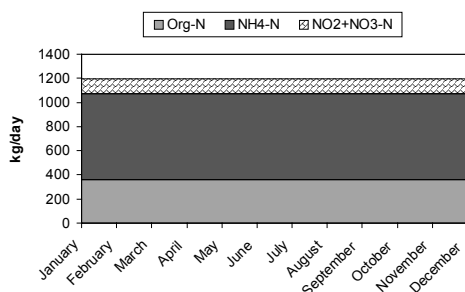


Figure 5. Generalised nitrogen content in incoming sewage water.

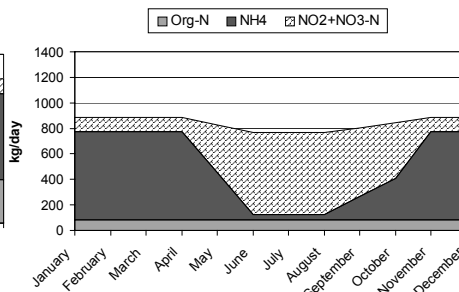


Figure 6. Generalised nitrogen content in outgoing water with current purification.

5.2 Heat sources and process alternatives for heating

Waste heat from the CHP plant could be used in order to enhance the nitrification process. The district heating network could facilitate this and be utilised as a heat source. To use the return of the district heating water would be more advantageous, as a lower return temperature improves the flue gas condensation in the CHP plant. Other heat sources, like combustion of internally generated sludge or biogas, could also be utilised. See paper II for further details.

Two different solutions for process configuration of sewage treatment works were investigated, both heating the incoming flow with the district heating return as heat source and with internal heat recovery (the incoming cold flow is heat exchanged with the warm outgoing flow). The internal heat recovery recovers the main part of the heat, implying that only the final duty from 14 to 16°C must be added from an external source (here, the district heating return). In one case the entire flow was heated (Figure 7) and in the other a part flow (1/3 of the entire

5.4 Results

The results show that environmental benefits may be achieved through heating of sewage water wintertime to attain a better nitrification process. This case study has demonstrated how to improve both energy and environmental performance by the integration of cogeneration system with waste heat recovery.

When heating the entire sewage water flow, a nitrification, and reduction of ammonium nitrogen, of over 90 % can be achieved on an annual basis, see Figure 9. That is equivalent of an effluent of 50 kg ammonium nitrogen per day (18 Mg/yr). Compared to today's effluent, the reduction is 137 Mg/yr to a cost of 3.5 US\$/kg reduced ammonium nitrogen.

A somewhat less reduction is achieved when heating a part of the sewage flow, although to similar cost, 3.4 US\$/kg reduced ammonium nitrogen. A 60 % reduction on an annual basis may be reached by heating 1/3 of the flow (Figure 10). On the other hand this solution gives a somewhat improved denitrification.

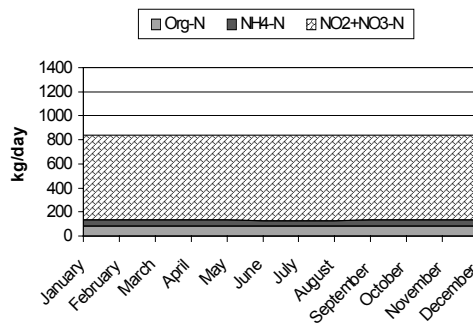


Figure 9. Prognosis for nitrogen contents in outgoing sewage water with heating of entire flow.

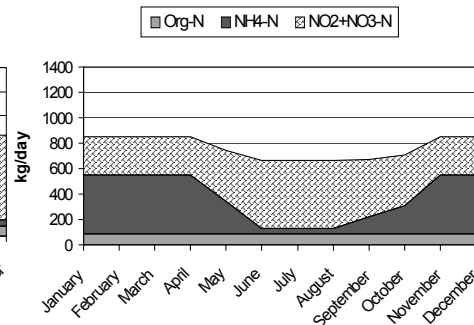


Figure 10. Prognosis for nitrogen contents in outgoing sewage water with heating of a part flow.

5.5 Discussion

Emissions of nitrogen (NO_x) in flue gases from biofuel-based combustion can be reduced with SNCR (Selective Non-Catalytic Reduction) or SCR (Selective Catalytic Reduction). This is justified considering acidification and eutrophication of the recipients. Through high fees for NO_x emissions from combustion (14 US\$/kg N) different de-NO_x incentives are promoted. In some cases relatively costly investments have been made, for example in catalytic de-NO_x, to achieve a proportionately small extra nitrogen reduction.

Paper III treats an alternative method to reduce the emissions of ammonium nitrogen to the recipient: through warming municipal sewage water which enhances the nitrification process in a sewage treatment works. This alternative way for ammonium nitrogen reduction appears to provide for a substantially enhanced environmental performance at lower costs.

6 The energy combine for producing fuel pellets

This chapter summarises two case studies, with different approaches, of an existing energy combine located in Skellefteå in northern Sweden. The energy combine produces the multiple products of heat, power and fuel pellets from local sawdust. The material is based on paper IV and V.

A unique and real system integration is examined, composed of the pellet-producing energy combine interlinked, over a long distance through transport of the fuel pellets, with a conventional CHP plant. This integration enables the biofuel to be transported from the forestry region with a surplus of biomass to a region with an unsaturated biofuel market, so that the logistic obstacles of biomass fuel, described in section 2.2, are overcome. Furthermore, it shows a real case for fuel substitution, discussed in section 4.2. The main issues addressed here are (a) the environmental impacts, in particular the reduction in CO₂ emissions resulting from this system integration, (b) if transportation of the fuel pellets constitutes an obstacle for the integration, (c) what non-technical factors influenced the realisation of the bioenergy combine, and finally, (d) what the cost of fuel substitution in the CHP plant is and the influence of CO₂ price. The material dealing with this is collected from paper IV.

With the aim to identify the irreversibilities and the possible ways for improvements of the energy combine, an exergy analysis is used. Modifications in the plant's configuration are suggested and preliminary simulations of the modified system are performed in order to study the feasibility of the modified system. The material for the exergy analysis is gathered from paper IV.

6.1 System description

The integrated system is composed of the energy combine, producing the multiple products of fuel pellets, heat and power, interconnected through pellet transportation with a CHP plant (Figure 11). By such an integration, the raw biomass (sawdust) can be upgraded into pellets by using part of the heat from the integrated CHP plant (energy combine) and the pellets can then be transported to the second CHP plant. The two plants are located in two different areas over 800 kilometres apart with different populations and thus different heat loads. The energy combine is located in Skellefteå in northern Sweden and the CHP plant in Hässelby in the Stockholm region. The produced pellets are transported 15 km by lorry and 800 km by boat to the other CHP plant in Hässelby in Stockholm.

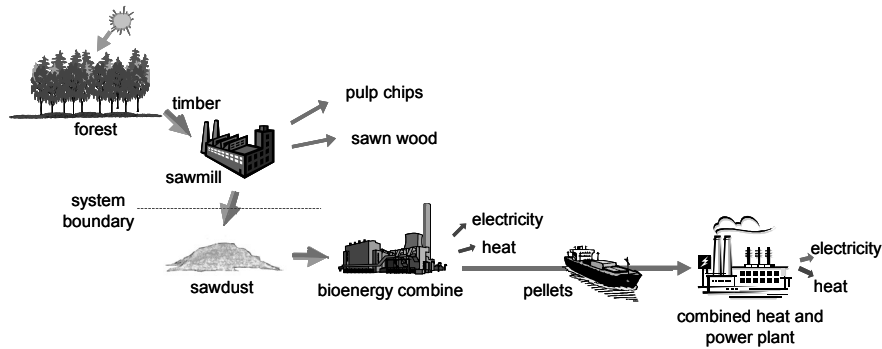


Figure 11. The integrated system: the energy combine interlinked with the CHP plant.

The **energy combine**, operated since 1997, consists of an integrated biofuel-based CHP plant and a pellet manufacturing facility, shown in Figure 12. It produces electricity, heat and fuel pellets from local sawdust and a small amount of peat. Its electricity is supplied to the Nordic power grid and the heat to the local district heating network. The combine is designed to annually generate 2185 TJ (130 Gg) fuel pellets and 540 TJ electricity. However, due to initial operating problems, production only reached 773 TJ (46 Gg) pellets and 292 TJ electricity in 2000. (Atterhem, 2001:a & b)

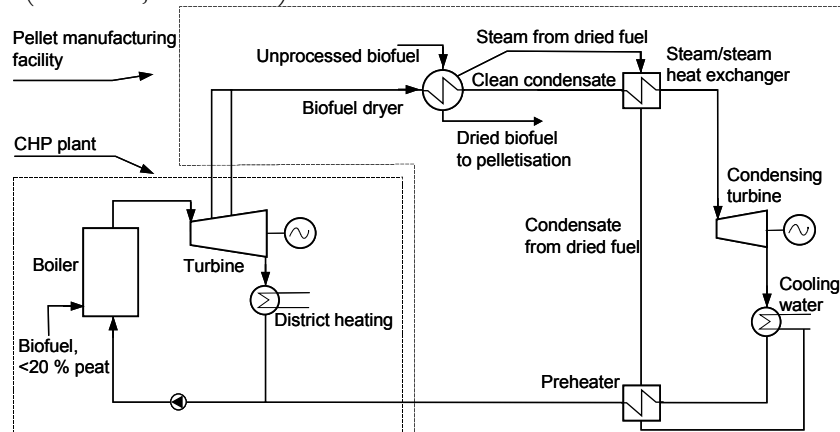


Figure 12. The simplified process layout of the energy combine.

The **Hässelby CHP plant** is a conventional steam cycle, which was originally coal-powder fired. During the 1990s it was converted to be fuelled with wood powder made from biofuel pellets. It is a large biofuel-based CHP plant of 300 MW fuel input. During 2000 the plant generated 756 TJ electricity and 2606 TJ district heat. (Källberg, 2001, Rågsmo, 2001)

Operating data for the energy combine and CHP plant are obtained from the operators (Atterhem, 2001:a & b, Källberg, 2001, Rågsmo, 2001). Further details on the energy combine and the CHP plant can be found in paper V, along with supplementary description of the integrated system as well as assumptions.

6.2 System efficiency

Energy balance calculations over the entire system have been made to investigate the system performance. The results show that the system's overall efficiency reaches 86-87 %, depending on the bioenergy combine's dryer load. The electrical efficiency for the system is between 24-27 %, also depending on the load.

The system's electrical efficiency is better than the average efficiency of existing conventional biofuel-based CHP plants, which have electrical efficiencies between 20-30 % (discussed in section 4.1). The total efficiency is, however, somewhat lower compared to other, existing CHP plants (80-110 % based on lower heating value). The system's efficiencies shall also be compared with emerging technologies for power generation, in which efficiency is, for example, estimated by the US Department of Energy and EPRI to reach 42-45 % in the future (EPRI, 1997). Although these plants have high electrical efficiency, they use the fuel inefficiently as opposed to the studied system (total efficiency equals the electrical).

6.3 CO₂ reduction achieved with the system

Along the examined fuel chain, CO₂ reduction can be achieved both by the energy combine in Skellefteå and in the CHP plant in Hässelby. The CO₂ reduction has been calculated in different ways for the two plants, according to methodology presented in section 3.2. The electricity produced in the energy combine substitutes marginal power (coal power) when added to the power grid and the fuel pellets substitutes coal in the Hässelby CHP plant. The exception from the methodology is that district heating produced in the energy combine is not assumed to reduce fossil-based district heat, and thereby oil. This is because the energy combine's alternative in this case would be a central biofuel-based district heating system producing the same amount of heat (Atterhem, 2001:b).

The result shows that with the energy combine's actual annual production of electricity (292 TJ in 2000), a reduction of 68.8 Gg CO₂ is achieved annually in the short-term approach, excluded CO₂ reductions in district heating networks. The 773 TJ pellets produced substitutes coal, which reduces CO₂ emissions from the Hässelby CHP plant by 70.1 Gg/yr. The transports of the biofuel produces in total 7.7 Gg CO₂/yr. However, these transport emissions are comparatively small, only 5.5 % of what is reduced. This yields the total CO₂ reduction, for the entire fuel cycle, of 131.3 Gg/yr in short-terms (based on production figures of 2000).

With the designed (nominal) production capacity of 2185 TJ pellets (130 Gg) and power production of 540 TJ annually, the total reduction of CO₂ would be approximately 270 Gg CO₂/yr, double that of the real production figures. This is equivalent to approximately 2.5 % of Sweden's CO₂ emissions from electricity and district heat production in 1990 and 2000 (in 2000 CO₂ emissions amounted to 10704 Gg CO₂/yr) (SEA, 2002:d).

6.4 Cost of fuel substitution in a coal-fired CHP plant and influence of CO₂ price

With the implementation of the Kyoto protocol, a CO₂ trading market will probably emerge. Therefore, it is of interest to analyse how a CO₂ price might influence individual CHP plants.

Substituting biofuel for coal in the Hässelby CHP plant increases the cost mainly due to a more expensive fuel and the investment cost to convert the plant. The investment cost amounted to approximately MUS\$ 16.3 and the fuel price increased from approximately 1.3 US\$/GJ of coal to 5 US\$/GJ of biofuel pellets, giving the total cost of 5.4 US\$/GJ_{biofuel}.

With the CO₂ emission factor of coal, presented in section 3.2, the increased cost can be expressed as a corresponding cost of specific CO₂ reduction of 45 US\$/Mg avoided CO₂⁴, which is the breakeven price. In order to illustrate the influence of the CO₂ price for coal and biofuel, the cost for both fuels have been calculated at varying CO₂ prices, shown in Figure 13. The capital cost for retrofit has been added to the cost of pellets

With current CO₂ taxes, equivalent to 43 US\$/Mg CO₂ for the CHP plant, fuel substitution comes out favourably, and if including other environmental taxes and fees, the substitution is even more economical.

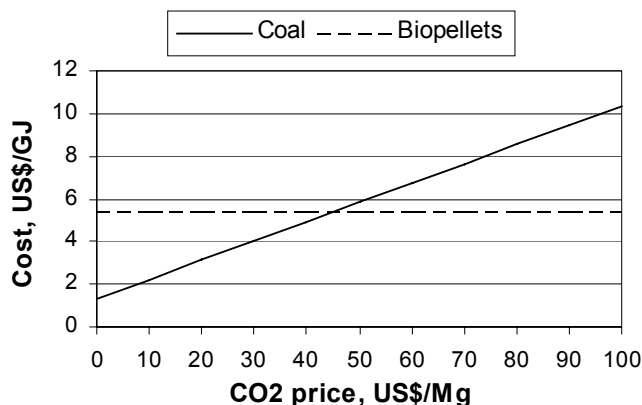


Figure 13. The dependence of the cost of coal and biofuel on the CO₂ price.

⁴ Calculated without considering other taxes and fees.

6.5 Non-technical factors influencing the realisation of energy combine

The question whether a plant is going to be built does not only depend on technical or economic factors. When studying the realisation of a plant like the energy combine, its socio-technical context should be taken into account.

Summarised in this section are the results from interviews performed in order to identify the main non-technical factors which influenced the decision making process around realising the energy combine (paper V). Four important actors, holding key positions in the Skellefteå municipality or the municipally owned energy company Skellefteå Kraft were interviewed. The actors were the chairman of the municipality's executive committee, the chairman of Skellefteå Kraft's board, the manager of the heat division at Skellefteå Kraft and the former managing director⁵ of Skellefteå Kraft. The chairman of Skellefteå Kraft's board was also active in the municipality as chairman of the personnel committee.

All of the interviewed actors point out that the main criterion behind the investment was a shared view of the potential for profitability and the objective of running the company in a businesslike fashion. It is also clear from the interviews that the municipality, as the plant owner, has taken a position of active responsibility for the whole region and its development, and that this factor has considerable importance in realising the project. The actors try to generate a good atmosphere for both the municipality and the company to operate and co-operate in. A good and co-operative atmosphere is viewed as important to realising a project like this one. Furthermore, like in many cases of new plants, the strong role of an enthusiast or "driving actor" has been an important factor behind the realisation of the project.

Perhaps surprisingly, environmental considerations do not appear to have been an important factor behind the realisation of the bioenergy combine. None of the interviewees emphasise the fact that the investment saves CO₂ and is environmentally beneficial. The positive environmental effects appear to have been a positive side effect – a bonus but no conviction. Even the company's utilisation of national biomass subsidies appear to have been an effect of what subsidies exist and the current political circumstances, rather than a result of the company's environmental conviction. This situation indicates that companies that operate in a local context have limited interest in global environmental issues. Therefore, it is the state or government that has to form an institutional framework to promote investments on the local level which impact positively on the global environment. The market cannot yet be expected to induce these globally beneficial investments, because global environmental concern and awareness among customers have not yet reached the stage where the market effects can be significant on a local level.

Similarly, while the creation of job opportunities is often used as an argument to promote the use of local biomass, in this case it appears to have had only a marginal effect on the decision of the investment in the bioenergy combine. At

⁵ Active as managing director during the period when the energy combine was developed

most, the bioenergy combine fosters a good business relationship between the sawmills and the energy company, thus contributing to keeping both jobs and the companies in the region.

6.6 Exergy analysis of the energy combine

In this section, the paper IV is reviewed, which concerns exergy analysis over the energy combine. The exergy analysis identifies the combine's irreversibilities, which provides information on how to improve configuration. Based on the identification of the irreversibilities, a modification is suggested and simulated by Aspen Plus.

The exergy analysis gives the efficiency of each respective unit, presented in Table 6. The greatest exergy loss (and destruction) occurs in the boiler, which is due to the irreversible combustion itself and large temperature difference in the heat transfer from hot gases to the working fluid. The exergy efficiency of the steam turbine depends on the load and at part load operation it decreases. Mixing of streams leads to exergy destruction. Therefore the mixing unit, used to regulate the steam parameters in the drying unit, is not desirable. In order to improve the exergy efficiency, it is desirable to operate the steam turbine at full load and avoid mixing streams in the mixing unit.

Table 6. Exergy efficiency for the energy combine and its major components.

Unit	Exergy efficiency
Energy combine	0.67
Boiler	0.40
Steam turbine in CHP plant	0.94
Mixing unit	0.93
Drying unit	0.99
Steam generating heat exchanger	0.96
Steam condensing turbine in pellet plant	0.82

6.6.1 Exergy improvements of the energy combine

The improvements studied consist of avoiding the mixing through abolishing the mixing unit and instead supply the steam to the drying unit directly from the turbine extraction. When abolishing the mixing unit, additional modifications of the plant's scheme have to be done to match all energy demands at different loads. A suggestion of the process layout without the mixing unit is to have the high-pressure steam turbine operating at full load almost the entire time. After the high-pressure steam turbine the steam parameters should match the parameters required in the drying unit. The steam flow is divided into two, and a part is fed into the low-pressure steam turbine and a part is supplied into the pellet facility. The advantage of this solution is that the high-pressure steam turbine and boiler may be operated at full load almost all the time, which gives higher efficiencies. More

details regarding the modifications, including the process schematic, can be found in paper IV.

The exergy efficiency for the existing configuration and the suggested modified system for both the energy combine and the CHP plant are presented in Table 7. The energy combine's exergy efficiency varies considerably compared to the CHP plant's. The main reason is that the exergy efficiency depends heavily on pellet production, as the exergy values for biomass and pellets are the largest in absolute values. Thus, they have the greatest weight when calculating the exergy efficiency for the dryer and energy combine. In the new configuration the pellet production increases with decreasing district heating load, implying that the exergy efficiency is higher when the district heating load decreases and pellet production increases.

Table 7. Exergy efficiency for different plant configurations and district heating loads.

DH load	100 %	95 %	50 %	30 %	0 %
ε (EC OLD) ^a	0.62	0.67	0.72	0.71	n. o.
ε (EC NEW) ^b	0.58	0.58	0.83	0.83	0.88
ε (CHP OLD) ^c	0.34	0.33	0.32	0.29	n. o.
ε (CHP NEW) ^d	0.32	0.32	0.33	0.33	0.34

^a exergy efficiency for the existing configuration of the energy combine (EC)

^b exergy efficiency for the new configuration of the energy combine

^c exergy efficiency for the existing CHP plant

^d exergy efficiency for the CHP plant within new configuration of the energy combine

n. o. the plant is not operated

With the modifications proposed, the operating time can be increased and thus the power production throughout a year, despite the somewhat decreased power output (duration curve in Figure 14, based on Atterhem, 2001:a).

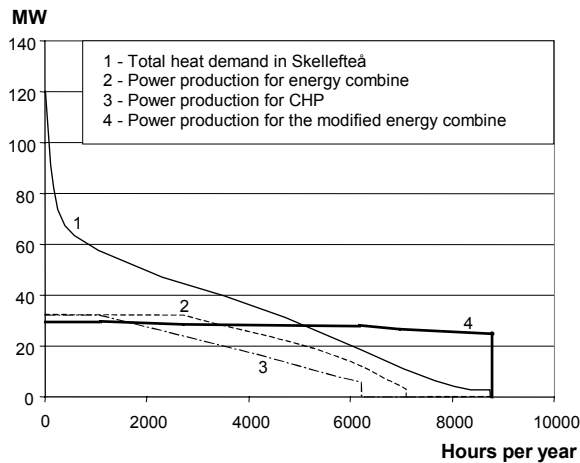


Figure 14. Heat duration curve for Skellefteå with power production for different plant configurations.

6.7 Results

The case study in paper V, reviewed in this chapter, has shown that the system integration of a CHP plant and a fuel pellet manufacturing plant provides a good opportunity for increased biomass utilisation, in regions with surplus of biomass, because a greater amount of fuel can be efficiently used for the limited district heating load.

Furthermore, it shows that the upgraded biomass can be competitively used for CO₂ reduction through substitution of coal. The study provides a case where it is competitive to shift to a CO₂ neutral fuel instead of using CO₂ capture in coal-fuelled plants with the present Swedish CO₂ tax. If including other taxes and fees, such as NO_x and SO_x, the fuel shift would be even more favourable. The breakeven price for CO₂ is 45 US\$/Mg CO₂.

The upgraded biomass can efficiently be transported over long distances because the CO₂ emissions in transports of the fuel pellets are comparatively small to the total reduction, which indicates that the transport of biomass from surplus regions to regions with unsaturated markets is environmentally feasible. Additionally, pellets serve as superior storage units for the biomass.

The CO₂ reduction of the entire fuel cycle has been quantified, showing that a large reduction of 130 Gg/yr can be achieved with today's production (270 Gg/yr with designed nominal production). These 270 Gg CO₂/yr is equivalent of 2.5 % of Sweden's emissions of CO₂ in power and heat generation in 1990/2000.

The annual operational hours and power production are increased with the integration, while maintaining a high system efficiency. The entire system's electrical efficiency is between 24-27 % and the overall efficiency reaches 86-87 %.

Factors that influenced the realisation of the project were identified through interviews, showing that the main criterion behind the investment decision of the energy combine was profitability. Another important factor that facilitated realisation was the co-operative environment between the local government and Skellefteå Kraft, both taking an active responsibility for the region. Environmental issues appeared not to be directly influential, but indirectly through government subsidies, indicating that companies that operate in a local context have a limited interest in global environmental issues. Therefore, it is the state or government that has to form an institutional framework to induce global environmentally friendly investments on the local level.

The exergy analysis of the energy combine, not surprisingly, identified the irreversibilities to be greatest in the boiler due to irreversible combustion and high temperature differences. The exergy destruction in the mixing unit appears to be rather high and if abolished from the process layout, along with some additional necessary modifications, the exergy efficiency of the entire plant may be increased. Furthermore, the annual power production may be increased through increased annual operating time, despite somewhat lower power output.

7 Options to increase biofuel utilisation and their impacts on CO₂ emissions

As mentioned earlier in this thesis, it is estimated that at least additional 108 PJ of Swedish woody biofuels could be available annually in the near-term future (Ekström et al, 2002; Lönner et al, 1998). This chapter addresses the critical question of how to use this potential efficiently in terms of CO₂ reduction and cost? Such a potential can only be realised if new applications for the efficient utilisation of biomass may be implemented, as discussed in section 2.2.

As stated in previous sections, (a) conventional and energy efficient combined heat and power generation demands large heat sinks (district heating loads) that usually do not exist in the forestry regions, and (b) unrefined wood fuel cannot be transported efficiently over long distances from the regions where the biomass grows to regions with unsaturated biofuel markets. Therefore, to enable transport, and seasonal storage of the biomass, one has to seek efficient paths for biofuel utilisation that includes processing without generating large quantities of heat.

In this chapter, a number of options are reviewed, that have been identified for an increased biomass utilisation which are not dependent on large heat demands, and can thus be applied in forestry regions. The options include the production of wood-fuel pellets, the biomass-based motor fuels methanol, ethanol and DME, and electricity from biomass. The comprehensive analysis of the different processes encompasses the biomass feedstock to the end energy products. The material in this chapter is based on paper VI.

7.1 Description of the options for bioenergy refining

In this section, the bioenergy conversion options compared for refining a wood fuel resource are shortly described. The raw unprocessed biofuel can either be dried and formed to pellets or combusted directly to produce power. It can also be converted to biomass-based motor fuels, such as ethanol, methanol or DME, see Figure 15. More detailed information can be found in paper IV. The input data are summarised in Table 8.

The main criterion for the processes is to refine the biomass to transportable products, which moreover are possible to store over seasons, without generating large quantities of heat. Ethanol process options are included in this study, as ethanol is greatly discussed among energy actors, and often given privileged treatment. The methanol and DME processes are also examined as a number of

independent studies indicate these are promising technologies. A further group consists of the pellet options as they at present form commercially available technology and have already been integrated in the energy system. Finally, power from biomass is also included as electricity is still a major energy carrier today. The energy products replace fossil fuels according to the methodology presented in section 3.2.

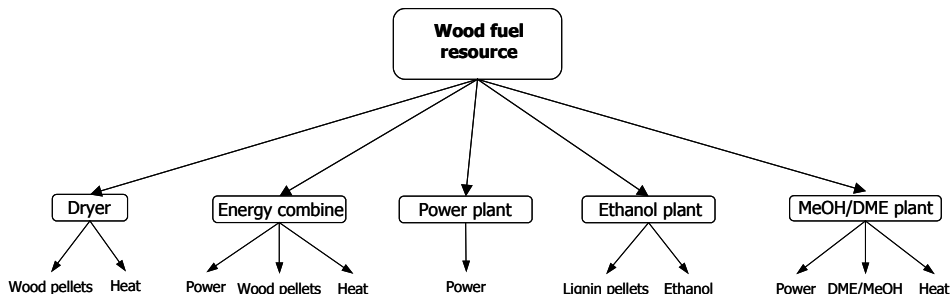


Figure 15. The alternative bioenergy refining processes from wood fuel resources to the end energy products (fuel pellets, heat, power, motor fuels). The end products replace fossil fuels.

The motor fuels **methanol** and **DME** can be produced from biomass via gasification and subsequent methanol or DME synthesis from the synthesis gas (syngas). Prior to this synthesis, the syngas must generally go through cleaning, shift reaction and compression. The methanol synthesis takes place over a catalyst at increased temperature and pressure. The gasification can either be atmospheric or pressurised. The gasifier is the crucial unit, as the methanol synthesis step is well known and commercially available, while the gasification step is still under development. The process for DME production is identical to the methanol production except the synthesis step, where the catalyst is modified for immediate dehydration of the formed methanol. The conversion of methanol to DME is more kinetically favourable and thereby the conversion of the syngas will increase, giving a 5 % higher yield of DME than when methanol is the product. (Elam et al, 1994; Winell and Svedberg, 1997; Ahlvik and Brandberg, 2001; Ahlvik and Brandberg, 2002).

Ethanol is produced through a completely different process. To produce ethanol from woody biomass, cellulose and hemicellulose must be hydrolysed to fermentable sugar prior to the fermentation. The hydrolysis can be performed with for example diluted acid or enzymes. The hydrolysis gives hexoses and pentoses, which are then fermented. At present it is only possible to ferment hexoses, although research is ongoing on pentose fermentation. The technologies for producing ethanol from woody biomass are still at the research stage. Ethanol production from woody biomass gives a lignin residue, which can either be combusted internally to cover the internal energy demand or pelletised and exported. (Elam et al, 1994; Winell and Svedberg, 1997; Ahlvik and Brandberg,

2001; Lynd, 1996; Wyman, 1999; Wooley et al 1999; Fransson et al, 2000; von Sivers and Zacchi, 1995)

To upgrade the biomass to wood-fuel **pellets**, the raw biomass is dried prior to pelletisation. The pellets can either be produced in a stand alone dryer or in an energy combine (co-production of pellets, heat and power; treated further in chapter 6).

The energy combine consists of an integrated biofuel-based CHP plant and pellet manufacturing facility. The CHP plant is a conventional steam cycle and the pellet manufacturing facility's dryer is a pressurised indirect steam dryer. A part of the steam is extracted from the turbines to the dryer. The system integration provides an extension of the annual operating hours and increased power production for a restricted heat load, as the additional production of pellets provides the possibility for the energy combine to use heat produced from biomass more effectively. An example of such an energy combine is located in Skellefteå in northern Sweden, and has been in commercial operation since 1997. (Atterhem, 2001:a & b; Wahlund et al, 2002)

The two dominating technologies for stand alone dryers are based on either pressurised steam drying (mainly used in large units) or atmospheric drying with flue gases in a rotary drum dryer. For the stand alone dryer, an atmospheric rotary dryer is the best alternative (Vidlund and Westermark, 2003). Drying of wood and pelletisation are a well-used and commercial technology.

To attain high electrical efficiency in **power** production with a solid biomass fuel, an advanced cycle, such as integrated gasification combined cycle (IGCC), may be used. The technology is based on gasification and combustion of the cleaned gas in a gas turbine cycle, with a steam turbine cycle as the bottoming cycle.

There are several competing technologies for gasification which can be classified as different types such as pressurised or atmospheric, oxygen-blown or air-blown, fixed bed or fluidised bed (Yan, 1998; EPRI, 1997). The gasifier and gas cleaner, in combination with the gas turbine, are the crucial units. The technology is not yet fully commercial. It has however been demonstrated in the Värnamo plant in Sweden (the worlds first demonstration biomass-fired IGCC) which was commissioned in 1995 and concluded in October 1999 (Sydkraft, 2001). Another demonstration plant, the Arbre plant in Yorkshire in England, has recently been constructed and is presently under start-up process (Rensfelt, 2002).

For each alternative, the products, in energy terms of motor fuels, fuel pellets, power and heat, are quantified as a percentage of the biomass energy input on a lower heating value basis (LHV).

Table 8. Main input data of performance of the bioenergy production processes.

Process	Abbreviation	Products	Efficiency products η (LHV)	Production cost US\$/GJ	Based on reference
Energy combine	Pellets, EC	Fuel pellets	0.59	5.1 ^b	Atterhem, 2001: ^a & b Wahlund et al, 2002
		Electricity	0.12		
		Heat	0.20		
Dryer, stand alone Power plant	Pellets, Dr Electricity, Pp	Fuel pellets	0.90 ^a	5.1 ^b	Vidlund, 2003 EPRI, 1997
		Electricity	0.45		
Energy combine	MeOH, EC	Methanol	0.25	23.2	Brandberg, 2000
		Electricity	0.17		
		Heat	0.05		
Methanol plant	MeOH, Mp	Methanol	0.54	13.9 ^d	Ahlvik, 2001
		Heat	0.11		
DME plant	DME, Dp	DME	0.57	13.2 ^e	Ahlvik, 2001
		Heat	0.11		
Ethanol, Diluted Acid	EtOH, DA	Ethanol	0.27 ^a	24.9	Elam et al, 1994
		Lignin pellets	0.44		
Ethanol, Enzyme	EtOH, Enz	Ethanol	0.41	16.1 ^f	Ahlvik, 2001 Wooley et al, 1999
		Power	0.04		

^a Internal power consumption not included in table

^b Market price for biofuel pellets from SEA, (2002:b)

^c Production cost from Barring et al (2000)

^d Production cost from Ekström et al (2002) and Elam et al (1994)

^e 5 % lower production cost for DME than MeOH (Ahlvik and Brandberg, 2002)

^f Production cost from Ahlvik and Brandberg (2002)

7.2 Results

7.2.1 CO₂ reduction

The CO₂ reduction achieved per TJ of added biofuel (Mg CO₂/TJ_{add, fuel}) with the different systems are presented in Figure 16, which exemplifies the best case where all produced heat can be utilised as district heating replacing oil, and Figure 17, where the produced heat is not utilised.

The CO₂ reduction is strongly linked to the total efficiency (fuel utilisation) of the systems. A high total efficiency gives a high reduction. The total fuel utilisation is more important in regards to the CO₂ reduction than the types of renewable energy products and what energy carrier is replaced.

An exception is power plants (without district heating) for the case when coal power is the marginal power production (short-term approach), which gives a reduction of 110 Mg CO₂/TJ_{add, fuel}. This is due to the assumption that each generated unit of electricity replaces 2.6 units of coal, because of the low efficiency in generating the power (efficiency of 38 % in marginal power production). It may, however, not be completely true for Sweden as this power production to a great extent would be located in Northern Sweden and due to bottlenecks in the national power grid, large amounts of electricity cannot be transmitted to where it can replace coal power. In longer terms, the reduction is much lower, about 40 Mg CO₂/TJ_{add, fuel}, when replacing NGCCs.

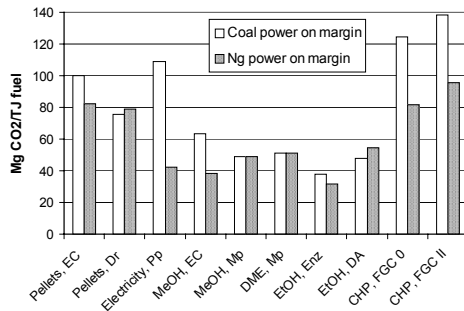


Figure 16. The CO₂ reduction of the different system options per added biofuel. CHP included as reference for comparison. Utilisation of all produced heat as district heating.

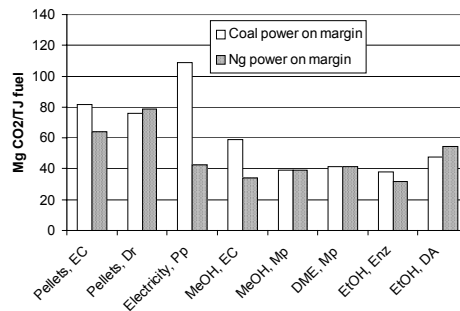


Figure 17. The CO₂ reduction of the different system options per added biofuel. No utilisation of produced heat. CHP is therefore not included.

It is clear that the largest long-term sustainable CO₂ reduction per added Joule of biofuel is achieved through fuel pellet production, either in the energy combine or a in stand alone dryer, regardless of if the produced heat can be utilised or not. A reduction of about 76-100 Mg CO₂/TJ_{add, fuel} is achieved when all produced heat can be utilised as a replacement of oil in district heating (Figure 16). Lower reductions, 64-82 Mg CO₂/TJ_{add, fuel}, are obtained with the pellet-energy combine if the heat cannot be used (Figure 17). It should be noted that those results are greatly related to the assumption that the pellets produced substitute coal elsewhere in the energy system. Further refining the biomass to motor fuels (ethanol, DME or methanol) gives a much lower reduction, with similar levels, 30-60 Mg CO₂/TJ_{add, fuel}, regardless of the process. Methanol, produced in the energy combine, is an exception as a somewhat high reduction may be attained in the short-term due to the high impact of replacing coal power, giving a reduction of over 60 Mg CO₂/TJ_{add, fuel}.

CHP is included as a reference for comparisons in Figure 16, but is not a relevant option for the case with a restricted heat load as CHP requires large heat loads. CHP is nevertheless the most CO₂ reducing technology in the short-term (up to 140 Mg CO₂/TJ_{add, fuel}), while in the longer term, the reduction is decreased to the level of the pellet producing options. This is due to the lower impact of replacing natural gas power. CHP's great reduction potential is highly dependent on the assumption that produced heat replaces oil-generated heat.

The break down of the CO₂ reductions can be found in paper VI.

7.2.2 Cost of specific CO₂ reduction

The cost of specific CO₂ reduction for the different systems in the case where all produced heat is used for district heating is presented in Figure 18.

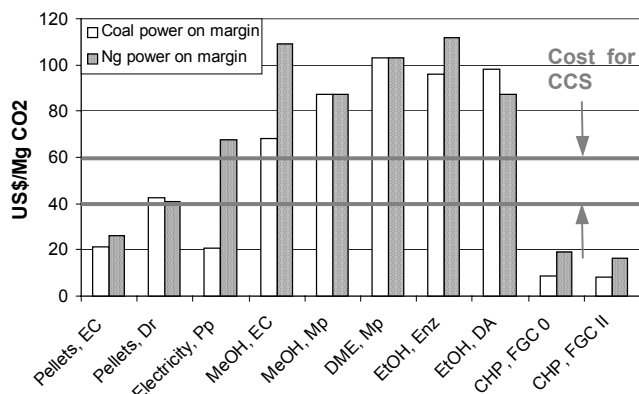


Figure 18. The cost of specific CO₂ reduction for the different system options. CHP included as a reference for comparison. All produced heat is utilised for district heating.

Production of fuel pellets attains not only the highest CO₂ reduction compared to other options, but also provides the cheapest solution for the reduction of CO₂. The cost of reduction for the pellet options is in the range 20-40 US\$ Mg/CO₂, while the cost of reduction for the motor fuels ethanol, DME and methanol options is about three times higher, 70-110 US\$ Mg/CO₂. A low cost of reduction, about US\$20 Mg/CO₂, can also be achieved with the production of electricity in biofuel-based power plants in the short-term. However, high performing biomass power plants (with the efficiency used here, 45 %) are not expected to be realised in the short-term. CHP provides CO₂ reduction at the lowest cost, and is therefore the best option for regions with sufficient heat demand.

Several studies indicate that the cost of fossil carbon capture and storage is expected to be about 40-60 US\$ Mg/CO₂ emissions avoided (IPCC, 1996, David and Herzog, 2000, Davison, 2000, Göttlicher and Pruschek, 1997). Virtually all motor fuels give higher cost than these figures and are thus a more costly option for CO₂ reduction, while pellet production and CHP are the most cost-effective options for CO₂ reductions.

7.2.3 Transportation of refined biomass

Internationalisation of the biofuel potential demands transportation of the processed fuels to the unsaturated biofuel markets in the form of fuel pellets, as discussed in section 2.2. The fuels must environmentally stand long transportations. A boat transport distance of 800 km is assumed in paper VI, which is the distance between Skellefteå and Stockholm. That gives transport CO₂ emissions corresponding to 3.5 % of the reductions achieved by the energy combine's energy

products. To investigate the internationalisation possibilities for fuel pellets, a boat transport distance of 1600 km is instead used, which increases the CO₂ emissions from the transportation to about 4% of the reduction achieved. For a stand alone dryer the CO₂ emissions from transport rise from 5 to slightly more than 6 %.

The conclusion from this is that transport of processed biofuels, in the form of fuel pellets, is highly feasible and does not constitute a hinder for the internationalisation of the biofuels, as the CO₂ emissions are small in comparison to the amount reduced.

7.3 Discussion

7.3.1 The potential for CO₂ reductions from a national and European perspective

In this section the discussion regarding potential for CO₂ reduction, presented in paper VI, is summarised. For a more extensive discussion, refer to paper VI.

If the estimated additional annual woody biofuel potential of 108 PJ (30 TWh) is used to produce pellets in pellet-energy combines – the option with the greatest reduction potential – about 64 PJ of pellets, 13 PJ of power and 21.6 PJ of district heating would be produced. In the short-term this would yield a total annual reduction of 10 800 Gg CO₂ (8860 Gg CO₂ in the long term). The largest reduction would be achieved outside Sweden with this option, however. This is due to the fact that the power produced reduces the CO₂ emissions in other Northern European countries (because of marginal power assumption), and that the major share of the produced fuel pellets would be exported for coal substitution abroad as the amount of pellets produced would exceed the Swedish utilisation of coal for energy use. The reduction obtained in Sweden, would totally amount to approximately 3240 Gg CO₂/yr, which corresponds to approximately 6 % of the Swedish total emissions 1990 and 2000. The rest of the short-term reduction, about 8000 Gg CO₂/yr would be achieved outside Sweden (emissions from transportation of the fuel feedstock and products are not included, however small).

The national Swedish reduction may be higher with production of motor fuels. If the estimated biomass potential of 108 PJ is used for DME production, the annual total reduction within Sweden would amount to 5500 Gg CO₂. It should, however, be pointed out that this reduction is only about half of the total achieved by pellet production in the energy combine.

CO₂ reduction by increased use of biofuel should thus not be restricted to national borders. Larger reduction can be achieved if Swedish fuel pellets are transported to other countries with coal consumption and difficulties implementing the Kyoto protocol. The production and export of fuel pellets can thus provide a cost-effective way for the EU to implement the Kyoto protocol. As regards Sweden, the fuel pellets alone may, by substituting the coal, give a reduction down to a level below 1990's emissions, despite the fact that only a part

of the fuel potential would be used domestically. The biomass potential is, thus, more than enough to achieve this reduction, implying that Sweden has good technical opportunities to fulfil the Kyoto protocol.

The domestic and other small-scale use (10 – 1000 kW) of pellets for oil substitution is a growing market and provides an additional potential for reducing CO₂ emissions in Sweden. An increase in transportation work with associated emissions, and dust emissions from combustion should, however, be expected. The CO₂ reduction per added Joule of biofuel is probably good, but the investment cost per kW is much higher than for large-scale boilers. Therefore, it is reasonable to assume that the cost of reduction would be higher.

7.3.2 Governmental subsidies of biomass-based motor fuels are likely to counteract the reduction potential

The substantial amounts of funding the Swedish government spends on subsidising R&D on alternative motor fuel utilisation and production from cellulosic material (woody biomass), are likely to counteract the total CO₂ reduction potential. The reason for this is that motor fuels and fuel pellets compete for the same wood fuel, and actions that increase the biomass use for motor fuels, would leave less fuel available for fuel pellets which have a greater reduction potential. This implies that actions that favour the production of motor fuels decrease the total CO₂ reduction potential, due to the fact that motor fuels only reduce about half of what is achieved with pellets. In other words, subsidies to biomass-based motor fuels constitute a hindrance to greater CO₂ reductions. However, a greater reduction (up to double the amount of CO₂) at probably a lower cost may be achieved with methanol and DME processes if CO₂ is extracted from the process prior to synthesis and then disposed of in aquifers.

It must, however, be pointed out that other environmental effects than CO₂, such as the reduced emissions of particles, NO_x and organic compounds, that may be obtained with alternative motor fuels are not considered.

8 Concluding remarks

8.1 Conclusions

The major finding from this thesis are summarised as:

- CHP with unrefined biofuel is the most cost-effective and energy efficient alternative for CO₂ emission reductions which shows the greatest reduction potential when a sufficient heat demand exists. The expansion of biofuel-based CHP during 80s and 90s has been successful in terms of CO₂ reductions. Large amounts of CO₂ have been avoided at a rather low governmental cost.
- For CO₂ lean energy production, biofuel-based systems are competitive compared to fossil systems with carbon capture and storage, especially with the development of emerging technologies.
- Due to the current situation in the energy system with limited remaining potential for profitable fuel switches and district heating network expansions, new markets for additional biofuels have to be found. Internationalising biofuels opens up the possibility to change the regional biomass surplus in Swedish into a national and international deficit. This is favoured by upgrading the biofuel as the processed biofuels can be transported more efficiently. The largest CO₂ reduction per energy unit fuel and most cost-effective CO₂ reduction is attained by upgrading the biofuel to pellets for coal substitution. Refining biofuel to motor fuels gives significantly lower and less cost-effective CO₂ reductions.
- Transportation of upgraded biofuel pellets over long distances appears to be very viable, as the pellets can be efficiently transported by boat with only limited emissions of CO₂ from forest-rich regions in Sweden to areas lacking biofuels. Furthermore, the pellets serve as storage units for the biofuel.
- Municipal sewage water is a large source of ammonium nitrogen emissions as biological nitrification cease to work during the winter due to low temperature. The emissions can substantially be reduced at a low cost through warming the sewage water with waste heat from biofuel-based boilers. This method of biofuel use has a potential to cost-effectively reduce large amounts of ammonium nitrogen emissions.
- The main factors that influenced the realisation of the energy combine located in Skellefteå were profitability and the co-operative environment between the local government and Skellefteå Kraft. Environmental issues appeared to be only indirectly influential through government subsidies, indicating that companies that operate in a local context have a limited interest in global environmental issues.

8.2 Suggestions for future research

Some suggestions of topics for future research are:

- To allow for a more accurate analysis of the CO₂ reduction potential and cost, the options for bioenergy refining need to be studied more in-depth and put on and evaluated from an identical technical and economic basis. To make the analysis more comprehensive, the methodology for estimating the CO₂ reduction should be expanded to include further fuel chains, such as the domestic utilisation of fuel pellets and substitution of electrical heaters. Moreover, the motor fuel options could be supplemented with the possibility of CO₂ removal from the syngas when producing DME, MeOH or H₂. The environmental and economic impacts on the society at large as far as infrastructure, production costs and job market could be concerned.
- The various options for appropriate integration of biofuel refining in the energy system, needs to be investigated. The interplay between feedstock availability, infrastructure, refining technology, market for products (including district heating production), are important factors to consider and should be intelligently integrated. The load variations over the year also needs to be considered, because it affects the facilities availability and operating time, which in turn have substantially influence on the annual CO₂ reduction potential and cost. The effects of different production and transport scales could also be explored.
- Market development and price formation, both nationally and internationally, of fuel pellets and other refined fuels could be explored. The emerging CO₂ trading market should be included. The possibilities for processed fuels to be a future export income for Sweden should be examined. The fuel feedstock situation should be problemised, including the differentiated price picture. The competition for biomass between the forestry industry and the energy sector, needs to be studied as well as synergetic effects of conjunctions.
- The various governmental subsidies aiming at reduce the emissions of CO₂ should be evaluated in terms of achieved CO₂ reduction and costs of specific reduction.

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10 Nomenclature and glossary

Abbreviations and symbols

BIGCC	Biomass Integrated Gasification Combined Cycle
CHP	Combined heat and power
CO ₂	Carbon Dioxide
DA	Diluted acic
DME	Dimethyl ether
Dp	Dimethyl ether plant
Dr	Dryer
EC	Energy combine
Enz	Enzyme
EtOH	Ethanol
F	Fuel
FGC	Flue gas condensation
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LHV	Lower Heating Value
MeOH	Metnaol
Mp	Metnaol plant
NGCC	Natural Gas Combined Cycle
NH ₄ -N	Ammonium nitrogen
NO ₂ +NO ₃ -N	Nitrite and nitrate nitrogen
NO _x	Nitrogen oxides
Org-N	Organic nitrogen
Pp	Power plant
Q	Heat
R	replaced energy carriers' total CO ₂ emissions
SEA	Swedish Energy Agency
SEK	Swedish krown (=0.1087 US\$)
W	Power produced
yr	year
κ	cogeneration effectiveness
η	efficiency or energy yield
ε	Exergy efficiency

Subscripts

2 and 3	secondary or by-products
add, fuel	added biofuel
dh	district heating
e	electricity
mp	main product
ref	reference

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