Sustainable production of bio-energy products in the sawmill industry

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Licentiate Thesis

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This thesis is based 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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Sustainable production of bio-energy products in the sawmill industry

Abstract
One of the great challenges facing society is to convert the global energy system to a sustainable process. Currently, 80% of the world’s energy is supplied through the combustion of fossil fuels. Not only are the fossil resources limited, the utilisation also increases the level of greenhouse gases in the atmosphere. The conversion to a sustainable energy system is problematic since the technology needed to exploit most non-fossil energy sources is not yet fully developed, e.g. solar energy. Biofuel is an available renewable energy source which is already widely used in many countries. If an effective switch-over from fossil fuels to biofuels is to be realised, biofuels must be viewed as a limited resource. Consequently, it is important that the handling, upgrading and utilisation processes involving biofuels are efficient so that its potential can be fully exploited.

This thesis considers efficient biofuel utilisation and upgrading within the sawmill industry. The goal has been to analyse not only the technical opportunities for energy savings in the sawmill industry, but also to analyse the cost effectiveness and environmental impact of studied measures. The heat demand of the sawmill industry is almost completely covered by its own by-products; primarily bark, sawdust and wood chips. The increased demand and improved economic value of woody biofuels on the market is thus an incentive for the sawmill industry to place more focus on energy issues. The sawmill industry also has a more or less constant heat load over the year, which is a beneficial factor for integration with district heating networks, biofuel upgrading plants and combined heat and power plants.

The conclusion of the study is that a variety of energy products such as heat, unrefined biofuel, pellets and electricity can be efficiently produced in the sawmill industry and sold for profit to external customers. The payback periods for the proposed investments are moderate and both the emissions of volatile organic compounds and global CO₂ are decreased. Should the proposed measures be fully implemented at Swedish sawmills, about 2.8 TWh of biofuel could be saved annually, 0.5 TWh of waste heat could be sold as district heating and 0.8 TWh of green electricity could be produced.

Language: English
Keywords: Sawmill industry, energy efficiency, heat recovery, integration, biofuel, upgrading, district heating, fuel pellets, CHP, VOC, CO₂
List of appended papers

The thesis is based on the following papers, referred to by Roman numerals I-III. The papers are appended at the end of this thesis.

I  Integrated systems enable energy effective drying of biofuels in the sawmill industry
   Vidlund A, Westermark M, Martin V
   In proceedings of the 16th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Aspects of Energy Systems, Copenhagen 30/6-2/7 2003, Volume III, pp 1539-1546

II Energy efficient pellet production in the forest industry – A study of obstacles and success factors
   Wolf A, Vidlund A, Andersson E
   Manuscript submitted for publication, 2003

III The sawmill industry as a producer of sustainable energy products – Strategies for increased system efficiency
   Vidlund A, Westermark M
   In proceedings of the 3rd European Congress on Economics and Management of Energy in Industry, Lissabon 6/4-7/4 2004

Comments on my participation:
I and III  Major part of calculations and writing
II  Part of economic calculations and writing

Related publications not included in this thesis

Energieffektiv biobränsleförädling i skogsindustrin (Energy efficient biofuel upgrading in the forest industry)
   Andersson E, Frimanzon A, Vidlund A
   Program Energisystem, Arbetsnotat Nr 24, ISSN 1403-8307, 2003, in Swedish
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1 Thesis outline

The thesis is based on the three appended research papers, but also include some earlier not published material. The outline of the thesis is as follows:

Chapter 2 gives a brief introduction and background to the thesis. The scope of the work is presented as well as a short review of related research.

Chapter 3 addresses the methodology used.

Chapter 4 describes the sawmill industry with an emphasis on the drying of sawn wood.

Chapter 5 addresses a broad evaluation of the technical, economic and environmental potential for waste heat recovery in the sawmill industry. The material is based on paper III.

Chapter 6 presents the possibilities for integrating the upgrading of biofuels to pellets with the sawmill industry. The benefits and feasibility of integrated pellet production compared to stand-alone production are discussed. The material is based on papers I-II.

Chapter 7 addresses the possibilities of using the heat load of wood drying as a heat sink for combined heat and power production.

Chapter 8 summaries the general conclusions from the research work and addresses interesting areas for further research.
2 Introduction

This thesis addresses the sawmill industry (SMI) with the objective to evaluate the potential for a more efficient use of biofuels within the industry as well as in the regional energy system in which the sawmill is situated. Here, the background to the study is presented and contributions to the research area both from previous studies and those contained within this thesis are discussed.

2.1 Background

The global energy demand is increasing and is expected to continue expanding. This is alarming since about 80% of the demand for energy currently is covered by fossil fuels (coal, oil, natural gas). This problem is twofold. Firstly, the global assets of fossil fuels are limited. It is difficult to predict how long the fossil resources will last, but with the economy and knowledge of today, the global coal assets are estimated to about 200 times the present annual production. The assets of oil and natural gas are even smaller (STEM 2003). Secondly, the utilisation of fossil fuels increases the concentration of greenhouse gases in the atmosphere. The greenhouse effect is not an environmental problem in itself. On the contrary, the greenhouse effect is a prerequisite for our existence on earth, since the planet would be frozen without it. The problem is the rapid increase of greenhouse gases in the atmosphere due to anthropogenic influences such as the combustion of fossil fuels. During the last 150 years, the concentration of CO$_2$ in the atmosphere has increased with about 30%, and this is predicted to lead to climate change.

International, as well as national, measures must be taken to ensure sustainable development. The challenge we face is great since non-fossil energy sources today are scarce, e.g. bio energy, or the technology needed for exploitation is not yet fully developed, e.g. solar energy. Biofuel supply about 11%$^1$ of the global energy demand, nuclear power 7% and water and wind covers about 2% (STEM, 2003). To satisfy the future demand for energy, and to enable a reduction of CO$_2$ emissions, renewable energy sources must be used as efficiently as possible.

This thesis considers efficient utilisation of biofuels within the SMI. Here, biomass fuels are regarded as possible substitutes for fossil fuels as it is renewable and can be assumed to have no net emission of CO$_2$. In Sweden, biofuel is the most important domestic fuel and is thus important for the supply-security of the national energy system as well as for the transition towards a CO$_2$ lean energy sys-

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$^1$ However, these figures do not include the wide spread usage of biofuels for heating and cooking in the developing countries, which makes biofuel the largest individual energy source outside of the OECD-region and the former Soviet union (STEM, 2002a).
tem. In this study, the focus is on woody fuels such as sawdust and bark, which are by-products from the sawmill industry. In the future, with a probable increasing demand for biofuels, new fractions of biofuels will be economically available from the forests. The portion of biofuels in the Swedish energy system in the year 2001 was about 16% (97 TWh). The economic and ecological potential for further exploitation of the wood fuel resources is, in a short-term perspective, estimated to at least 30 TWh/y (Ekström et al, 2002) while the potential demand for biofuels in the year 2010 has been estimated to 160 TWh/y (STEM, 2003). It is reasonable to believe that both the demand and supply of biofuels will continue to increase, and at some level, the economic and environmental limit for exploiting wood fuel resources will be reached. To enable a substitution from fossil fuels to renewable fuels, biofuels should thus be viewed as a limited resource. It is hence important that the handling, upgrading and utilisation processes concerning biofuel are efficient so that its potential can be fully exploited.

Due to high taxes on fossil fuels and large assets of woody biofuels, Sweden has experienced a significant increase in the national utilisation of biofuels since the early 1990s and has also taken a leading role in the market for upgraded biofuels (Geißlhofer et al, 2000) (Hillring, 1999). Earlier, biofuel was a free resource in the SMI since its by-products (bark, sawdust etc.) had little or no economic value. Today, their by-products have become co-products as biofuel is used to substitute fossil fuels at, for example, district heating plants and in private houses. The increased demand and improved economic value of bark and sawdust on the market is an incentive for the wood industry to place more focus on energy issues (FAO, 1993). The SMI also has a more or less constant heat load over the year, which is a beneficial factor for integration with district heating networks, biofuel upgrading plants and combined heat and power plants (CHP). By using energy within the sawmill industry efficiently, a variety of energy products (such as heat, unrefined biofuel, pellets and electricity) can be sold for profit to external customers.

The Swedish wood industry annually uses around 8 TWh of their biofuel by-products internally (STEM, 2002a), and about 6 TWh are used within the SMI. Sawmills are situated close to their supply of raw material and constitute a geographical network over areas with forestry, processing large amounts of biomass every year. With good internal know-how and systems for handling biofuels, the sawmill industry is well equipped to become an important actor for efficient biofuel exploitation.

2.2 Previous studies
Since the incentives for heat recovery within the SMI have been small, little international research has been done on the subject. The main efforts have been placed

In a study performed by Stridsberg and Sandqvist (1985), the energy balances of five sawmills were closely monitored and the mass balances of additional 22 sawmills were compiled. The objective of the study was to depict the current state of the SMI and to point out feasible measures for energy savings. The data collection for the mass- and energy balances has been especially valuable for later studies. Measures for energy savings listed by Stridsberg and Sandqvist correspond to the findings by other authors, for example Esping (1996) and Cooper (2003). Frequently mentioned measures are improved fuel characteristics (drying), improved equipment for heat generation and distribution, decreased electric consumption by implementing frequency inverters for pumps and fans, improved kiln insulation and heat recovery through heat exchanging between the inlet- and outlet-air streams of the dryings kilns. The studies thus cover a broad area, and none of them closer examine the potential for waste heat recovery.

Wimmerstedt (1999) has conducted a survey of techniques, the economics and operating experiences from biofuel drying in Sweden and concludes that rotary flue gas dryers dominate the market, but that steam dryers are better suited for integrated systems. He also includes a comparison between different locations of the dryer; stand-alone, integrated with the district heating network (DHN), pulp mill or a CHP plant. Other studies of pellet production plants combined with industry cover an existing heat and power plant in Skellefteå (Atterhem, 2001), (Wahlund et al, 2002), (Wahlund, 2003) and an integration with a pulp mill (Andersson et al, 2003). Wahlund (2003) concludes that the integrated fuel pellets plant improved the annual power production from the CHP plant and decreased global emissions of CO$_2$ by 0.1 Mt/year. Andersson et al (2003), concluded that it is economically feasible and environmentally sound to integrate the biofuel-upgrading process with the pulp industry. An important conclusion from the study was that waste heat from, e.g. flue gases, should be used instead of steam for the drying of the fuel in order to maximise the reduction of global CO$_2$ emissions. It was then assumed that the alternative use for this steam is power production.

Little focus has previously been placed on integrating pellet production with the SMI. A pilot plant with an atmospheric steam-heated dryer has, however, been studied at a sawmill in southern Sweden, producing warm water of about 95°C (Ahnland, 1997). Berghel and Renström (2002) have evaluated the performance of the dryer and they also propose integrating the drying process with either a sawmill or a DHN. Since the dryer is atmospheric, the condensation temperature is limited to a maximum of 100°C. This can be sufficient for low temperature dryers, but is
generally too low for the demands of the SMI. A low feed water temperature brings about large and costly heat exchangers in the dryers to provide the drying capacity of the drying kilns. A more relevant integration for the atmospheric dryer is thus with the DHN.

It can be concluded that, even though drying sawn wood and woody biofuels have been covered in previous research, little effort has been placed on the potential for heat recovery from these processes. The recent development of the biofuel market and emerging of large-scale sawmills have also improved both the incentives and the prerequisites for sawmills to play a larger roll in the national energy system as producers of energy products. This development, in turn, leads to a demand for a more comprehensive description of the SMI and its potential importance for efficiently utilising and upgrading biofuels.

2.3 Contributions of this work
This thesis work has been performed at the division of Energy Process at the department of Chemical Engineering and Technology at KTH in Stockholm, and the author has a master in chemical engineering from the same university. The scientific and technical base is thus founded on engineering skills, but the work has also been influenced by the interdisciplinary graduate school and research programme in which the author has participated, the Energy Systems Programme. This has resulted in a thesis which attempts to evaluate not only the technical prerequisites for energy savings, but also the impact of the sawmill’s internal and ambient socio-technical environment on the potential of the proposed measures.

This study thus approaches energy related aspects of the SMI with a system perspective and an attempt is made to generalise the results. The objective has been to evaluate the technical and economic possibilities for energy savings within the SMI and the energy system\textsuperscript{2} in which it is situated. The overall potential for the industry to sell sustainable energy products such as unrefined biofuels, pellets, waste heat and electricity is analysed. The consequences for global CO\textsubscript{2}-emissions are estimated and the effect on the local emission of volatile organic compounds (VOC) is discussed qualitatively.

The calculations are based on theoretical systems composed of, what is assumed to be, the most relevant technical data valid for the Swedish sawmill sector with a 5-10 year time perspective. Since the study covers a broad area, it has been beyond the scope of this thesis to completely describe or consider technical and economical

\textsuperscript{2}The term “energy system” refers to the local and regional energy system in which the industry is situated, including both the technical and social possibilities and limitations for, e.g. integration with DHN or selling of wet fuels.
details. Rather, it has been the goal to analyse the feasibility and environmental benefit of the proposed measures and thereby enable a rough estimation of the SMI’s potential for the energy efficient production of biofuel based energy products. Before investing in any of the proposed measures, a detailed analysis of the prerequisites is of course needed for each specific sawmill.
3 Methodology

The general methodologies for each paper are summarised and presented briefly here, but for more detailed information, see the respective section or paper. Input data was collected through inquiries and literature and the potential for energy savings was based on mass and heat balances over the studied systems. The impact on the global emissions of CO$_2$ was calculated with the data in table 3.1 and the impact of proposed measures on the local emissions of VOC was qualitatively discussed.

Contacts have been taken with sawmills as well as with manufactures of drying kilns and biofuel dryers to ensure the validity of the chosen data and base cases used for the calculations. The relevance of the study has also been confirmed in discussions with the actors.

3.1 Papers I-II

In papers I and II, integrated biofuel upgrading was compared to conventional stand-alone upgrading. Appropriate techniques for integration were selected and evaluated on the basis of technical, economic and environmental factors. In paper II, case studies together with a more detailed economic feasibility study were used to assess the obstacles and driving-forces for the realisation of a biofuel combine. To insure validity and credibility, different sources of information have been used, such as interviews, direct observation at the sites, web sites, newspaper articles, etc. The informants in the case studies have also been able to study and comment on drafts of paper II in order to increase its relevance.

3.2 Paper III

In paper III, the research focused on assessing existing and emerging opportunities for energy savings in the SMI. Attempts were made to generalize the results as far as possible and compiling data from literature and industry was an important part of the work. The calculations were based on theoretical industries composed as improved versions of a reference sawmill, see chapter 3.5.

3.3 Estimating CO$_2$ reductions

When considering the potential to reduce CO$_2$ emissions through different energy measures, it is important to point out that the result depends heavily on the choice of reference system. The estimation of CO$_2$ reduction in this thesis is based on two assumptions: 1) biofuel is assumed to be CO$_2$ neutral; and 2) biofuel is a limited resource. The first assumption, if stated alone, leads to the conclusion that biofuel,
from a CO₂ perspective, can be freely utilised without increasing the global emissions of greenhouse gases. The second assumption, however, changes this. Biofuel can be used to replace fossil fuels, decreasing global emissions of CO₂. Saving biofuel through increased energy efficiency thus enables more fossil fuels to be replaced by the limited biofuel resource. As a limited resource, it is thus important that the biofuel is utilised as efficiently as possible. For a detailed discussion of the validity of these assumptions, see for example Grönkvist et al (2003) and Schlamadinger et al (1997).

Wet woody biofuels, such as bark and sawdust, are assumed to replace coal, since coal-fired plants can be converted to accept wet biofuels. Waste heat sold to district heating plants is assumed to replace either coal or oil (If the waste heat should replace biofuel, the saved biofuel can be used to replace coal elsewhere in the energy system). It is also assumed that the efficiency of the heat plant is 0.9, and that 1 TWh of waste heat hence replaces 1.1 TWh of fossil fuel.

When electricity is produced, the produced electricity is assumed to replace the marginal electricity production. In a short-term perspective, the marginal electricity production is assumed to be coal-fuelled condensing power (CCP) and, in a long-term perspective, natural gas fuelled combined cycles (NGCC) (STEM, 2002c). Since biofuel is a limited resource, the alternative use of the use of the biofuel (replacing coal) is accounted for.

<table>
<thead>
<tr>
<th>Energy carrier</th>
<th>Direct emission of CO₂ /kg CO₂/MWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>330</td>
</tr>
<tr>
<td>Oil</td>
<td>274</td>
</tr>
<tr>
<td>Biofuel</td>
<td>0</td>
</tr>
<tr>
<td>Electricity, CCP, electrical efficiency 0.4</td>
<td>820</td>
</tr>
<tr>
<td>Electricity, NGCC, electrical efficiency 0.6</td>
<td>350</td>
</tr>
</tbody>
</table>

### 3.4 Economic assumptions and used data

The payback period has been used as a rough indication of the feasibility of the proposed measures. For the economic analysis of integrated pellet production, a more detailed economic analysis was also performed, using the annuity method for discounting capital costs. The investments costs and income from saved biofuel or sold heat are estimated using the prices compiled in tables 3.2 and 3.3. An exchange rate of 9.183 SEK per euro has been used for translating costs.
Table 3.2: Investment costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Investment costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas and drying gas condenser ¹</td>
<td>0.97 M€ for a capacity of 11.5 kg dry airflow/second</td>
</tr>
<tr>
<td>Steam condenser</td>
<td>0.05 M€ / MW</td>
</tr>
<tr>
<td>Increased boiler capacity</td>
<td>0.22 M€ / MW</td>
</tr>
<tr>
<td>Steam dryer for drying of biofuel, 25 bar ²</td>
<td>2.6 M€ for a capacity of 12 tonnes H2O/hour</td>
</tr>
<tr>
<td>Flue gas dryer for drying of biofuel ²</td>
<td>1.7 M€ for a capacity of 11 tonnes H2O/hour</td>
</tr>
<tr>
<td>Pelletisation process ³</td>
<td>2.1 M€ for a capacity of 5 tonnes pellets/hour</td>
</tr>
</tbody>
</table>

¹ Wet scrubber system
² Based on Wimmerstedt & Linde (1998).
³ Including grinding, pelletisation, cooling and storage, based on Zakrisson (2002)

Table 3.3: Fuel prices (STEM, 2002b)

<table>
<thead>
<tr>
<th>Item</th>
<th>MC [%]</th>
<th>LHV [MWh/t]</th>
<th>Price [€ /MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pellets</td>
<td>10</td>
<td>4.8</td>
<td>20-30 ¹</td>
</tr>
<tr>
<td>Sawdust</td>
<td>55</td>
<td>2.1</td>
<td>13</td>
</tr>
<tr>
<td>Bark</td>
<td>55</td>
<td>2.1</td>
<td>7</td>
</tr>
<tr>
<td>Waste heat sold to DHN</td>
<td>-</td>
<td>-</td>
<td>16</td>
</tr>
</tbody>
</table>

¹ Depending on the market-mix of the sold biofuel. The price is higher at the small-scale market (e.g. private customers) than at the large-scale market (e.g. heat plants).

3.5 The reference sawmill

The calculations of the heat recovery potentials are in all papers based on, and compared to, a reference sawmill. The choice of input data has been made with the ambition to depict an average sawmill of the SMI. The reference sawmill is thus assumed to employ the technology available and conventionally used in a time perspective of 5-10 years. It is assumed that the average drying temperature will increase somewhat under this time period, but no dramatic changes as compared with today are foreseen.

In Sweden, 80% of the production of sawn wood is performed at sawmills with a production capacity above 50 000 m³ sawn wood annually. The reference sawmill has been chosen with an annual production capacity of 100 000 m³/year, and thus represents a fairly large sawmill. The reference sawmill dries 70% of its sawn wood in high temperature dryers (HTD) with an average exit air temperature of 75°C and the remaining production is assumed to consist of temperature sensitive products, which are processed in low temperature dryers (LTD). The exit air from the LTD is set to 55°C and the average relative humidity of the outgoing air from all dryers is set to 80%.

To ensure the correct drying temperatures during the drying cycle without reducing the capacity of the dryers, the temperature of the heat delivered to the dryers is set according to table 3.4. The water in the wood is assumed to be liquid in the calculations. If it should be frozen, the total energy demand for the drying kilns in-
creases by 10-15%. The average heat demand for drying the sawn wood in the reference sawmill is 3.7 MW (296 kWh/m³ sawn wood) and the total heat demand is 4.5 MW, when comfort heating is included. The average power demand is approximately 1 MW (Stridsberg & Sandqvist, 1985). Input data can be found in table 3.5 and a Sankey diagram of the reference sawmill is found in figure 3.1. Transmission losses in the heat distribution system are neglected and the heat duty stated for the flue gases in figure 3.1 includes both sensible and latent heats.

Figure 3.1: Sankey diagram of the reference sawmill.

Table 3.4: Assumed and calculated data for the drying of sawn wood in the reference sawmill.

<table>
<thead>
<tr>
<th>Item</th>
<th>HT-dryers</th>
<th>LT-dryers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of production capacity [%]</td>
<td>70</td>
<td>30</td>
</tr>
<tr>
<td>Mean dew/dry temperatures of exiting air [°C]</td>
<td>70/75</td>
<td>51/55</td>
</tr>
<tr>
<td>Maximum dry air temperature in dryers during the drying cycle [°C]</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>Minimum temperature of feed water [°C]</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Mean temperature of return water [°C]</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>Dry air flow of exiting air from dryers [kg/s]</td>
<td>2.6</td>
<td>3.5</td>
</tr>
<tr>
<td>Specific heat demand for drying [kWh/m³ sawn wood]</td>
<td>285</td>
<td>309</td>
</tr>
</tbody>
</table>

1 Calculated values.

Table 3.5: Assumptions and used data for the reference sawmill and the proposed, improved systems.

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production capacity</td>
<td>100 000 m³ dried wood/year</td>
</tr>
<tr>
<td>Density of dry wood</td>
<td>430 kg/m³</td>
</tr>
<tr>
<td>Annual operating hours for sawmill</td>
<td>8000 h</td>
</tr>
<tr>
<td>Annual operating hours for DHN &amp; comfort heating</td>
<td>5000 h</td>
</tr>
<tr>
<td>Average rel. humidity of outgoing air from dryers</td>
<td>80%</td>
</tr>
<tr>
<td>Amount of water evaporated per m³ dried wood</td>
<td>288 kg H₂O/m³ wood</td>
</tr>
<tr>
<td>Water content of sawn wood before drying</td>
<td>0.85 kg H₂O/kg dry wood</td>
</tr>
<tr>
<td>Water content of sawn wood after drying</td>
<td>0.18 kg H₂O/kg dry wood</td>
</tr>
<tr>
<td>Outdoor temperature</td>
<td>0 °C</td>
</tr>
<tr>
<td>Biofuel boiler efficiency</td>
<td>80% of LHV</td>
</tr>
<tr>
<td>Electricity demand ¹</td>
<td>85 kWh/m³ dried wood</td>
</tr>
<tr>
<td>Transmission losses from dryers [% of input heat]</td>
<td>16</td>
</tr>
</tbody>
</table>

¹ Based on Stridberg & Sandqvist (1985).
4 The sawmill industry

Here, the SMI is described with the emphasis on drying the sawn wood.

4.1 History and current state

The SMI was important for the formation of Sweden from an agricultural to an industrial economy during the 19th century. The industrialisation of western Europe created a demand for sawn wood that led to a strong SMI in Sweden and in the beginning of the 20th century, sawn wood corresponded to about 40% of Sweden’s exports. (Ullenhag K & Jörnmark J, 2003)

Sweden is today the second largest exporter of sawn wood in the world. Exports from the wood industry accounted for 1.3% of Sweden’s BNP in 2000 and 5% of the total production value of the Swedish industry in 2001 (Statistics Sweden, 2000). In the year 2002, the production of sawn wood in Sweden was 16,4 Mm³, corresponding to about 4% of the world production. North America and Europe are the largest producers of sawn wood in the world with 37% and 34% of the total production respectively (FAO, 2004).

There are about 300 Swedish sawmills with an annual production capacity above 1000 m³ and the present development is towards a higher concentration of production. The small mills are disappearing and the production at medium-sized and large sawmills is increasing. Today, sawmills with an annual production capacity above 50 000 m³ stand for about 80% of the total production of sawn wood (Staland et al, 2000). Softwood stands for the main part of production (about 90%), divided into 43% pine and 57% spruce.

4.2 The manufacturing process

The sawmill production process includes debarking the incoming timber, sawing timber into planks and boards, and drying the sawn wood. Many sawmills are also integrated with, for example, planing or carpentry to further upgrade the sawn wood.

About half of the incoming raw material to the SMI becomes different fractions of by-products, see figure 4.1. The main fractions of by-products are wood chips, sawdust and bark. In addition to these by-products, upgrading the sawn wood produces dry sawdust and planer shavings.

About 90% of the wood chips are sold as raw material to the pulp industry while sawdust can be sold either as a raw material to the particle board industry or used...
as a fuel. Bark is normally used to fuel the heat production within the SMI together with varied portions of sawdust (Svensk sågverksindustri 1996). The fuel mix at Swedish sawmills was in 1985 70% bark, 25% sawdust and 5% dry wood chips (Stridsberg & Sandqvist, 1985). Since then, the by-products have become more valuable and are now used more efficiently. Today, most of the heat demand is covered by bark and the share of fuel by-products used within the SMI in the year 2000 corresponded to about 11% of the incoming timber (Staland et al, 2000).

![Figure 4.1: Material flow at a sawmill based on m³ solid (Stridsberg & Sandqvist, 1985)](image)

### 4.3 Drying the sawn wood

For centuries, simple air drying was the most popular drying method for sawn wood. The wood was dried in outdoor air for a year or more, achieving about 20% moisture content, depending on the climate, species and lumber thickness. Limitations of air drying are generally associated with weather and the uncontrollable nature of the process and the lumber industry is moving towards more advanced drying techniques in developed countries (Denig et al, 2000). Today, about 90% of the sawn wood drying in Sweden is performed in drying kilns according to Staland et al (2000).

Commercial methods for drying sawn wood are warehouse pre-drying, low temperature kiln drying and conventional kiln drying, with maximum drying temperatures between 66-93°C. The main part, about 80%, of the energy use of a sawmill can be traced to drying the sawn wood in the drying kilns, see figure 4.2, and the heating requirement in sawmills is usually satisfied by biomass-fuelled hot water or steam systems. In the US, dehumidification dryers using electricity-driven heat pumps are common for small sawmills (Denig et al, 2000).

In addition to drying the sawn wood, there is a need to heat the sawmill buildings during the cold season and a possible demand for cooling during the warm season. Comfort heating of office and process buildings often use between 10 and 20% of the boiler capacity (Esping, 1996). Since the temperature levels for comfort heating are relatively low, heating the buildings constitutes a potential heat sink for waste heat recovery. Other low temperature heat sinks, which are occasionally used but
not quantified in this study, are hardwood pre-drying (30°C) (FAO, 1993) and dry wood conditioning prior to further upgrading.

Today, there is a tendency towards higher drying temperatures in the wood drying kilns. The reason for this is quality aspects and the rate of the drying, since a high drying temperature increases the production capacity of the dryer.

Figure 4.2: Schematic sketch of the heat system of a sawmill.

4.4 Environmental impact of wood drying

The environmental aspects of wood drying addressed in this thesis are the emissions of CO₂ related to the energy utilisation during the drying process and the emissions of organic compounds from the drying. The energy aspect of drying is the main subject of chapter 5 and 6. Here, the environmental impact on the local environment of the drying process, through emissions of organic compounds, is described.

The organic compounds emitted when wood is dried can be categorised into two groups, Volatile Organic Compounds (VOC) and Condensable Organic Compounds (COC). The VOC emitted from wood at reasonable temperatures mainly consists of terpenes. The COCs are fatty acids, resin acids and higher terpenes (Ek et al, 2000). The latter compounds might condense on equipment surfaces and thus cause technical problems. Moreover, sublimation of the organic condensable compounds can form “blue haze” as the flue gases are cooled down after the chimney. The emissions of VOC are of environmental concern since they are known to form ground level ozone in the presence of NOₓ.

The composition and concentration of terpenes in wood vary between different species, but is also dependent on a number of additional factors. The amount of mono terpenes is according to Granström (2001) 1-2 kg/m³ for pine and about 0.5 kg/m³ for spruce, in Swedish species. The emission of VOC from kiln drying at 100°C is 0.4-1.0 kg/m³ dried wood for pine, while the corresponding value for
spruce is approximately 0.1 kg/m³ sawn wood (Mc Donald et al, 2002), (Nussbaum & Englund, 1999). Assuming an average emission of 0.5 kg VOC/m³ dried wood, the annual VOC-emissions from the Swedish SMI is about 7500 tonnes. The corresponding figure for the reference sawmill is approximately 50 tonnes of VOC emitted to the local surroundings of the sawmill annually.

Drying at high temperatures, which is often the case in biofuel dryers, increases the emissions from thermal decomposition of the wood. Directly heated atmospheric flue gas dryers are the most common dryers for biofuel today. In these dryers, the drying temperature is relatively high and the emissions of organic compounds are diluted in the flue gas and emitted through the chimney (if flue gas condensation after the dryer is not utilised). Steam dryers are often used in integrated processes where heat recovery through condensing the waste steam from the dryers is utilised. Experience has shown that the condensate from steam dryers can cause problems for the de-nitrification process of sewage plants. To avoid this problem, the condensate can be treated by precipitation and biological oxidation before it is led to a recipient. The non-condensable gases (terpenes) can be destructed in the boiler.

There is no legislation regulating VOC emission from wood drying in Sweden today, but the formation of the blue haze from COCs is sometimes restricted. USA has a large production of both sawn wood and plywood and has enforced VOC restrictions in the plywood industry, requiring advanced control equipment such as thermal or catalytic oxidation. Furthermore, even more stringent requirements are to be expected in the future (Hedman, 2004). It is thus likely that the Swedish VOC emissions will also be subject to legislation in the future.
5 Efficient use of waste heat

The waste heat streams available for heat recovery in the SMI are primarily the warm, humid exhaust air from the wood drying kilns and the flue gases from the boiler. In this chapter, based on paper III, the technical, economic and environmental aspects of heat recovery in the SMI are discussed. Furthermore, if the sawmill upgrades biofuel in a drying process, waste heat can potentially be recovered from the biofuel dryer, see chapter 6.

5.1 Waste heat recovery from humid gas streams

Here, primarily technical issues regarding waste heat recovery from humid gas streams are discussed and the choices made for the proposed systems in chapter 5.2 are motivated.

5.1.1 The impact of the drying temperature on the heat recovery

The tendency during the last 10-20 years in the SMI has been to increase the temperature in the drying kilns. The development has been spurred by a demand for more efficient drying and is limited by the material properties of the equipment and the quality of the produced wood. Drying at very high temperatures (>100°C) has been developed, but has not become widespread in Sweden. The development towards higher drying temperatures is assumed to stagnate at approximately the temperatures assumed for the reference sawmill in this study. (Lundmark, 2003)

The largest heat losses at sawmills can be traced to the release of warm, humid air from the drying kilns to the surrounding. A simple measure for improved energy efficiency is thus heat recovery by recuperation between the dry, cool inlet air and the warm, humid outlet air. In a number of northern European countries (e.g., Finland, Sweden and Norway), simple heat recovery systems, in the following text called “conventional heat exchangers”, are sometimes incorporated into newly built drying kilns. The heat exchangers are often of cross-flue type; typically made of stainless steal since aluminium recuperators are short-lived due to the corrosiveness of the exhaust air (Larsson, 2004).

The specific energy demand of a sawmill depends on e.g. the dew point temperature of the outlet humid air from the dryers. As the average temperature for drying sawn wood increases, so does the energy economy of the drying since less air is passed through the dryers, see figure 5.1. The smaller airflow also decreases the potential for conventional recuperation since less air needs to be heated, as can be
seen in figure 5.2. An alternative system for heat recovery at stand-alone sawmills is proposed in section 5.2. The proposed system utilises the wet scrubber, described below, to condense water from flue gases of the biofuel boiler.

![Figure 5.1: The airflow needed to dry sawn wood as a function of the dew point temperature of the dryer exit air. The relative humidity of the exit air is set constant (80%).](image)

![Figure 5.2: Recovered energy in a conventional air-air heat exchanger as function of the dew point temperature of the exit air from the drying kiln. The relative humidity of the exit air is set constant (80%).](image)

### 5.1.2 Equipment for condensation of polluted humid gas streams

The humid air from the drying kilns is polluted with both VOC and COC (see chapter 4.4) and problems with heat exchanger fouling have been reported. An alternative technique to conventional recuperators, as proposed in this study, is the wet scrubber system. In the wet scrubber, the water content of a humid air stream is condensed in direct contact with re-circulated cooling water in a packed column, see figure 5.3.

![Figure 5.3: Wet scrubber system for heat recovery from humid gas streams to, for example, the DHN.](image)

As compared to conventional recuperation, problems with corrosion and clogging of equipment can be avoided and more energy can be recovered as the waste heat can be distributed to different heat sinks more easily. The waste heat can, for

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3 The term “stand-alone sawmill” refers to sawmills for which integration with the surrounding energy system (for example a DHN or another industry) is not feasible due to, e.g. technical, economic or social factors.
example, be used for comfort heating in buildings or for district heating purposes, in addition to preheating inlet air. To level-out heat peaks and to prevent freezing during winter, a glycol system can be used as a heat carrier. The same technique can also be used for flue gas condensation.

5.1.3 Re-circulation of exhaust air from the drying kilns

The heat in the exit air from the drying kilns can be recovered in an open process, see figure 5.4, or in a more energy efficient process, where the exhaust air is recycled after the condenser, see figure 5.5. According to this study, the latter process is not utilised in the SMI today, even though re-circulation is more energy efficient\(^4\). A drawback with re-circulation is that air with a higher humidity than the ambient air is used as the dryer inlet air. A smaller difference in humidity between the intake and exit air brings about an increased airflow through the dryer and a large air stream results in oversized apparatus and high power consumption for the fans. Favourable condition for recycling the air stream is thus a drying processes working at high temperatures, since the temperature of the heat sink, hence the recycle temperature, is usually limited (e.g. district heating).

Re-circulating the air stream also enables, and implies, efficient VOC abatement as the organic compounds will be accumulated in the air stream. To avoid high concentrations of VOCs in the dryer and the emission of VOC to the environment, an air bleed-off or some kind of abatement technique should be implemented. The polluted bleed-off can be combusted in the boiler and the condensate should be treated by, for example, precipitation and biological oxidation, before it is led to a recipient.

![Diagram of Drying Kilns](image1)

![Diagram of Drying Kilns](image2)

Figure 5.4: Condensing exhaust gases from a wood drying kiln. Open system.

Figure 5.5: Condensing exhaust gases from a wood drying kiln. Closed system with air recycle.

5.1.4 Using drying exhaust air as combustion air in the boiler

Flue gas condensation (FGC) is commonly utilized at district heating plants fired by wet fuels, such as biofuel and domestic waste. The dew point temperature of the

\(^4\) A pilot plant working according to figure 5.5, using district heating as cooling water, is planned to enter operation in Sweden during 2004.
Flue gases from biofuel combustion is usually around 65°C, limiting the temperature of the recovered heat to about 60°C. A conventional way to increase the dew temperature is to humidify the combustion air, see figure 5.6. By introducing warm, humid air to the combustion process, dew point temperature of the flue gas as high as 74°C can be achieved.

In a similar way, it is possible to increase the potential for flue gas condensation at sawmills by using the humid exhaust air from the dryers as the combustion air in the boiler, see figure 5.7. This solution is thus implemented throughout this study for all proposed systems utilising flue gas condensation. The benefits are both an improved heat recovery in the flue gas condenser and decreased emissions of VOC. Since the air flow through the drying kilns is larger than the air flow needed in the boiler, only part of the total amount of exhaust air can be treated this way.

5.1.5 Heat pumps in the sawmill industry

When the temperature of the waste heat is too low to enable direct heat recovery, a heat pump can be implemented. Especially at sawmills with a limited boiler capacity, the use of heat pumps can be an economic alternative to investing in an increased boiler capacity.

It is important to find heat pump techniques that are environmentally friendly, in respect to its working media and energy consumption. Since sawmills have access to biomass-fuelled heat, heat driven techniques can be interesting and environmentally friendly alternatives to electricity driven heat pumps. The absorption heat pump (AHP) is heat driven, and can work both as an open or a closed process, see figures 5.8 and 5.9. By implementing an AHP at a sawmill, the waste heat temperature can be improved without increasing the fuel demand and it
also enables low temperature waste heat (under 50°C) to be utilised, increasing the total potential for heat recovery.

The working media in an AHP is a hygroscopic fluid, which absorbs water vapour exothermically. The diluted working media is then regenerated using high temperature (>150°C) heat and the concentrated fluid is returned to the absorber. The maximum delivered temperature from a closed AHP is just above 100°C, so the heat can, for example, be used for district heating or to heat low temperature dryers. An open system with, for example, Potassium Acetate (KAC) as the working media can reach higher temperatures, but cannot raise the waste heat temperature as much as compared to a conventional closed heat pump. The coefficient of performance (COP) for an AHP is usually around 1.7 and in contrast to the compressor heat pump is insensitive to fluctuating heat duties, has a low electricity demand, low maintenance cost and a long lifetime. The potential for AHPs has not been examined closer in this study.

In a conventional compressor-driven heat pump, waste heat is upgraded by a closed thermodynamic cycle using electricity as the driving energy. Conventional compressor heat pumps are used for internal heat recovery in the SMI today, but only in dryers with low temperature demands, usually below 60°C (Denig et al, 2000). The COP for a compressor heat pump is usually 3-4.

### 5.2 Proposed systems for energy savings

Possible energy savings through waste heat recovery have been calculated for four different systems. Systems A and B are implemented for stand-alone sawmills and systems C and D are implemented for sawmills integrated with a DHN. The proposed systems are all improved versions of the reference sawmill, see chapter 3.3. The aim is to address the overall potential for heat recovery, and solutions other than those proposed are, of course, possible.
5.2.1 Heat recovery within a stand-alone sawmill

By constructing an efficient energy system within a sawmill, biofuel can be saved and sold to e.g. heat plants or pellet producers.

System A - Conventional recuperation

In conventional recuperation, see chapter 5.1, the exit air heats the incoming air to the wood drying kilns. Using data valid for the reference sawmill, recuperation saves on average 0.3 MW heat during 8000 hours. This corresponds to 2.9 GWh saved heat per year or 29 kWh per m³ dried wood.

System B - Flue gas condensation

In contrast to conventional recuperation, system B recovers heat from the boiler flue gases which is then used for comfort heating and preheating the inlet air to the dryers, see figure 5.10. It is assumed that 5000 hours of comfort heating is required annually and that preheating the drying air saves on average 0.3 MW during 8000 hours. The total amount of recovered heat is thus 6.4 GWh annually, or 64 kWh per m³ dried wood, but the savings are not constant over the year. During the winter, more heat is used both for preheating the inlet air to the dryers and for comfort heating in buildings.

Figure 5.10: System B, waste heat recovery through flue gas condensation at a stand-alone sawmill.

5.2.2 Heat recovery through integration with the DHN

Through pre-heating the DHN return water, the low temperature waste heat found in a sawmill can be utilised. When DHN feed water needs to be produced, however, improved temperatures will be required. This can be accomplished by burning additional biofuel in the boiler, as proposed in system D, or by implementing a heat pump. The calculations are based on the energy system of the reference sawmill.
System C - Preheating of return water
In a large DHN, with typical return temperatures of 45-50°C, return water preheating can be utilised, see figure 5.11. Relatively low temperature waste heat can thus be utilised for district heating.

System C is built on system B, i.e. flue gas condensation is implemented, but heat is rejected to the DHN instead of used for inlet air preheating and comfort heating. Furthermore, the air in the HTD is re-circulated and heat is recovered to the DHN through condensation in a wet scrubber system.

The recovered heat duty is 3.4 MW and it is assumed that heat can be sold to the DHN during 5000 hours/year. The total amount of waste heat sold to the DHN is thus 17 GWh, or 170 kWh per m³ dried wood. In a large DHN, the base heat load of the network could be large enough to enable preheating all year around. Should this be possible, up to 30 GWh waste heat could be recovered to the DHN annually through sawmill integration according to system C.

System D - Production of feed water by increased fuel consumption
A small DHN might not be able to receive large amounts of low temperature waste heat. To enable delivery of waste heat to the DHN feed water, the temperature of the recovered heat is thus raised in the boiler, see figure 5.12. It is assumed that the boiler capacity is limited, so the investment cost will include the cost for increased boiler capacity.

The amount of waste heat sold to the DHN is the same as in system C, 3.4 MW, but since the boiler capacity is increased with 2.5 MW, it is now possible to recover an additional 0.9 MW heat in the flue gas condenser. System D thus produces 3.4 MW more heat for the DHN as compared to system C, but all this heat is viewed
as prime heat. The total amount of heat sold to the DHN is thus 32 GWh, of which 17 GWh, or 170 kWh per m³ dried wood, is waste heat.

![Diagram](image)

Figure 5.12: System D, a sawmill integrated with the DHN, producing feed water to the DHN from the waste heat by burning of additional fuel.

## 5.3 Results and discussion

The potential for efficient heat recovery is dependent on the local and regional energy system and socio-technical environment in which the specific sawmill is situated. The result of this study implies that it is economically and technically possible to recover between 9 and 50% of the heat used at a sawmill. To implement the proposed measures, the economic and technical prerequisites must be met, but there must also be an awareness of energy related issues and a will to act. The latter parameters have not been examined in this study.

### 5.3.1 Potential savings through heat recovery

The amount of heat recovered through the proposed measures is shown in table 5.1 and compared to the annual heat demand of the reference sawmill (34 GWh). It is shown that the potential for energy savings within a stand-alone sawmill is about 9%, if a conventional heat recovery system is used. This is at the lower end of the potential spectra according to some main European manufactures, whom estimate the potential savings of 10-23% (Cooper G, 2003). This is not surprising, however, since the potential for heat recovery depend on the temperature in the drying kilns, see figure 5.2. With a larger proportion of LTD than in the reference sawmill, the amount of saved heat through internal heat recovery measures would increase. One of the manufacturers further reported a PBP just over two years for a retrofitted system installed on existing batch drying kilns. This agrees well with the findings of this study, where the PBP was calculated to 2.3 years.
When flue gas condensation is implemented at a sawmill, as proposed in system B, the potential for heat recovery is about 18% of the heat demand of the reference sawmill. The investment cost is higher than for conventional heat recovery, but the PBP is only slightly longer. Benefits of System B, compared to System A, are a higher degree of waste heat recovery, lowered CO₂-emissions and lowered emissions of VOC.

Table 5.1: Results from calculations. Based on the reference sawmill (100 000 m³ dried wood per year).

<table>
<thead>
<tr>
<th>Stand alone sawmill</th>
<th>Integration with district heating</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>System A</td>
</tr>
<tr>
<td></td>
<td>Conventional recuperation</td>
</tr>
<tr>
<td>Recovered heat [GWh/year]</td>
<td>2.9</td>
</tr>
<tr>
<td>Recovered heat [% of RS]</td>
<td>9</td>
</tr>
<tr>
<td>Investment cost [M€]</td>
<td>0.07 VII</td>
</tr>
<tr>
<td>Income [M€/year]</td>
<td>0.03</td>
</tr>
<tr>
<td>Operational cost [M€/year]</td>
<td>-</td>
</tr>
<tr>
<td>PBP [year]</td>
<td>2.3</td>
</tr>
<tr>
<td>CO₂ reduction [kt CO₂/year]</td>
<td>1.3</td>
</tr>
<tr>
<td>Impact on VOC emissions</td>
<td>Unchanged</td>
</tr>
</tbody>
</table>

1 8000 operating hours for dryers and 5000 operating hours for comfort heating and DHN.
2 As compared to the heat demand of the reference sawmill (34 GWh).
3 Income from sold fuel and heat. The amount of fuel is calculated with a boiler efficiency of 0.8.
4 PBP=Investment cost/(Income–Operational cost)
5 For system A and B, it is assumed that the proposed measures saves biofuel, which is sold and replaces coal somewhere else in the energy system. In systems C and D, it is assumed that waste heat is sold to the DHN, replacing either heat produced from oil or coal. See chapter 3.3 for more information.
6 Note that an additional 17 GWh heat/year, which is not included here, is also sold to the DHN due to the increased boiler capacity.
7 Air-air heat recuperators (0.07 M€)
8 Flue gas condenser (0.16 M€) + heat exchangers and glycol system (0.07 M€)
9 Flue gas condenser (0.20 M€) + Drying gas condenser (0.31 M€)
10 Flue gas condenser (0.32 M€) + Drying gas condenser (0.31 M€) + increased boiler efficiency (0.35 M€)
11 Increased fuel demand. The amount of fuel is calculated with a boiler efficiency of 0.8.

When the sawmill can be integrated with the DHN, as much as 50% of the heat demand of the sawmill can be recovered. However, it is only possible to sell waste heat to a DHN if the distance to the municipality and the DHN is short, since the total investment cost for the integration largely depends on the cost for piping. There are approximately 20-30 Swedish sawmills that are integrated with a DHN today, but none of these sawmills sell waste heat from the drying kilns to the network. The sawmills can instead buy heat from the DHN and the biofuel boiler at the sawmill can also be owned by or out-sourced to an energy company. A typical installation involves a boiler close to the sawmill fired by sawmill by-products. The heat for drying the sawn wood is taken from the hot water circuit of the boiler and the rest of the heat, including possible flue gas condensation, is exported to the DHN. However, a demonstration plant, where waste heat is to be
sold to a DHN, is planned to be installed at a sawmill in southern Sweden during year 2004 (Lundmark, 2003).

The annual consumption of biofuels in the Swedish SMI is approximately 6 TWh. Assuming that 20% of the production capacity of sawn wood is performed at sawmills integrated with the DHN, about 0.5 TWh of heat can be sold to district heating plants every year. The potential for internal heat recovery is a further 0.9 TWh of biofuel annually if all stand-alone sawmills implement heat recovery equipment.

5.3.2 **Economic aspects**

Even though conservative economic data are used in the feasibility assessment of this study, short payback periods (PBP), 2-3 years, are calculated. The measures proposed for stand-alone sawmills are judged to be economically feasible for most sawmills, while integration with the DHN is assumed to be economically feasible for medium-sized and large sawmills due to economies of scale.

5.3.3 **Environmental aspects**

The environmental impact of energy savings in the SMI is both local and global. Locally, the emissions of VOC can be lowered due to re-circulating the air from the HTD kiln and utilising the exit air from the dryers as the combustion air in the biofuel boiler. Globally, the CO$_2$ emissions can be lowered as saved biofuel is used to replace fossil fuels. Saved fuel is assumed to replace coal and waste heat sold to the district heating net is assumed to replace coal- or oil based heat.

5.3.4 **Systems aspects**

The technical prerequisites to integrate sawmills with the DHN are better at sawmills with a large share of HTD, since the temperature of the waste heat then is higher. The economic prerequisites are dependent on many things, one being the size of the network. In a smaller network, the base load demand might not be large enough during the warm months to make use of all the waste heat. For the calculations, it is assumed that heat can be sold to the DHN during 5000 hours/year and that the energy company pays for the connection. In a large network, the waste heat can constitute the base load of the system and thus be utilized all year around, thus increasing the amount of waste heat that is utilised considerably compared to the results of this study. This further decreases the emissions of VOC and CO$_2$ and improves the economic feasibility of the investment. It should also be noted that the existing heat production facilities of the DHN affects the potential for integration. If the heat plant is fired by waste
incineration, the fuel costs for such a plant are negative, and hence it is difficult for industrial waste heat to compete.

5.4 Conclusions

- The potential for energy savings at a sawmill depends on the local energy system in which the sawmill is situated. Being located close to a DHN improves the potential for heat recovery as compared to stand-alone sawmills.

- The result of the study is that 9-50% of the heat duty of the sawmill can be recovered through the proposed measures.

- All the proposed measures are judged to be economically sound.

- Assuming that biofuel is a limited resource, the energy conserving measures in the sawmill industry results in lowered global CO₂ emissions.

- Re-circulation of humid air enables effective reduction of VOC emissions.

- The potential for savings within the entire Swedish SMI through heat recovery is estimated to about 0.9 TWh of biofuel, and 0.5 TWh of waste heat, annually.
6 Integrated pellet production

This chapter is based on papers I and II, and evaluates the economic and technical potential for improving the energy efficiency of pellet production by integrating the drying process with a sawmill. The environmental impact of the integrated system and socio-technical obstacles and success factors for the formation of a bio-energy combine are identified. The sawmill integrated pellet production is compared to both a stand-alone production unit and a pellet plant integrated with a pulp mill.

There are several reasons why biofuel upgrading integrated with a sawmill is advantageous. One reason is an almost constant heat demand over the year, which promotes a high degree of utilisation of the recovered heat. Another reason is that the sawmills constitute a network over the geographical areas where the woody biomass grows, with an already existing transport system for both the biomass raw material and for the upgraded products. The integration of sawmills with biofuel upgrading enables a more efficient use of know-how, personnel and equipment compared to stand-alone biofuel upgrading.

6.1 Upgrading of biofuel

Upgrading biofuels enhances the energy density of the fuel and enables long-term storage and more economical and environmentally efficient transportation. Furthermore, the upgraded fuel can be used in new markets, such as replacing oil in domestic houses or in the power industry. The production of pellets from sawdust, bark, wood chips or other wood residues is one way of upgrading biomass to a fuel with a higher energy density. When wet biofuel is dried and further upgraded to pellets, a significant amount of heat is needed in the drying process, making the development of more energy efficient production methods important.

6.1.1 The pellet market

The pellet industry grew rapidly during the 1990s; this was partly due to the energy and environmental taxes on fossil fuels, and partly due to the situation in the biofuel market (Roos et al, 1999). As the particleboard industry decreased production, excess sawdust became available on the market (Geißhöfer et al, 2000). Sweden, together with USA and Canada, is one of the world’s largest producers of pellets with an annual production capacity of 1 million tonne pellets (about 5 TWh) (Olsson, 2001). The market for fuel pellets is growing in several European countries, such as Denmark, Austria, Finland and Germany, see for example Berggren (2003), Cotton & Griffard (2001) and (Fisher, 2002). Examples of existing Swedish pellet production factories combined with industry are found in, for example, the pulp industry (Mönsterås), at heat and power plants (Skellefteå) and at district
heating plants (Värnamo, Norberg). There is also an example of biofuel upgrading at a sawmill (Forssjöbruk) where the biofuel is dried in a direct contact flue gas dryer.

6.1.2 The pellet production process
The technical analysis is in this study based on the integration of the biofuel drying process with a sawmill. The pellet production process further includes forming pellets from the dry biofuel, a process step which is viewed as a black box in this study, since it does not influence the prerequisites for integration.

Dryers can be divided into two groups based on their heat transfer principle: direct- and indirect-heated dryers. The most common biofuel dryer is the atmospheric direct-heated flue gas dryer, which is relatively cheap and reliable (Wimmerstedt, 1999). In a direct-heated dryer, the water, which is evaporated from the biofuel is diluted by the drying media (e.g. air or flue gas). In an indirect-heated dryer, on the other hand, the heat carrier (e.g. steam, flue gases, water) does not come in direct contact with the biofuel and the dryer can thus operate under pressure or vacuum. Being less diluted and of a higher temperature, the latent heat in the waste steam from an indirect dryer is easier to recover and use in other processes by integration than the waste heat from a direct dryer. The indirect dryers are generally more expensive, but the operational costs can be held low if the dryer is integrated so that the waste heat from the dryer can be recovered.

6.2 Proposed system for integrating biofuel upgrading
Alternative integration possibilities for biofuel drying at the reference sawmill were evaluated in paper I, and a system was proposed where the biofuel dryer is integrated so that waste heat from the biofuel dryer heats the drying kilns, see figure 6.1. The temperature demand of the waste heat implies the need for a pressurised biofuel dryer, and a flash steam dryer has been chosen for the analysis.

Since the dryer is connected in series with the boiler and the drying kiln, primary energy is used for biofuel drying and waste heat is used for the wood drying kilns. The design parameters for biofuel drying are defined by the process parameters of the drying kiln, so that the waste heat from the dryer covers the average heat load of the drying kilns at the sawmill. The production capacity of the integrated process is then calculated to about 5 tonnes of pellets per hour (40 thousand tonnes annually), resulting in a product mix of about 2 MWh pellets per m³ dried wood. Should comfort heating in the sawmill buildings also be covered by waste heat from the biofuel dryer, the production capacity of pellets would need to increase to about 6 tonnes per hour. It is, however, assumed that the sawmill buildings are
heated by waste heat from e.g. condensation of drying exhaust gases or flue gases from the boiler.

To ensure the operation of the board-drying kilns, and to provide enough heat during peak load, an extra warm water system provides the drying kilns with energy. To further improve the energy efficiency, the condensate of the waste steam can be used to pre-heat the inlet air to the drying kilns. The system should also be equipped with a cooling tower, if free cooling is not available, so that the biofuel dryer can be used stand-alone, if necessary.

### 6.2.1 The reference pellet plants

The proposed system for integrating pellet production is compared to two reference pellet plants, one stand-alone plant and one plant which is integrated with a pulp mill. The pulp mill combine is based on Andersson et al (2003). Both reference plants use atmospheric flue gas dryers for drying the biofuel, see figure 6.2 and 6.3.

There are different types of direct flue gas dryers and the choice of equipment depends on the temperature of the flue gases. In stand-alone pellet production, the temperature of the boiler flue gas is high and the cheaper rotary drum dryer can be used. When the drying is integrated so that waste heat from, e.g. a pulp mill, is used
for drying, the temperatures of the flue gases are lower which makes more expensive techniques, such as the flash dryer, necessary.

### 6.3 Results and discussion

The economic and environmental analysis consists of a comparison between pellets produced in an integrated and a stand-alone pellet plant. The technical analysis is based on the integration of the drying processes, but it is assumed that the dried biofuel is further refined into pellets. The economic analysis therefore includes the entire pellet production process, including cooling and storage, see table 6.1. The production cost for the integrated pellet plant is according to the economic evaluation, equal to, or lower, than the stand-alone case. Furthermore, the environmental benefits from integrated pellet production in the SMI are decreased CO₂ and VOC emissions. It is assumed that the biofuel is dried from 55% to 10% water content (expressed as kg water/kg wet fuel). For each tonne of pellets produced, one tonne of water is thus evaporated. The HHV is set to 20.8 MJ/kg dry substance.

#### 6.3.1 The efficiency of upgrading

The upgrading efficiency (η_{ug}) of the integrated pellet plants have been calculated using equation 6.1 and 6.2, and compared to the efficiency of a stand-alone plant. The energy contents of the pellets (E_p) and the raw material (E_{rm}) are based on the lower heating value (LHV). The net heat demand (Q_{net}) and the electricity demand (W_{el}) of the process are accounted for and it is assumed that electricity is produced in a power plant with 40% efficiency (η_{el}) and heat is produced in a boiler with 80% efficiency (η_{b}). The net heat demand is the difference between heat input (Q_{in}) to the pellet plant, and the recovered waste heat (Q_{rc}) from the plant, see equation 6.2.

\[
\eta_{ug} = \frac{E_p}{E_{rm} + \frac{W_{el}}{\eta_{el}} + \frac{Q_{net}}{\eta_{b}}} \quad \text{(Equation 6.1)}
\]

\[
Q_{net} = Q_{in} - Q_{rc} \quad \text{(Equation 6.2)}
\]

In figures 6.4-6.6, the efficiency of upgrading of 1 MWh of wet biofuel (218 kg dry fuel) to pellets is shown. It can be seen that sawmill integration and pulp mill integration are equally efficient and both enable about 20% more pellets to be produced from a limited amount of wet biofuel as compared to the stand-alone pellet plant.
Table 6.1 Comparison between different systems for the production of biofuel pellets. It is assumed that the biofuel is dried from 55% to 10% water content and that the HHV is 20.8 MJ/kg dry substance.

<table>
<thead>
<tr>
<th>Drying technique</th>
<th>Sawmill-integrated pellet production</th>
<th>Pulp mill integrated pellet production</th>
<th>Stand-alone pellet production</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pressurised steam dryer (flash dryer)</td>
<td>Atmospheric flue gas dryer (flash dryer)</td>
<td>Atmospheric flue gas dryer (rotary dryer)</td>
</tr>
<tr>
<td>Production capacity [tonnes pellets/year]</td>
<td>40 000</td>
<td>70 000</td>
<td>40 000</td>
</tr>
<tr>
<td>Energy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net heat demand I [kWh heat/MWh pellets]</td>
<td>17</td>
<td>0</td>
<td>174</td>
</tr>
<tr>
<td>Electricity demand, dryer II [kWh electricity/MWh pellets]</td>
<td>8</td>
<td>17</td>
<td>6</td>
</tr>
<tr>
<td>Electricity demand, pelletisation [kWh electricity/MWh pellets]</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Net fuel demand of the pellet plant III [kWh fuel/MWh pellets]</td>
<td>79</td>
<td>78</td>
<td>269</td>
</tr>
<tr>
<td>Energy content of raw material (55% water) based on LHV [kWh raw material/MWh pellets]</td>
<td>858</td>
<td>858</td>
<td>858</td>
</tr>
<tr>
<td>Efficiency of upgrading IV [%]</td>
<td>107</td>
<td>107</td>
<td>89</td>
</tr>
<tr>
<td>Economy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total investment cost for pellet plant V [M€]</td>
<td>4.3</td>
<td>5.4</td>
<td>3.5</td>
</tr>
<tr>
<td>Annual capital cost VI [M€ /year]</td>
<td>0.5</td>
<td>0.8</td>
<td>0.4</td>
</tr>
<tr>
<td>Annual operation cost VII [M€ /year]</td>
<td>0.7</td>
<td>1.1</td>
<td>0.9</td>
</tr>
<tr>
<td>Specific production cost for pellet plant VIII [€ /t pellets]</td>
<td>31</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>Environment IX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of CO₂ emissions X [kg CO₂/MWh pellets]</td>
<td>50-60</td>
<td>50-60</td>
<td>-</td>
</tr>
<tr>
<td>Impact on VOC emissions</td>
<td>Decreased</td>
<td>Unchanged</td>
<td>-</td>
</tr>
</tbody>
</table>

I The heat demand for energy efficient biofuel dryers are approximately 3000 kJ/kg evaporated water (Wimmerstedt & Linde, 1998). For the sawmill integration, it is assumed that 90% of the energy from the integrated steam dryer can be recovered. For the pulp mill case, the entire heat demand is covered by waste heat.

II Wimmerstedt (1999)

III It is assumed that heat is produced with an efficiency of 80% and electricity is produced with an efficiency of 40%.

IV The efficiency of the upgrading process is calculated as the energy content in the produced pellets divided by the energy content in the raw material and the net fuel demand of the pellet plant.

V Including grinding, drying, pelletisation, cooling and storage

VI The discount rate was set to 7% and the economic life was set to 10 years for process equipment and to 50 years for storage and buildings.

VII Including personnel, heat, electricity and maintenance.

VIII The specific production cost is calculated as the total annual cost (capital cost + operation cost) divided by the production capacity.

IX The environmental impact of the integrated pellet plant as compared to the stand-alone plant.

X The net fuel demand of the integrated processes is lower than for the stand-alone process. The saved fuel is assumed to substitute oil or coal and the resulting impact on global CO₂ emissions has been calculated. See chapter 6.3.3 for a discussion.
About 90% of the heat needed to dry the biomass in the sawmill integrated process can be recovered. The net heat demand of the sawmill is thus more or less unchanged, whereas the production is increased to include refined biofuel. The efficiency of biofuel upgrading is as high as 107% based on the LHV (92% based on the HHV).

![Figure 6.4: Sawmill integrated pellet plant.](image)

In figure 6.5 and 6.6, the reference systems are depicted. In the stand-alone pellet plant, a large portion of the available biofuel is used in the upgrading process, resulting in an upgrading efficiency of 89% based on the LHV and 76% based on the HHV. The efficiency of the furnace is set to 80%. This might seem low, but includes the heat losses due to the release of warm flue gases to the surroundings after the flue gas dryer.

![Figure 6.5: Stand-alone pellets plant](image)

The pulp mill integrated pellet plant uses only waste heat for drying, but has a somewhat higher electricity demand, and the efficiency of upgrading is the same as for the sawmill-integrated pellet plant, 107%.
6.3.2 Technical aspects

The development trend in the SMI is towards higher temperatures in the wood drying kilns. To satisfy this future temperature demand, the minimum temperature of the waste heat from the biofuel dryer has in this study been set to 120°C and pressurised indirect biofuel dryers are judged to be generally applicable for integration. Steam dryers are used for biofuel drying today, so to facilitate the economic analysis, a steam dryer is chosen for the integration. It can, however, be argued that an indirect flue gas dryer would be a more convenient choice since sawmills seldom have access to a steam system.

An alternative to the pressurised dryers could be the combination of atmospheric biofuel drying and heat pumps. The waste heat from atmospheric, flue gas driven biofuel dryers is 80-85°C, which is too low to enable direct integration with the wood drying kilns. If an atmospheric steam dryer is used, the waste heat temperature is higher, reaching 100°C in the ideal case, but still too low for most sawmills. The open absorption heat pump, see chapter 5.1.5, can be an interesting technique for upgrading of the waste heat.

It is important to consider the operating experiences for different types of techniques, as an important factor for a company when investing in a new process is the risk involved. Biofuel drying has suffered from difficulties where the established techniques, such as flue gas dryers, have had problems with fires, odour, high energy consumption and emissions, while the new technologies, such as steam dryers, have had performance problems (Martin & Säterberg, 2001). Wimmerstedt (1999) also highlights the problems with feeding and removing material from the pressure chamber in steam dryers as well as problems with corrosion. The risk of integrated pellet production causing operational disturbances.
may be an obstacle for an investment decision. However, the growing amount of experience from the operation of existing units is a valuable asset for the implementation of new pellet plants.

### 6.3.3 Environmental aspects

The environmental impacts of integrated pellet production are both local and global. The system’s effect on the emissions of CO₂, which contribute to the greenhouse gas effect, is of a global character, while, for example, the emissions of VOC from the drying process are of a local character.

**VOC**

The biofuel drying process proposed for integration with the SMI is indirect and enables better emission control than the reference stand-alone drying process. After the indirect dryer, the waste steam from the biofuel dryer is condensed to recover the heat. The resulting condensate can be treated by precipitation and biological oxidation and led to a recipient, while the uncondensable gases (e.g. terpenes) can be destroyed in the boiler. In direct drying processes, the organic compounds are diluted in the flue gases and usually emitted directly to the air after the biofuel dryer. The proposed biofuel drying process for integration with the pulp industry is atmospheric and has the same impact on the local environment as the stand-alone reference plant.

**CO₂**

The impact on global CO₂ emissions by the integrated pellet production can be calculated in several different ways, giving somewhat different results. Here, the fuel saving of the integrated process compared to the stand-alone process is considered. Saved fuel is assumed to replace coal elsewhere in the energy system, decreasing global emissions of CO₂ with about 60 kg per MWh produced pellets.

Another way to calculate the CO₂ impact, used in paper I, is to assume that saved fuel is further upgraded to pellets. It was there assumed that the additionally produced pellets, compared to a stand-alone pellet plant, was used to replace oil with the ratio 1:0.9, resulting in a lower CO₂ impact than calculated here. It is beyond the scope of this study to determine how the CO₂ impact best is calculated.

### 6.3.4 Economic aspects

The economic evaluation of integrated pellet production includes two different analyses. In the first analysis, the feasibility of the increased investment in an integrated process is calculated using the payback period (PBP). The aim is to estimate the PBP of the heat recovery measure without considering the economic
feasibility of pellet production. In the second analysis, however, the economic prerequisite for pellet production is evaluated.

**Payback period for the energy related investment**

Since the choice of drying technique for biofuel drying is made based on its favourable properties for integration, the payback period for the investment has been calculated as the increased investment relative to a more conventional atmospheric flue gas dryer, see figure 6.7. The investment cost for efficient heat recovery thus includes the cost difference between a pressurized dryer (steam dryer) and an atmospheric dryer (flue gas dryer) plus a steam condenser and a steam system. If, however, the investment decision for a biofuel upgrading process coincides with the need to re-invest in a new boiler, the steam system can be assumed to replace the more common hot water system for heating at no cost. The payback period would then be around 2 years for a production capacity of 5 tonne pellets/h as compared to 4-5 years when a new boiler is included in the investment cost.

As can be seen in figure 6.7, the production capacity influences the economic prerequisites for upgrading. A larger production capacity brings about large-scale advantages that lower the investment cost and thereby also the specific production cost. How the pellet plant should be optimally dimensioned is a balance between the prerequisites for heat recovery, economies of scale, the market size, the local assets of raw material etc.

![Figure 6.7: The payback period for the extra investment in an integrated dryer compared to a stand-alone dryer as a function of the production capacity. The investment cost for the steam dryer includes the cost for steam system and condenser. A scale factor of 0.7 was used for the calculations.](image)

**Feasibility of integrated pellet production**

There is a large price gap between pellets sold to the large- and small-scale markets, according to information from the Swedish Energy Agency (STEM, 2002b) and information from producers. There are also diversified prices for the raw material. The pellet price on the small-scale market (for example private houses and schools)
is around 30 €/MWh. This is significantly higher than the price paid by large-scale consumers (such as heat plants), which is around 20 €/MWh. However, costs for, e.g. marketing and handling of the product, might increase the cost for pellet production when the product is to be sold on the small-scale market.

In figure 6.8, the specific production cost for pellets is plotted for different discount rates. The production cost is compared with the added value (the price difference between the wet fuel and the upgraded fuel) for pellets sold on different markets to show the impact of the market mix on the profitability of the pellet factory. It can be seen that it is difficult to evaluate the feasibility of a pellet plant without closer knowledge of the market mix, i.e. the share of production that will be sold on the large- and small-scale market, respectively.

This was also confirmed in a sensitivity analysis presented in paper II, where the payback periods for pellet plants integrated with a sawmill and a pulp mill, respectively, were calculated. The pulp mill was assumed to produce bark pellets and the sawmill was assumed to produce pellets from sawdust or wood chips. When a cheaper raw material, such as bark, is used to produce pellets, the product can only be sold to large-scale consumers, since bark pellets are not as suitable for small-scale combustion. When using a high quality raw material such as sawdust, the pellets can be sold either via long-term contracts to large-scale consumers or on the open market to small-scale consumers. The payback period was shown to be less than two years for pulp mill integration and between two and eight years for sawmill integration depending on the market mix. The longer payback period for the sawmill case corresponded to a scenario where all the pellets were sold to the large-scale market, which yields a lower added value for the pellets. To minimise the risk of long payback periods for pellet plants producing pellets from sawdust, it is thus important that a local small-scale market for pellets exists. For the pulp mill
In paper II, the socio-technical aspects of integration of a pellet plant with the forest industry were evaluated through case studies and this section summarises the main conclusions.

It was seen in the case studies that policy issues and market factors were important for the decision to invest in a pellet factory. The profitability of an investment is, of course, crucial for the investment decision and the demanded payback periods for investments were less than three years in the studied industries. However, longer payback periods were accepted for strategic investments. The informants felt that the instability of the bio energy market could be an obstacle, since the profitability of the project is important in the decision-making process. One of the most important factors for the realisation of the biofuel combines was a surplus of the by-products bark and sawdust, which can be used as raw material for pellets.

Wahlund et al (2002) studied pellet production integrated with heat and power production and found that global environmental issues had little or no influence on the decision-making process in those companies. It was confirmed by the case studies that local environmental aspects had a greater influence on, for example, the choice of equipment. An example of this is that a pulp mill included in the study chose an indirect steam dryer for pellet production due to lower VOC emissions, although a direct-contact flue gas dryer would have been cheaper. The reason was that the company assumed that it would be hard to get permission for a direct biomass dryer with high VOC emissions.

6.4 Conclusions

- A pressurised, indirect biofuel dryer enables the efficient integration of pellet production with a sawmill.

- The net heat demand of a sawmill is more or less unchanged when integrated with a pellet plant, whereas the production is increased to include refined biofuel.

- The upgrading efficiency of an integrated pellet plant can be as high as 107% (based on LHV) as compared to 89% in a stand-alone production process.
• Assuming that biofuel is a limited resource, fuel savings due to the more efficient upgrading process can be used to replace fossil fuels elsewhere in the energy system, thus contributing to lowered CO₂ emissions.

• Indirect drying techniques enable effective VOC abatement.

• The economic feasibility of pellet production is good, but the uncertainties due to market factors are large.
7 Co-production of heat and power

A new market based policy instrument, green certificates, was introduced to the Swedish power market in 2003, promoting electricity production from renewable energy sources. Through the system with green certificates, it is today possible to receive an additional 20 €/MWh over the market price (of about 30 €/MWh) for electricity produced from biofuels. This suggests that the potential for co-production of electricity at sawmills should be examined. There is also an ongoing expansion of small-scale biomass fuelled CHP plants at Finnish sawmills, furthermore implying the need for a study of the Swedish prerequisites for sawmill based electricity production.

The objective of this chapter is to depict the present development of small-scale co-production of heat and electricity in the SMI, and hence enable a more comprehensive description of the SMI as a producer of sustainable energy products. An overview of combined heat and power production (CHP) in the SMI has thus been performed, based on written information from market actors as well as newspaper articles and other published material.

7.1 State-of-the-art

Savola et al (2003) have reviewed the state-of-the-art for small-scale CHP plants using biofuels. The most common technique in the Nordic countries in the range of 1-20 MW \(_{el}\) is the Rankine cycle (steam turbine). The electrical efficiencies are 10-15\% for the smallest plants (< 5 MW \(_{el}\)) while the corresponding figures for larger plants are 20-30\%. The total efficiency is usually 85-90\% (105\% if flue gas condensation is utilised). The specific cost for steam turbines below 5 MW \(_{el}\) is 300-650 €/kW according to Nyström et al (2001). Gas engines are common for the smallest CHP plants (< 1 MW \(_{el}\)) and their electrical efficiencies are 30-40\%. The fuel can for example be gasified biomass, as is the case at the Finnish CHP plant in Tervola. According to Savola et al, the specific cost for some commercial and demonstration plants around 1 MW \(_{el}\) is about 550 €/kW (not including gasification of biomass).

7.2 Existing CHP plants

In table 7.1, data for some commercially operating small-scale biofuel based CHP-plants have been compiled. There are a few small bio-fuelled CHP plants in the
Swedish wood industry. Two examples are Malå and Myresjö sawmills, which both have implemented backpressure steam turbines and the heat is used for wood drying, comfort heating of process buildings and district heating (Nyström et al, 2001). Lately, there have also been a number of CHP plants based on the Rankine cycle taken into operation integrated with Finnish and Irish sawmills. The electrical outputs of these plants are typically between 1 and 3 MWel and the plants are designed for moderate steam data (around 20 bar/350°C.). According to one manufacturer, it is a high degree of modularisation and standardisation together with the European and national subsidy schemes that makes the sawmill market available for co-production of electricity (Wärtsilä, 2003).

According to Ahlbeck et al (1987), almost all large West German sawmills had steam engines to cover the internal power demand during the eighties, due to the high price of electricity. The profitability of small-scale CHP has, however, been low in Sweden and many of the existing plants have received subsidies. For steam cycles, the problem is often the high investment cost of the steam boiler whereas the turbines are standardized and relatively cheap (Nyström et al, 2001). In a CHP plant in Eksjö, a steam generator is used to produce low-pressure steam for a 1 MWel turbine directly from hot water, hence avoiding the investment cost for a steam boiler. Kullendorff and Tilly (1997) argue that it is essential to take the secondary economic consequences of small-scale co-production into consideration when evaluating the feasibility of an investment, such as lowered fees due to a decreased power outtake from the net and possible tax savings.

7.3 The potential for sawmill-integrated CHP

The heat load at a sawmill is more or less constant over the year and electricity stand for about 15-20% of the annual energy demand. The drying kilns operate around the clock, however, whereas the sawmill itself might only operate during daytime. The heat demand is thus more constant than the electricity demand and the dimensioning of the CHP plant depend on the prerequisites for selling surplus heat and electricity on the external market.

Even though the economic environment for small-scale CHP has been harsh, there are factors favouring sawmill-integrated CHP plants. An example is the present development towards a concentration of the production of sawn wood to a fewer number of large sawmills, thus increasing the heat load in these mills. Moreover, integration with district heating plants and subsidies from green certificates further improves the conditions for CHP production. Simultaneous investment in a steam

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6 The electricity demand in sawmills was according to Stridsberg & Sandqvist (1985) about 85 kWh/m³ sawn wood divided at sawing (25-30%) and drying of wood (35-40%). For the reference sawmill this lead to an average power demand of 1 MW as compared to the heat demand of 4,5 MW.
Table 7.1 Compiled characteristics for some commercially operating small-scale biofuel based CHP-plants. The information is based on written information from market actors as well as newspaper articles and other published material.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Start-up year</th>
<th>Power output/Thermal capacity</th>
<th>Technique</th>
<th>Comments</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malå sawmill, Sweden</td>
<td></td>
<td>3 MW&lt;sub&gt;el&lt;/sub&gt;/12 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Steam turbine</td>
<td>Heat for drying and DHN. Produces 230 000 m³ sawn wood/year.</td>
<td></td>
</tr>
<tr>
<td>Myresjö sawmill, Sweden</td>
<td></td>
<td>1.6 MW&lt;sub&gt;el&lt;/sub&gt;/7 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Steam turbine</td>
<td>Heat for drying and comfort heating.</td>
<td></td>
</tr>
<tr>
<td>Lieksa, Vapo Timber, Finland</td>
<td>1994</td>
<td>8 ME&lt;sub&gt;el&lt;/sub&gt;/22 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>CFB + Steam turbine</td>
<td>Heat for sawmill + DHN. Surplus electricity is sold to the community.</td>
<td>Kvaerner Power/Fortum engineering</td>
</tr>
<tr>
<td>Eksjö CHP plant, Sweden</td>
<td>1997</td>
<td>1 MW&lt;sub&gt;el&lt;/sub&gt;/7 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Flash steam generator + Steam turbine</td>
<td>Low-pressure steam from flash generator (10 bar). Investment cost 0.7 M€.</td>
<td></td>
</tr>
<tr>
<td>Kiuruvesi, Finland</td>
<td>1999</td>
<td>0.9 MW&lt;sub&gt;el&lt;/sub&gt;/8 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Boiler + steam engine (25 bar, 350°C)</td>
<td>Heat for sawmill and DHN.</td>
<td>Sermet Oy (Wärtsilä co-operation)</td>
</tr>
<tr>
<td>Buchanan Flooring, Alabama, USA</td>
<td>1999</td>
<td>-</td>
<td>Boiler + steam turbine</td>
<td>Heat for drying kilns and electricity for internal use. Excess electricity is sold to a neighbour industry.</td>
<td>SEECCO</td>
</tr>
<tr>
<td>Honkarakenne Oy, Karstula, Finland</td>
<td>2000</td>
<td>1 MW&lt;sub&gt;el&lt;/sub&gt;/10 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Boiler + Steam engine (22 bar, 350°C)</td>
<td>Electricity for a wood processing company. Heat for wood drying and DHN. Investment cost 4.5 M€.</td>
<td>Sermet Oy (Wärtsilä co-operation)</td>
</tr>
<tr>
<td>Tervola CHP, Finland</td>
<td>2001</td>
<td>0.5 MW&lt;sub&gt;el&lt;/sub&gt;/1.1 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Gasification + gas engine</td>
<td>Heat for DHN. Investment cost 1.2 M€. Total efficiency around 80%.</td>
<td>Entimos Ltd /VTT Energy</td>
</tr>
<tr>
<td>Vippula sawmill, Finland</td>
<td>2003</td>
<td>2.9 MW&lt;sub&gt;el&lt;/sub&gt;/13.5 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Boiler + Steam turbine</td>
<td>One of the largest sawmills in Europe (600 000 m³/y). Power for internal use and heat for drying + DHN</td>
<td>Wärtsilä Biopower</td>
</tr>
<tr>
<td>Renko sawmill, Finland</td>
<td>2003</td>
<td>1.3 MW&lt;sub&gt;el&lt;/sub&gt;/8 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Boiler + Steam turbine</td>
<td>Heat for drying of wood and 50% of the sawmills power demand.</td>
<td>Wärtsilä Biopower</td>
</tr>
<tr>
<td>Grainger sawmill, Ireland</td>
<td>2004</td>
<td>1.8 ME&lt;sub&gt;el&lt;/sub&gt;/3.5 MW&lt;sub&gt;th&lt;/sub&gt;</td>
<td>Boiler + Steam turbine</td>
<td>Heat for sawmill and DHN.</td>
<td>Wärtsilä Biopower</td>
</tr>
</tbody>
</table>
dryer for biofuel drying, a steam system and a steam turbine might also improve the feasibility of a CHP-project. The potential for small-scale CHP further depends on the technique used.

If the heat load in medium-sized and large Swedish sawmills should be fully exploited as heat sinks for biomass fuelled CHP plants\textsuperscript{7}, 0.5 TWh power can be produced annually if steam turbines with an electric efficiency of 10% are used. If small-scale gasification and a gas engines, similar to the plant in Tervola, Finland, are utilised, the potential is more than the double, about 1.1 TWh.

7.4 CO\textsubscript{2} impact of small-scale CHP

To enable a rough estimation of the CO\textsubscript{2} impact of sawmill integrated power production, it is assumed that the potential for electricity production at small-scale CHP plants in the Swedish sawmill industry is about 0.8 TWh (see discussion above). It is further assumed that the total efficiency of the CHP plants is 80%. The amount of biofuel needed to produce the electricity is thus 1 TWh.

Assuming that the marginal method of electricity production is coal based condense power, global CO\textsubscript{2} emissions will be decreased by 820 kg CO\textsubscript{2} per MWh of electricity produced in a biofuel CHP plant. But, since biofuel is a limited resource, the alternative use of the biofuel must be accounted for. In this study, it is assumed that biofuel can replace coal, thus inhibiting 330 kg CO\textsubscript{2} per MWh fuel to be emitted. The CO\textsubscript{2} impact of sawmill integrated CHP is accordingly 408 kg CO\textsubscript{2} per MWh green electricity, corresponding to about 0.3 Mt CO\textsubscript{2} annually, based on the Swedish potential.

It should here be noted how important the choice of reference system for CO\textsubscript{2} calculations are. In a long-term perspective, it can be argued that the marginal method of electricity production will be based on natural gas (STEM, 2002c), and the emissions from a NGCC plant is approximately 350 kg CO\textsubscript{2} per MWh electricity. Hence, if the alternative use for biofuel still is to replace coal, the result of small-scale electricity production will be an increase of global CO\textsubscript{2} emissions.

\textsuperscript{7} The annual utilisation of biofuel in the sawmill industry is about 6 TWh, and 80% of production is performed at sawmills with a production capacity above 50 000 m\textsuperscript{3} sawn wood/year (here called medium- and large-sized sawmills).
8 Concluding remarks
This study clearly shows that the overall potential in the SMI to a more efficiently utilise and upgrade of biofuel is considerable, but also that it is essential to take the energy system in which the specific sawmill functions into consideration when evaluating its potential for heat recovery. In this chapter, the most important results from the study are presented and interesting areas for further research are suggested.

It is difficult to present the total potential for energy savings in the sawmill industry in an illustrative way, since the energy saved through the suggested measures is divided into different energy carriers (wet biofuel, pellets, waste heat and electricity) and the actual saving furthermore is realised at different places. Selling waste heat to the DHN saves fuel at the local heat plant, while an internal heat recovery measure saves biofuel at the sawmill. The production of electricity can, for example, save coal in a Danish power plant while efficient pellet production saves biofuel at the pellet plant (or can be said to produce extra pellets from a limited amount of wet biofuel).

8.1 Potential bio-energy savings in the sawmill industry
Below, the energy saving measures suggested in this thesis are summarised and environmental impacts are discussed. The estimations are based on an annual biofuel utilisation in the sawmill industry of about 6 TWh fuel, and that 80% of the industry output is attributed to sawmills with a production capacity above 50 000 m³ sawn wood/year (termed medium- and large-sized sawmills here). It is further assumed that 80% of the production is performed at stand-alone sawmills and that 20% of the sawmills in the future will be integrated with district heating.

8.1.1 Saving biofuel by internal heat recovery
The largest heat losses at sawmills can be traced to the release of warm, humid air from the drying kilns to the surrounding. In addition to drying the sawn wood, there is a need to heat the sawmill buildings during the cold season and a possible demand for cooling during the warm season. A simple measure for improved energy efficiency, here called conventional heat recovery, is recuperation between the dry, cool inlet air and the warm, humid outlet air. This conventional method can, according to this study, save 29 kWh/m³ dried wood, or about 9% of the heat demand at the reference sawmill. An alternative system for internal heat recovery proposed in this thesis utilises a wet scrubber system to condensate water from the flue gases of the biofuel boiler. The recovered heat is used for comfort heating and
pre-heating the inlet air to the dryers. The total amount of recovered heat is 64 kWh/m³ dried wood, or 18% of the heat demand at the reference sawmill.

Internal heat recovery measures are judged to be economically feasible at most sawmills, with PBPs calculated to 2-3 years. Assuming that all stand-alone sawmills implement the proposed equipment, thus saving 18% of the fuel demand, 0.9 TWh of biofuel is saved annually.

8.1.2 Waste heat for district heating

Through pre-heating the DHN’s return water, the low waste heat temperatures of a sawmill can be utilised. When feed water should be produced, improved temperatures will, however, be required. This can be accomplished by burning additional biofuel in the boiler or by implementing a heat pump. It is possible to recover 170 kWh/m³ sawn wood, or 50% of the sawmill’s annual heat demand, if the DHN can buy waste heat during 5000 hours/year. If the sawmill is integrated with a large DHN, it might be possible to sell waste heat all the year round, hence recovering over 80% of the plant’s annual heat demand.

At least 0.5 TWh waste heat per year can thus be sold to district heating plants, assuming that 20% of the production capacity of sawn wood is performed at sawmills that are, or can be, integrated with the DHN. The total amount of industrial waste heat sold to Swedish DHNs is today about 4 TWh annually.

8.1.3 Pellet production

There is a great potential to save energy by integrating biofuel upgrading with the SMI. An integrated biofuel upgrading process is so efficient (107% based in LHV) that it has the potential to increase the value of the available biofuel feedstock. Conventional upgrading at stand-alone pellet plants has an efficiency of about 89%. It can thus be concluded that about 20% more pellets can be produced from a limited amount of wet biofuel in an integrated production process compared to a stand-alone plant.

The integrated pellet production process has been shown to be economically feasible and the production cost for an integrated pellet plant is equal to, or lower than, the stand-alone case. It can be concluded from the economic calculations that the payback times are short, but the uncertainties are large. In order to make the biofuel-sawmill combine profitable it is important to have an advantageous market mix between large-scale and small-scale consumers.
The potential for energy savings through integrating pellet plants with the sawmill industry is estimated to be 1.9 TWh biofuel annually. It is then assumed that the total pellet production in Sweden increases from 5 TWh to 15 TWh and that all additional production is performed in integrated drying processes. It is further assumed that the alternative development would have been upgrading in stand-alone pellet plants.

8.1.4 Co-production of electricity
Co-production of electricity at sawmills is not widely implemented in Sweden today, but is developing in, for example, Finland. Favourable subsidies for green power production are an incentive for a similar development in the Swedish SMI, and the potential for power production is estimated to around 0.8 TWh/year. It is then assumed that the heat load at medium-sized and large Swedish sawmills is fully exploited as heat sinks for biomass fuelled CHP plants, and that a mix of steam turbines and gas motors are utilised.

8.1.5 Potential savings and its CO₂ impact
The potential energy savings of efficiently utilising and upgrading biofuels have been summarised in chapter 8.1.1-8.1.5. Here, a rough estimation of the CO₂ impact of these improvements is presented:

- Internal heat recovery measures can save 0.9 TWh of biofuel. If the wet biofuel is assumed to replace coal, global CO₂ emissions are decreased with 0.3 Mt annually.
- The potential for waste heat utilisation in the national DHN is 0.5 TWh and if this waste heat replaces coal or oil-based heat, between 0.1 and 0.2 Mt CO₂ emissions can be avoided annually.
- The future Swedish annual pellet production is assumed to increase by 10 TWh of pellets. About 1.9 TWh of biofuel can then be saved through integrating the new production capacity with the sawmill industry. If the saved biofuel replaces coal, global CO₂ emissions are decreased with 0.6 Mt annually.
- The potential power production through small-scale CHP is estimated to 0.8 TWh and the corresponding fuel demand is estimated to 1 TWh of biofuel. It is assumed that the produced power replaces CCP or NGCC and that the alternative use for the biofuel used in the CHP plant would have been to replace coal. The CO₂ impact with CCP as marginal electricity production is decreased emissions by 0.3 Mt CO₂ annually. Should NGCC be the marginal method of production, the result would instead be an increase of 0.05 Mt CO₂ annually.
The total amount of CO$_2$ emissions which can be avoided every year if the stated potential is fully exploited is thus 1.0-1.5 Mt. This corresponds to between 1 and 2% of the annual Swedish emission of CO$_2$ equivalents, which was approximately 70 Mt in year 2001 (Hjelm-Wallén, 2001).

The Swedish government’s ambition is to decrease the emissions of greenhouse gases by 4% until 2008-2012 as compared to year 1990 (STEM, 2003). However, the estimated CO$_2$ impact is of global character, and does not necessarily directly impact upon the Swedish CO$_2$ emissions. Furthermore, sawmills have no incentive to reduce global emissions of CO$_2$, since the CO$_2$ savings calculated in this thesis are indirect effects. Even though Sweden has high CO$_2$ taxes, the proposed measures address a more efficient utilisation of biofuel, which is not affected by any policy instruments (except the green certificates for power production). Instead, the sawmills will be indirectly affected by policy measures, since CO$_2$ taxes, green certificates and tradable emission permits increase the demand for biofuel on the energy market.

8.1.6 Impact on VOC emissions

Both VOCs and COCs are emitted when wood is dried. The annual VOC emission from the Swedish SMI is estimated to approximately 7500 tonnes and drying of biofuels bring about additional emissions.

The proposed measures to increase the SMI’s energy efficiency also reduce the amount of VOC emitted, since less polluted exhaust air from wood and biofuel drying is directly emitted to the surroundings. One example is recycling the exit air from the wood drying kilns. To avoid the accumulation of VOC in the drying kiln, an air bleed-off can be extracted and combusted in the boiler. Another suggested method is to utilise the exit air from the wood dryers as combustion air in the boiler. This measure both increases the effect of the flue gas condensers and effectively destructs organic compounds.

When the water content of the exhaust gases from a wood drying kiln or a biofuel dryer is condensed, the condensate can be treated by precipitation and biological oxidation before it is led to a recipient. The non-condensable gases can be destructed in the boiler.

In many countries there are legal restrictions to the amount of VOC that may be released, however, this is seldom the case in Sweden today (Wimmerstedt, 1999). Lowered VOC emissions can be an important investment for the future, even if there is no restriction in the emissions of today. This is especially important if the sawmill is situated in a densely populated area.
8.1.7 Implementing the proposed measures

This study has shown that there is a large potential to more efficiently utilise and upgrade biofuels in the sawmill industry. The proposed measures are also judged to be economically feasible, with payback periods ranging between two and four years. However, the sawmill industry is composed of many small actors, with a limited ability to finance research and development on energy related issues. To enable a widespread implementation of energy saving technology, it is thus important that experience and knowledge is communicated to, and between, the market actors.

Compared to internal heat recovery, the investment costs of a biofuel upgrading plant and waste heat utilisation in district heating are high and sawmills may be reluctant to invest in complicated techniques which lie outside their core business. A recent development in Sweden has been that sawmills focus on their core business, which is the rational production of high quality wood products, and outsourcing the heat production to energy companies. This development will hopefully promote both improvements in the internal energy efficiency and the possibility for the SMI to play a larger role as a producer of sustainable bio-energy products in local and national energy systems.

8.2 Suggestions for further research

This study has shown that there is a large potential for energy saving measures in the sawmill industry. To improve the possibilities for an investment decision at a specific sawmill, it is important to gain more practical experience and to spread valuable information. Case studies of existing industries, where equipment for heat recovery are implemented, are thus important. Some of the suggested measures would also benefit from further development of new technologies, such as the open absorption heat pump and indirect, pressurised flue gas dryers to dry biofuel.

To reach the Swedish goal for greenhouse gas emissions, an increase of biofuel-based electricity production is desirable. According to the overview performed in this study, there is a potential to better utilise the heat load of the sawmill industry for small-scale CHP plants. Both the technical and economic feasibility of such plants needs to be evaluated. An interesting aspect would also be to study the cost of CO₂ reduction for the proposed measures as compared to alternative measures.
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10 Nomenclature and glossary

AHP  Absorption Heat Pump
CCP  Coal-fuelled condensing power
CHP  Combined Heat and Power
CO₂  Carbon dioxide
COC  Condensable Organic Compounds
COP  Coefficient of performance
DHN  District Heating Network
E   Energy content of a fuel (based on LHV)
FGC  Flue gas condensation
HHV  Higher heating value
HTD  High Temperature Dryer
KAC  Potassium Acetate
LHV  Lower heating value
LTD  Low Temperature Dryer
MC   Moisture Content [kg water/kg wet fuel]
η   Efficiency
NGCC Natural gas combined cycle
PBP  Payback period
SMI  Sawmill Industry
T   Tonne
T   Temperature [°C]
Tw  Dew point temperature [°C]
Q   Heat duty
VOC  Volatile Organic Compounds
W   Electrical power

Subscripts
b  boiler
el  electric energy
in  input
net  net
p  pellets
rc  recovered
rm  raw material
th  thermal energy
ug  upgrading
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