Improving Energy Use in Sawmills

From Drying Kilns to National Impact

Jan-Olof Anderson
LICENTIATE THESIS

Improving energy use in sawmills:
from drying kilns to national impact

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Preface

This work has been carried out at the Division of Energy Science at Luleå University of Technology in Sweden under the supervision of Associate Professor Lars Westerlund, Professor Marcus Öhman and Senior Lecturer Erik Elfgren. This work is summarizing the project titled Surplus Biomass by Energy Efficient Lumber Drying. The project has been funded by the Swedish Energy Agency. I would like to thank my supervisors for their guidance and the time spent during this project.

I would like to thank the following people for their advice and helpful comments regarding the project; Professor Tom Morën at Luleå University of Technology in Skellefteå, Robert Larsson at Valutec, Andreas Jonsson Product manager in Martinssons såg at Bygdsiljum, Henrik Annerman Product manager at Tunadal SCA Timber, Niclas Larsson Kiln dryer manager at Bolsta Sawmill SCA Timber, Thomas Wamming, SP Technical Research Institute of Sweden, and Tommy Vikberg, Ph.D Student at SP Technical Research Institute of Sweden.

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I would also like to express my gratitude to Professor Björn Esping for his preeminent research contribution in the area.

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Abstract

Increased concern about environmental problems has amplified the public’s interest in energy usage. The improved subsidies for biomass, together with the rising energy prices have made biomass a desirable product on the energy market. Energy intensive industries in the field of wood and biomass now have nowadays an opportunity to decrease energy consumption and to sell their biomass surplus on the energy market.

This Licentiate thesis focuses on strategies to decrease biomass usage in sawmill industries in order to increase their surplus biomass and increase their profit. This is done through system analysis of sawmill industries in terms of mass and energy flows. The energy analysis focuses on the drying kiln using psychrometric and thermodynamic relationships. State-of-the-art technologies, available on the market, have been studied to determine their possible effect on the total energy usage in the sawmills.

This study was undertaken to determine the national use of energy due to sawmills and the potential magnitude of improvements. Sawmills are important suppliers to the biomass market, since medium to large capacity sawmills contribute with 95% of the Swedish annual lumber (sawn boards) production (17.3 Mm³) with a lumber interchange of only 47%. The rest of the timber (unsawn logs) is transformed into biomass through the lumber production processes. An essential part (12%) of the timber is used for supplying heat to the production processes, mainly to the drying process which is the most time and heat consuming process in the sawmill. The main conclusions are that the heat demand for drying lumber in Swedish sawmills was found to be 4.9 TWh per year and the drying process can be made more effective by use of state-of-the-art technologies. Hence the internal use of biomass in sawmills can be decreased, thereby increasing the biomass that can be sold to the market and/or to generate heat and/or electricity, resulting in more profitable sawmills and a significant increased supply of biomass to the market.

It was also found that with available state-of-the-art technologies it is possible to recycle the heat in the evacuated air from the dryer, and if the recovered heat is used for heat sinks inside or close to the sawmill a large decrease of the energy usage can be achieved. If the technologies are implemented up to 5.56 TWh of equivalent biomass can be saved, depending on the technology, the specific sawmill conditions, kiln settings and drying system operation. However, some of the considered technologies consume a substantial amount of electricity, so the economic benefit should be carefully evaluated.
Outline of appended papers

A. Anderson Jan-Olof, Westerlund, Lars; Surplus biomass through energy efficient kilns; Applied Energy, 2011; 88; 3838-4853.
B. Anderson Jan-Olof, Westerlund, Lars; MIND based optimisation and energy analysis of a sawmill production line; Presented at PRES 2010; Prag, Czech Republic; 2010.
C. Anderson Jan-Olof, Westerlund, Lars; Improved energy efficiency in sawmill drying system; Not yet submitted.

Related papers (not appended)

Anderson, Jan-Olof, Westerlund, Lars; Analysis of the heat demand in batch kilns; Presented at WDC 2012 12TH International IUFRO wood drying conference; Belém, Para, Brazil; Aug, 2012
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Introduction

The worldwide increase in energy demand has contributed to an increased use of fossil fuels, which has led to higher greenhouse gases emission. The strong correlation with environmental issues has amplified the public’s interest in energy usage and environmental problems. The European Union has implemented new reforms and amendments to the energy market: they recommended the highest possible energy efficiency in the use of energy resources, they urge a lower use of fossil fuels, they implemented larger tax benefits on the usage of renewable energy resources and taxes on fossil fuels were increased etc. This reforms have reduced the gap in competitiveness between renewable energy resources and fossil fuels. Sawmills contribute with a significant part of the resources of the biomass market in the Northern countries since they provide a large quantity of biomass as a by-product from lumber production (Nilsson 2006). During the last decade, the biomass market has changed drastically. Nowadays, sawmills can make a good profit by selling their surplus biomass to the biomass market, while a few decades ago they were forced to give it away and in some cases even pay to get rid of it. Furthermore, higher competition in the lumber industrial field has forced larger production capacities and lower production times, with decreased lumber interchange, affecting the use of energy and raw material. The majority of the sawmills were built during the years when biomass was a very low value product at the market, so their energy intensive processes were not designed to achieve the lowest possible heat usage. Instead, low lead time and high quality were prioritized. Furthermore, investing in new facilities, dryer, furnace etc. is a long term investment (the replacement of these components often takes place only 30-40 years after the installation). These factors have resulted in an unnecessarily large use of biomass.


This licentiate thesis is focused on how to decrease the internal biomass usage by achieving higher energy efficiency in the sawmill industry, in order to increase the available biomass to the market and to improve sawmill competitiveness.
Objectives

The objectives of this work are to:

- Analyze the possible strategies to increase the availability of biomass at the market;
- Decrease the energy usage for lumber production in sawmills;
- Find appropriate technologies to be implemented in the drying facilities to achieve an effective lumber drying;
- Determine the national impact of these technical improvements from an energy and surplus biomass point of view

Overview of a Sawmill

The main purpose of sawmills is to produce lumber boards from forested timber without branches, roots and tree crown. Lumber production can be summarized into the following processes:

- Timber handling: when the timber arrives at the sawmill it is roughly sorted and stored in the lumberyard;
- Debarking: the timber needs to be separated from the bark before the sawing process;
- Sawing: the timber log is sawn to different types of lumber boards, depending on dimension, length, quality type of tree etc.;
- Sorting: the sawn lumber are sorted into different lumber packages;
- Drying: when the timber is forested it contains a large amount of water, For Norwegian spruce and Scotch pine, which are the common species in Sweden, the moisture content is 70-90%wt, depending on the season etc. (Esping 1992, Staland 2002). Natural drying (i.e. lumber is dried outdoor in ambient air) works according to the equilibrium principle. However, natural drying takes a lot of time and may lead to unwanted cracks and lumber modifications. To avoid low lumber quality and productive bottlenecks, the drying process is performed with artificial techniques in facilities called drying kilns. Despite these techniques, the drying remains the most time and energy consuming process in the sawmill;
- Packaging: The lumber is then sorted once more, and in some cases grinded, and finally packaged for transportation.

During these processes a large quantity of by-product is produced: bark, sawdust, wood chips (i.e. different types of biomass). In fact, less than half (Anderson 2011) of the entering dry mass content of timber is transformed into lumber for final transportation to the market. The material flows through a sawmill are shown in Figure 1, highlighting the different products.
Sawmill processes need heat and electricity to be carried out. Heat is normally supplied through a furnace, fired with the biomass produced by the sawmill itself; otherwise it is bought from nearby biomass industries. The major part of the heat is used during the drying process, and the remaining part is used for room heating. Heat and electricity requirements in a typical sawmill are shown in Table 1. The drying process accounts for about 87% (Johansson 2000) of the total consumed heat in sawmills. The wood drying techniques conceived in the past, when energy and biomass prices were low, are now outdated from the point of view of energy efficiency, and the expansion of the biomass market and the increase in biomass prices have made it profitable to invest in more effective drying facilities to decrease heat and electricity consumption. Electricity is used for electrical driven transportation, sawing, grinding, room lighting, fans for the drying kilns etc.

**Table 1, Heat and electricity consumption in lumber production processes (Esping 1996, Tronstad 1993, Anderson 2011, Stridberg 1985).**

<table>
<thead>
<tr>
<th>Process</th>
<th>Electricity [kWh/m$^3$lumber]</th>
<th>Heat [kWh/m$^3$lumber]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barking</td>
<td>4</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Sawing</td>
<td>23</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Sorting</td>
<td>2</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Drying</td>
<td>31</td>
<td>299</td>
<td>75</td>
</tr>
<tr>
<td>Dry handling</td>
<td>4</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Grinding</td>
<td>13</td>
<td>5</td>
<td>30</td>
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<tr>
<td>Office</td>
<td>15</td>
<td>-</td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>77</strong></td>
<td><strong>339</strong></td>
<td></td>
</tr>
</tbody>
</table>

In Sweden about 139 sawmills are operative, each producing more than 15 000 m$^3$ lumber annually (Nylander 2009). About 95% of Swedish lumber production comes from 111 sawmills which dry the lumber using forced drying techniques and produce at least 50 000 m$^3$ (Nylander 2009). The total distribution of sawmills according to lumber production volume is shown in Figure 2.
The biomass surplus obtained from lumber production is nowadays sold to the biomass market for industrial usage: often pellet plants, district heating plants, CHP (combined heat and power) plants and pulp and paper mills are the consumers. Different purchasers prefer different types of biomass as can be seen in Figure 3. Due to the high moisture, low heating value and high ash content, bark is the least commercially interesting among sawmill by-products and it has the lowest market value (Bisaillon 2008, Parikka 2011, Axelsson 2010, Juntikka 2012). For the same reasons, the combustion of bark alone is challenging and, therefore, the internal consumption mainly consists of bark but with the addition of small fractions of sawdust and wood chips. The internal usage of biomass consists of 85% bark, 4% dried wood chips, 2% moisture wood chips and 9% sawdust, see Figure 3. If the internal energy usage could be decreased, this would affect the surplus biomass available at the market. Since mostly bark would be made available, the most likely purchasers of this surplus would be CHP plants and, to a lesser extent, pellet plants.
**Drying of lumber**

Different perspectives of the drying process are given in this chapter. The elementary physics of wood drying is described from a heat and mass transfer point of view. Furthermore, the industrial lumber drying process is described and some frequently encountered problems are presented. Finally, the energy usage in sawmills is discussed according to the situation in Nordic countries.

**Industrial lumber drying**

The lumber drying process aims at a compromise among high quality, low lead time and low energy usage. Quality and lead time have always been prioritized before the energy usage. In order to decrease the lead time, forced drying techniques are applied in drying facilities called drying kilns, which are responsible for the large heat and electricity demand in sawmills. The most common types of wood dryer are the progressive and batch kilns, the latter being schematically shown in Figure 4 with the different thermodynamic states of air during the drying cycle in a Mollier diagram. The main difference between the two kiln types is about the spatial and time arrangement of the drying process. Inside the batch kiln the air state changes in time according to the planned drying scheme. Inside the progressive kiln, several separated zones at different air states are present, and the lumber package changes zone as it is moved through the kiln. The kiln type is a factor affecting energy use and lead time, so the most suitable kiln type depends on the different drying conditions.

![Figure 4, Drying air circulation cycle inside a batch kiln with thermodynamic states.](image)

Conventional drying techniques use heated outdoor air circulating through the lumber package as the moisture transport medium of evaporated water from the lumber. An air circulation cycle is described in the following (see Figure 4). The outdoor air, state 1, at low temperature and humidity enters the kiln and is mixed with the circulated air, resulting in state 2. The air is then heated at the desired drying temperature (state 3) causing an enthalpy increase, but no moisture transport is accomplished so far. As a fan circulates the air through the lumber package, some moisture from the lumber is transported by the circulating air that increases its humidity and decreases its temperature to state 4.
temperature distribution in air states 2, 3b, and 4 can be seen in Figure 5, which is valid for a batch kiln in which Scotch pine is dried.

The water vapour in the air has a lower partial pressure compared to the air layer close to the lumber. The equilibrium principle forces a transport of moisture from the lumber to the circulation air in the surrounding, which results into a drying effect. On the lumber side, the bound and free water between and inside the wooden cells will be transported towards the wooden surface, but if this occurs too quickly an uneven distribution of the water can cause cracks and large deformations, i.e. an unwanted low quality of the lumber. On the other hand, a too low difference in partial pressure will lead to an unwanted slow drying. In the meanwhile, the temperature of the circulation air decreases and its humidity increases reaching state 4, which is close to saturated conditions. To maintain a high drying effect, a part of the circulation air flow needs to be evacuated from the dryer before becoming saturated and to be replaced with outdoor air having lower humidity. A typical behaviour of the moisture transport is shown in Figure 6 when forced drying techniques are used (this is valid for batch dryer, Scotch pine, lumber dimensions 50x150mm, 18%wt end moisture content).

Figure 5, Circulation air temperature depending on air states in a batch kiln.

Figure 6, Lumber moisture content in time during kiln drying of lumber.
Most of the lumber is dried to 18%wt end moisture content, the remaining part is often dried to 12%wt or to 6%wt (Staland 2002)

**Energy usage during lumber drying**
The replacement of circulation air close to saturation with outdoor air is responsible for the largest energy losses, called evacuation losses, accounting for about 78% (Johansson 2000) of the heat consumption in a kiln. Other losses due to the drying lumber process in kilns can be separated into the following parts (see Figure 7 for their percentage distribution):

- Conduction losses through walls, roof and floor i.e. transmission losses;
- Leakages, which mainly occur when the kiln is opening during lumber loading;
- Lumber heating, at the beginning of the drying processes the lumber is warmed up to the drying temperature;
- Melting heat, which occur when the lumber have been stored at a temperature below zero.

![Figure 7. Normal heat and electrical consumption in progressive kiln (Johansson 2000).](image)

Kilns with heat recycling are uncommon, but the most popular type of recycling makes use of air/air heat exchanger for heat recovery. The most common tree species that are used in Sweden are Norwegian spruce and Scotch pine (with some minor fraction of broad-leaves tree). The drying of the two different tree species is similar but not identical. This is because of the difference in the initial moisture content, the density and the cell structure of the wood itself (Esping 1996).
Summary of appended paper

In **Paper A**, the standard sawmill in Nordic countries was investigated. The location, the market potential and the biomass purchasers were studied. Production capacity, ownership of forest and distance to industrial biomass purchasers were analyzed. Historical reforms and modifications in the area due to the sawmill, lumber production, energy prices etc. were evaluated. Production and internal use of biomass, type of wood, start and end moisture contents at drying, on both sides of sawmills and purchasers is analyzed statistically. This allows to estimating the percentage of the national lumber production that has been dried under each specific drying condition. The national energy demand for lumber drying in kilns can be established if the annual lumber production, the energy demand for each specific drying condition and the corresponding percentage of the production are known. The lumber production and the percentages of this production for each drying condition are known from statistical databases and previously published work in the field. Experimental measurements were carried out at Tunadal Sawmill, SCA timber in Sundsvall to complement the available database for the evaluation of the total energy distribution among national sawmills. The national use, imports and exports of biomass were studied using databases in the field and former market reports in order to establish the market potential. The production of biomass from sawmills and the preferred types according to consumers were determined by market reports from purchaser industries and sawmills.

The purpose of this paper was to analyze the sawmill market according to lumber production, heating system, drying system and biomass demand at the market. In addition, the analysis aimed at showing in what process the largest benefit can be achieved by an increase of the energy efficiency.

**Paper B** proposes an alternative way to reduce the heat consumption in batch kilns by recirculating the evacuation air and addresses particular problems encountered in sawmills, which today suffer of bottlenecks in the heating system due to high heat load from the dryers as a result of the increased production. The possibility of recycling the evacuation air from each kiln is theoretically investigated. The energy usage and air conditions were obtained during several experimental measurements on the drying process at Tunadal Sawmill, SCA Timber in Sundsvall, Sweden. The objective of this work was to show the potential of recycling the drying air by using the drying effect of the air evacuated from one kiln and sent into another, in order to increase the overall energy efficiency and decrease the thermal load of the heating system.

In **Paper C**, the impact of different state-of-the-art technologies to be implemented on an existing drying kiln were studied, considering the wood types, lumber dimensions and kiln types that are most commonly used in Sweden (according to the results in paper A). The drying schemes were designed with help of a simulation program called Torksim to ensure high lumber quality. Torksim is developed by Technical Research Institute of Sweden, SP.
A calculation program IGOR was used to analyze how energy usage in the kiln was affected by drying conditions and other variables. The program was used to simulate the six most common drying situations (taken from paper A) hour by hour according to certain drying schemes. The main objective of this work was to compare different technologies that can be implemented in order to achieve increased energy efficiency and to show, if possible, which is the most profitable to use under given conditions. The results were then considered from a biomass and energy usage point of view to show the impact on a national level.

Conclusion

From Paper A it can be concluded that the Swedish national biomass consumption for lumber drying in sawmills is 4.9 TWh, the major part being consumed in the drying kiln during the drying process. More than half of the energy used for lumber drying can be utilized in other processes, i.e. making resources available to the society. The possible additional availability of biomass can be used by the biomass market due to the present and future market potential. Thanks to the higher efficiency of the drying process the market may gain a substantial amount of biomass without the need of increasing wood harvesting from the forest.

The research in Paper B points out that it is possible to decrease the overall heat consumption by 12%. This is possible if the starting time of the kilns is displaced according to eight drying steps of the drying cycle, so that the evacuation air with low humidity from one kiln can be recycled into another. This will result in less bottlenecks for the drying processes, and a more uniform load for the heating system. If this strategy is implemented into larger heating systems, which embrace a larger amount of kilns, it is possible to achieve higher efficiencies and to design heating systems that are less sensitive to the fluctuations of the drying scheme.

In Paper C a numerical model of the drying cycle is developed. It provides appropriate data in terms of drying temperatures and moisture content over the drying cycle. By changing the initial boundary conditions, the model can simulate each type of drying scheme and drying condition for different lumber drying processes in batch and progressive kilns. This gives a heat demand analysis for each specific drying condition instead of performing an experimental test. The investigation shows that a substantial quantity of biomass could be saved and used for other purposes in the society if available energy recovery technologies were implemented into the sawmill industry. The use of heat exchanger technology to recycle the heat in the evacuation air makes only a marginal improved efficiency, between 4-10% (depending of the drying scheme and sawmill conditions). In a national system perspective for the sawmill industry in Sweden this corresponds to 0.33 TWh, with an additional electricity consumption of 2.4 GWh. The impact on the drying kiln efficiency is
low because only a small part of the energy in the evaporated water that is present in the evacuation air is recovered.

The mechanical heat pump is an effective technology that can decrease the energy usage considerably and generate a large heat surplus if implemented into the drying system. The disadvantage of the technology is the high electrical consumption, mainly due to the compressor. In a national perspective the mechanical heat pump can decrease the internal biomass usage by 5.56 TWh and also create a surplus heat production of almost 1 TWh, available for external heat sinks. The disadvantage is the large increase in electricity use, 1.04 TWh. The fact that the electricity price is much higher than the biomass price results in a large drawback from an economic point of view.

The open absorption system will decrease the heat usage by 67.4% in average if implemented into the drying kilns. In a national perspective this technology will decrease the annual use of biomass among the sawmill industry by 3.44 TWh, lower than the mechanical heat pump but with a significantly lower electricity consumption, 49.2 GWh.

The heat reduction potential presented for the different technologies has been determined assuming steady state conditions. Since the operation of the single kilns and the timing of their drying cycles affect the load of the overall heating system, the possible usage of surplus heat from these technologies will be affected as well by these factors. It should therefore be clear that dryer operation will have an impact of the system efficiency improvement that is possible to achieve.

Possible additional heat sinks which can make use of the surplus heat made available by some technologies are e.g. district heating networks, pellet plants, ORC (Organic Rankine Cycle) power plant or other industrial processes.

**Future work**

Further studies are needed to show the impact of the considered technologies in a system perspective. A suggestion would be to perform a process integration study on a reference sawmill to show how the overall system thermal cascade is changed depending on which kind of technology is used to recover the heat.
Acknowledgements

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Paper A
Surplus biomass through energy efficient kilns
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1. Introduction

In the last 50 years the sawmill market has undergone huge reforms and modifications; increasing competition has resulted in larger production capacity and lower production time with less lumber quotient (the mass quotient in dry substance between the entering timber and produced lumber). This has affected the use of energy and raw material. The drying process is the most time and heat consuming process at sawmills and a substantial process to achieve adequate lumber quality and behavior. To avoid huge bottlenecks in the drying process artificial drying technique is done with the sawmill's own firing furnace, otherwise the heat is used from the sawmill’s own firing furnace, otherwise the heat is bought from nearby industries. The research on energy efficient kilns was very limited due to the low biomass prices in the 1980s and 1990s. Reducing drying time and increasing the lumber quality with less structural deformation were highly prioritised instead. Several authors have therefore done research in the area of lumber quality and behavior during drying [1,4–9]. The Swedish sawmills, their production, use of wood, drying facilities and location have been investigated and written about [1,10,11]. The imports, exports and taxes of lumber, timber and biomass have also been studied and determined [12–14]. Field studies and measurements of the energy use in sawmills with different facilities and behavior have been published.
of over 50,000 m³ each and exclusively use forced drying techniques in a future perspective. These sawmills have an annual production of biomass which today been used inefficient to supply heat to lumber kiln with low energy efficiency can instead provide an additional supply of biomass in line with market demand. Increasing energy prices make it profitable to invest in higher energy-effective drying techniques.

So far, there is no published research compiling these different areas. The main objective has therefore been to analyze the amount of biomass used in the drying processes at Swedish saw-mill companies. An evaluation was done to estimate the potential biomass reduction by using kilns with better energy efficiency.

The work concerns facilities with regard to the Swedish climate and market circumstances. To increase the knowledge of this area, including the users of possible surplus too, the historical use of biomass and the biomass market were studied and a future market potential was analyzed.

2. Methodology

2.1. Sawmill and biomass purchasers

A mapping was conducted concerning sawmills’ location and market potential with regard the biomass purchasers. This investigation entirely concerns those sawmills that are believed to stand the hard competition in a future market. Theirs production capacity and geographical position, their own possessions of forest and nearby biomass purchasers appear to sustain the competitiveness in a future perspective. These sawmills have an annual production of over 50,000 m³ each and exclusively use forced drying techniques to decrease the fixed cost due to shorter lead time. The biomass production and use, type of wood, start and end moisture contents at drying, among sawmills and purchasers are analyzed statistically. This reflects the percentage part of the national lumber production that has been dried under each specific drying condition.

2.2. Energy demand

The national energy demand for lumber drying in kilns can be established if the annual lumber production, the energy demand for each specific drying condition and the corresponding percentage of the production are known. The energy demand when drying lumber in kilns depends on kiln type, lumber dimensions, outside air condition and type of wood, end and start moisture content, etc. The lumber production and each drying condition corresponding percentage of the production are known from statistical branch databases and previously published work.

The main part of the lumber is dried to three different end moisture contents, 18%, 12% and 6%. This represents 81%, 13% and 3% of the total lumber production, respectively. The remaining part of the production is dried to other end moisture contents [1]. To decide the national heat demand for the different drying conditions one needs to calculate the start moisture content. The average water evaporation in the drying process, \( \frac{m_{\text{water, evap}}}{C_{\text{water}}} \), amounts to 325 kg H₂O/m³ [15] and 275 kg H₂O/m³ [15] for pine and spruce respectively. The average lumber density at dried basis, \( \rho_{\text{D}} \), is 430 kg/m³ and 385 kg/m³ for pine and spruce respectively [1].

\[
\rho_{\text{D}} = \rho_{\text{ap}} \times (1 + \varepsilon_v) \quad (1)
\]

\[
\rho_{\text{ap}} = \rho_{\text{av}} + m_{\text{water, evap}} \quad (2)
\]

\[
\varepsilon_v = \left( \frac{\rho_{\text{D}}}{\rho_{\text{av}}} \right) - 1 \quad (3)
\]

Through previously published work in the field, the kilns heat consumption, \( q \), can be established at 242 [16] and 315 kW h/m³ [1] for progressive kilns and for batch kilns 272 [16] and 325 kW h/m³ [1] when drying spruce and pine respectively. These constants correspond to the average heat consumption when drying lumber with the valid type of kiln and tree type. Due to the different outside air temperatures and end and start moisture contents among the studied measurements and the close relation between those conditions and the kiln heat consumption, temperature and moisture normalization was required. Esping B stated that each 5 °C decrease in outside temperature \( T_{\text{out}} \), increases the heat consumption, \( \Delta q \), by 5,4 kW h/m³ or 2,8 kW h/m³ for batch and progressive kilns respectively [15]. This statement is confirmed by experimental study and agrees well with the theory. The temperature normalization was done towards 0 °C through Eq. (4). The normalization due to the lumber moisture contents was established with Eq. (5). The temperature normalization was made towards an end moisture content of 18% and a start moisture content of 85% and 70% for pine and spruce respectively. The heat consumption was assumed to have a linear relationship with the outside temperature and the moisture content.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Subscripts</th>
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<tr>
<td>( P )</td>
<td>National, ( P ) normalized of temperature</td>
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<tr>
<td>( Q )</td>
<td>National, ( Q ) normalized of moisture</td>
</tr>
<tr>
<td>( q )</td>
<td>Dry, ( q ) evaporated water</td>
</tr>
<tr>
<td>( \Delta q )</td>
<td>( \Delta q ) temperature ( (\text{h} \text{kg}^{-1} \text{C}^{-1}) )</td>
</tr>
<tr>
<td>( T )</td>
<td>Start, ( T ) temperature ( (\text{C}) )</td>
</tr>
<tr>
<td>( v )</td>
<td>Specific condition, ( v ) specific condition</td>
</tr>
<tr>
<td>( s )</td>
<td>Start moisture content, ( s ) start moisture content</td>
</tr>
<tr>
<td>( o )</td>
<td>Outside, ( o ) outside</td>
</tr>
<tr>
<td>( T )</td>
<td>Tree type, ( T ) tree type</td>
</tr>
<tr>
<td>( K )</td>
<td>Kiln type, ( K ) kiln type</td>
</tr>
</tbody>
</table>

\[
q = C_{\text{water}} \times \frac{m_{\text{water, evap}}}{C_{\text{water}}} 
\]

\[
D = C_{\text{water}} \times \frac{m_{\text{water, evap}}}{C_{\text{water}}} 
\]

\[
S = C_{\text{water}} \times \frac{m_{\text{water, evap}}}{C_{\text{water}}} 
\]

\[
C_{\text{water}} = 4,2 \text{kJ/kg} \text{C}^{-1}
\]

\[
C_{\text{water}} = 4,2 \text{kJ/kg} \text{C}^{-1}
\]
To assess the dependence of the end moisture content on the energy demand, Eq. (6) is used.

\[
q_{\text{Norm},T} = \frac{q + \Delta q \times T_{\text{air}}}{C_3} \quad (4)
\]

\[
q_{\text{Norm},v} = \left( \frac{(P_v - P_s)}{(P_v - P_s)} + \frac{q_{\text{Norm},T}}{C_2} \right) \left( \frac{S_v}{C_0} \right) \left( \frac{E_v}{C_2} \right) = \frac{q_{\text{Norm},v}}{C_3} \quad (5)
\]

To achieve an annual heat demand for each specific drying condition, \( Q_i \), the specific energy demand, \( q_i \) needs to be implemented with the percentage, \( x \), of the total production, \( P \), for each specific drying condition, \( i \) (tree type, end moisture content and kiln type) known from the sawmill mapping and statistical analysis. This is made in Eq. (7).

\[
Q_i = P \times q_i \times (X_{\text{tree}} \times X_{\text{kiln}} \times X_{v}) \quad (6)
\]

The national heat demand for drying lumber, \( Q_{\text{National}} \), can then be established with Eq. (8).

\[
Q_{\text{National}} = \sum Q_i \quad (7)
\]

\[
Q_{\text{National}} = \sum Q_i \quad (8)
\]

2.3. Experimental setup

The experimental measurements of a batch kiln were carried out as a validation of former theoretical work to determine the kiln’s heat consumption. The measurements were made at a sawmill named Tunadal, located in Sundsvall in the middle of Sweden with a yearly lumber production of 335,000 m³ (2008) [10]. The experimental study was made in February with the most commonly used kilns, tree sort and lumber dimensions (batch kiln with Norwegian spruce of dimension 50 × 175 mm, an end moisture content of 12%). The average outside air temperature was −8.3°C during the experiment. The kilns are supplied with heat through district heating from a nearby pulp mill. The drying cycle is presented in a Mollier diagram, see Fig. 1. The experimental values were collected from the kiln’s control system, the sampled items were dry and wet-bulb temperature on both sides of the lumbers packages, C and D (which are dependent on the air circulation direction and the heat supply from the heating coil). Mark B is a theoretical calculation point and A represents the outside air conditions. The outside air conditions; air temperature and relative humidity were measured by a nearby control station of the Swedish Road Administration. The overall amount of vaporized water and the heat consumption can be determined through well-known thermodynamic and psychometric relationships of desired items, such as water content and enthalpy in positions A-D. The experimental values were normalized, according to Eqs. (4) and (5), for temperature and end moisture content in the same way as the heat consumption from the literature.

2.4. Potential purchasers of biomass

The national use, imports and exports of biomass were studied through branch databases [11] and former market reports in order to establish the market potential [10,15]. The production of biomass and purchasers from sawmills were determined by market reports from purchaser industries and sawmills [3].

3. Result

3.1. Sawmills and lumber quotient

The annual Swedish production of lumber is about 17.3 Mm³ (2008) [10] and is produced by 139 sawmills that annually produce

![Fig. 1. Kiln moisture air state presented in a Mollier diagram](image-url)
more than 15,000 m³ respectively [10]. Of this 95% is produced by sawmills with an annual production of over 50,000 m³ and exclusively uses forced drying techniques; these are presented in Fig. 2 with the number of sawmills in brackets for each production span. The production which is dried by batch kilns corresponds to 60% and the rest by progressive kilns [3]. The different types have differences in the use of heat, electricity and drying time. A major part of the sawmills are located along the coastline because of the logistic advantage, and most of them have nearby industries using biomass. Nearly all of the lumber is produced from coniferous trees, 43% Scotch pine and 57% Norwegian spruce, and hence the use of broad-leaved trees is rare in lumber production in the Nordic countries [3].

Due to sawing, barking and shaving processes, the lumber quotient is nowadays less than half of the incoming timbers causing the major part to become by-products such as biomass; these are visualized in Fig. 3. Most of the produced biomass is sold to the biomass market, but a significant part, 12% of the incoming timbers, is mainly used to supply the kilns with heat in the drying process.

3.2. Energy demand

The use of electricity for lumber production is about 125 kW h/m³ lumber. The majority is consumed in the drying process for air circulation through fans and electric motors in the sawing and refinement processes (planning and grinding). The use of heat in a sawmill is about 330 kW h/m³, where the drying process stands for 80% of the total heat consumption, the remaining heat being used for local heating [15]. The use of heat varies widely among outside air conditions, lumber types, drying techniques, kiln condition, etc. By using Eqs. (1)–(6) the average heat consumption was determined at 247 kW h/m³ and 315 kW h/m³ for progressive kilns and for batch kilns 295 kW h/m³ and 325 kW h/m³ when drying spruce and pine respectively. The average start moisture content was determined at 88% and 92% for spruce and pine respectively, through Eqs. (1)–(3). The experimental study determined a heat consumption of 272 kW h/m³ at the batch kiln with a maximum variation of 1.4% among different kilns with an additional use of heat for steaming and conditioning in the beginning and end of the drying cycle. The heat demand is valid for an end moisture content of 18% and an outside air temperature of 0 °C. The heat consumption is higher when drying pine, mostly due to the higher moisture content compared with spruce. The additional use of electricity is about 21–33 kW h/m³ [5,15]. The national electricity consumption for drying lumber in kilns is 0.45 TW h annually.

The total heat use for drying lumber among the Swedish sawmills can be estimated by determining the amount of produced lumber, 16.4 Mt (2008) [10] and heat use for each specific drying condition. Through Eqs. (6)–(8) and the previously named specific heat consumptions the national heat consumption can be established. Table 1 shows the national heat consumption divided among each specific drying condition and totalized results to a heat consumption of 4.9 TW h annually.

The annual heat consumption when drying lumber represents 10% of the total biomass use in the industrial sector in Sweden [24]. With new available techniques, for instance condenser devices, the heat consumption can decrease by 60% [5,20]. This corresponds to a decreased biomass consumption of 2.9 TW h.

3.3. Biomass purchasers and use

Biomass was historically dealt with as an unwanted by-product, almost without any commercial value, due to the low price of alternative energy sources, before the 1990s. The competitiveness of biomass has increased drastically due to the European Union's strategic goal to subsidize biomass to make a higher contribution to the national use of energy. The improved domestic market potential, shown in Fig. 4, is due to the high subsidies. These subsidies have increased the competitiveness of biomass against other energy sources such as coal, oil and electricity. The restriction in the biomass market is mainly due to the limitation of

<table>
<thead>
<tr>
<th>End moisture content</th>
<th>Progressive kilns</th>
<th>Batch kilns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spruce (TW h)</td>
<td>0.74</td>
<td>1.33</td>
</tr>
<tr>
<td>Pine (TW h)</td>
<td>0.72</td>
<td>1.33</td>
</tr>
<tr>
<td>Spruce (TW h)</td>
<td>0.23</td>
<td>1.12</td>
</tr>
<tr>
<td>Pine (TW h)</td>
<td>0.19</td>
<td>0.19</td>
</tr>
<tr>
<td>6%</td>
<td>0.01</td>
<td>0.16</td>
</tr>
<tr>
<td>0%</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Other</td>
<td>0.03</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 1 National heat consumption by to kiln, tree type and end moisture content.
biomass production and not to the field of usage. Due to the low energy content per weight of unprocessed biomass [26], the exports and imports potentials are mainly limited to processed biomass (pellets and briquettes) with the exception of low transportation distance. This primarily applies to the northern region between Sweden and Finland. Russia is a huge timber exporter to the EU, mainly to Baltic countries and Finland. Russia has increased the export taxes for timber to the EU with a start of 15 EUR/m³ in 2010 [12]. This will affect the domestic and neighboring countries’ supply of lumber and biomass and will increase the demand for biomass. In only the last three years has the price increased by 60% for the industry, and between 2005 and 2006 the Swedish pellet production increased by 14% while district heating industries increased their use of biomass fivefold between 1990 and 2006 [25,27]. The higher price of biomass has made longer transport distances possible.

The produced biomass among the sawmills; dried and moist wood chips, bark and sawdust, have different behaviors and qualities due to the energy content, chemicals, ash and moisture content, etc. This leads to their adaptability to various uses and purchasers; mass and paper, biomass used by themselves through combustion for heat production and the rest sold off. The rest sold off part mostly correlates to CHP (Combined Heat and Power plant), district heating and pellet plants. Fig. 5 illustrates what kind of biomass is used by different kinds of purchasers. An investigation has to be made to validate the possible deposition potential to nearby biomass purchasers, in case of less biomass usage at sawmills. The purchasers require making use of the identical kind of surplus from increased efficiency at the kilns.

It may be seen in the figure above that the sawmills’ own use of biomass mainly consists of bark with 9% of sawdust and less wood chip, the last being mostly used in the process of the pulp and paper industry. More adaptable purchasers than the pulp and paper industry are CHP, district heating companies and in some case the pellet plants. Those are possible to use the rest that is sold off and are more valid as possible biomass depositions for the sawmills.

4. Discussion

In general, the result showed that the use of biomass due to the heat supply to the kiln, stands for a vast part of the total biomass use at the industrial sector. It is partial because of the low energy efficiency at the lumber dryer. Implementation of available state-of-the-art techniques will reduce the national heat consumption with a substantial part of the biomass use at sawmills. Table 1 indicates that further research on increasing the energy efficiency at kilns should be based on the specific drying conditions valid for the largest part of heat use for the lumber production. An end moisture content of 18% and 12%, for spruce and pine dried at progressive and batch kilns respectively, includes 94% of the national use of heat at kilns.

The difference between the energy consumption, when drying pine compared with spruce, has mostly to do with the start moisture content being higher for pine in general. The difference in fiber structure affects the heat consumption too and in turns affects the part of the free water in the structure. The calculation proceeding was made to establish the overall heat demand for drying the national lumber production. The heat demand for each specific case can be made with higher accuracy if wanted, if more influential variables are taking into consideration i.e. the free water effect, kiln condition, different fiber structures among lumber types and what part the lumber appertains to, etc.

Furthermore, the results showed that any decrease of the internal biomass use among the sawmills, can be sold to biomass purchasers because of the increased marketing of biomass.

5. Conclusions

The national biomass consumption for lumber production at sawmills is 4.9 TW h. With available techniques the consumption can be decreased by approximately 2.9 TW h. This means that
more than half of the energy used for lumber drying can be utilized in other processes in society. The possible additional accessibility of biomass is required in the biomass market due to the present and future market potential. However, it is important to pay attention to the fact that different purchasers use different types of biomass for their processes. Due to low energy content the unprocessed biomass is often unprofitable to transport long distances. Often, but not always, the purchasers are adjacent to sawmills. An alternative option is to use the biomass in the sawmill to produce processed biomass as briquettes or pellets, for district heating or for electricity production. With greater efficiency of the drying process it is possible to gain a substantial amount of biomass to the market without increased production from the forest. This will increase the availability of biomass and will have a positive impact on the emission of carbon dioxide, nitrogen dioxide, hydrocarbons and sulfur compared with fossil fuels.

Acknowledgment

The research is funded by the Swedish Energy Agency and is the first part of a research project that will analyze the energy use among sawmill drying facilities.

References


Paper B
MIND based optimisation and energy analysis of a sawmill production line

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The lumber drying process uses about 80% of the total heat consumption in sawmills. Efforts to increase energy efficiency in lumber kilns were very restricted due to the low biomass prices between the 80th and 90th. Today with higher production and biomass prices, companies want to decrease their own use of biomass and increase the heating system efficiency. The study proposes alternative ways to reduce the heat consumption at batch kilns by recirculation of the evacuation air and addresses particular problem encountered in sawmills. Which produce their own heat and suffer from bottlenecks in the heating system due to high heat load from the dryers and increased production. The study shows the possibility to recycle the evacuation air from each kiln which reduces the overall heat consumption of the kilns by 12%. At nationally basis this corresponds to a decrease of heat consumption of 440 GWh annually, among Swedish sawmill. This will decrease the individual heat consumption of the kilns, heat load in the heating system and the bottleneck effect in the drying process. The decreased own use of biomass brings benefits of more available biomass to the market and increased profits for the sawmill.

Introduction

The Swedish sawmill industries produce 16.4 Mm³ lumbers annually (Staland J., et al. 2002). The drying process uses 78-83% (Vidlund A., 2004, Stridberg S., et al. 1984) of the total used heat in sawmills. This makes lumber drying the largest heat and time consuming process in the lumber production process. A modern kiln dryer uses about 285 kWh/m³ (Vidlund A., 2004), which corresponds to a national heat consumption of 4.7 TWh. Normally is heat produced in a furnace by own by-products from the sawmill processes, biomass as bark, woodchips, sawdust. The interests in increased energy efficient kilns were very limited due to the low biomass prices under the 80th and 90th. Reducing drying time and increasing the lumber quality were highly prioritised instead. With larger lumber demand on the market and increased energy prices have led to higher priority of energy efficient kiln and heating system. This study brings solutions to lower the heat consumption in lumber drying by recycling of evacuation air.
**Technical description**

The drying process is necessary to gain sufficient quality and moisture content of lumber with less structural deformations. The lumber undergoes a specific drying scheme with different temperatures and moisture contents of surrounding air. The appearance of the drying scheme is depending on the end moisture content of the lumber, type of wood and dimensions etc. The outdoor air is heated by firing biomass in a furnace, the air then enters the drying kiln and is circulated beside the lumbers. To maintain a high drying capacity among the circulation air and avoid an equilibrium state between the air and the lumber, it is necessary to evacuate a part flow from the kiln and exchange it with fresh air. The air is evacuated to the outside for a conventional kiln, which results in high drying losses and decreased drying efficiency. The used heat, air humidity and temperature in a kiln during a drying cycle are presented in Figure 1. The two diagrams (see Figure 1 (c)-(d)) show the temperature and humidity inside the kiln over time. As can be seen in Figure 1 (a), the heat consumption in the beginning part of the drying scheme (the first eight drying steps) corresponds to 50 % of the total heat consumption. This high consumption is related to the large amount of evacuation air, high lumber moisture content and the lumber warm up process which stands for 6 % (Johansson L., et.al. 2000) of the kiln heat consumption.

![Figure 1: Lumber drying cycle in kiln dryers](image)

The extend of this high heat load in the beginning of the drying cycle can cause problems in form of bottlenecks in the heating system, particularly if several kilns are started simultaneously. The evacuated air humidity is largest at drying steps 2-8 where the mass flow of evacuated air is highest, shown in Figure 1(b) and (d). It renders possible to recycle some of the evacuated air from kilns which no longer is in the same drying step and have lower moisture content in the evacuated air, to kilns which is in the...
beginning part of the drying cycle. This can be achieved if some of the dryers are
displaced in starting time between each other.

**Methodology**

The energy demand at kilns was determined by experimental measurements in a batch
kiln and from former published research. The measurements were made in Tunadal
sawmill, located in Sundsvall, Sweden. The sawmill was chosen due to their use of
drying technology which represents the most common used, with new heating system
and kiln facilities and accurate control system. Those correspond to the latest drying
facilities at the market. The experiments were performed in February on batch kilns,
with Norwegian spruce with a dimension of 50 x 175 mm and an end moisture content
of 12 %. The experimental data were collected by the kiln control-system. Sampled
variables were dry and wet temperature at both sides of the timbers package (marked
(C) and (D) in Figure 2), air mass flow and the heat supply from the heating coil. The
conditions of the outside air marked (A) in Figure 2, temperature and relative humidity,
were measured in a nearby control station by the Swedish road department. Mark (B)
refers to a theoretical calculated point which corresponds to the air condition at the
heating battery, where an adiabatic process is obtained due to pure heating of the
entering air towards point (C). The air enthalpy between point (C) and (D) have been
considered as constant. Hence, only moister absorbing without heat reduction occurs,
after the lumber heat up process. When the air passed the lumber package, at point (D),
has the air been considered as saturated.

![Figure 2](image.png)

*Figure 2, Measurement points of air cycle in kiln and mollier diagram*

The air enthalpy, evaporated water and heat consumption can be established through
well known thermodynamic and psychometric relationship. The experimental values of
one drying scheme were sampled each minute and turned into 39 drying steps with arithmetic average of the sampled experimental values. The overall load at the heating system was analyzed by studying five kilns which had the same drying cycle and drying conditions. A comparison over time was then established between the mass flow and the outside and entering air enthalpy. A kiln with lower air humidity in the evacuation air was accepted to recycle air into a kiln with higher air humidity. To obtain this condition, the kiln needs to be displaced in starting time compared with the other kilns. The heat consumption was calculated with the air mass flow and the enthalpy difference between the evacuated air, the air outside and inside of the kiln.

Result

The following results are established with 8 drying step displacement in starting time between each of the five kilns. Figure 3 shows the individual heat consumption for the kilns. The solid lines represent the consumption without heat recycling between the kilns and the dashed line represent the consumption with recycling. When comparing the dashed and the solid line, in Figure 3, it can be seen that there is more efficient use of heat in drying step nr 2-7 when recycling the evacuation air. The individual consumption was reduced with 9 %, 6 %, 13 %, 15 %, and 17 % respectively. This results in an overall decreased heat consumption of 12 %. The experimental measurements were repeated three times for identical kilns, the data was then analysed in the same way as previously. This resulted in a maximum variation of 3 % between the measurements.

Figure 3, Heat consumption for five identical kilns

Among Swedish sawmills this represents a reduction of 440 GWh in heat consumption annually. For a specific sawmill this will lead to increase the production capacity due the reduced and more even heatload at the heating system and thus, with a result of less
drying bottlenecks. The use of heat which are produced from own biomass will decrease, resulting in benefits for the biomass market and the sawmill profit.

**Conclusion**

The investigation points out that it is possible to decrease the overall heat consumption by 12 %, for heating the entering air into the kiln. This is possible if each of the kilns is displaced in starting time with about eight drying step, to be able to recycle the evacuation air from one kiln with low humidity into another. This will result in more uniform load at the heating system and less bottlenecks at the drying processes. If implement this into larger heating system which embrace larger amount of kiln it is possible to achieve higher efficiency and a heating system which is less sensitive of fluctuations of the drying scheme.

**Discussion**

The high variation of reduced heat consumption, between kiln 1 – 5 (9 %, 6 %, 13 %, 15 %, and 17 %), can be explained by the specific displacement in time between the specific kiln and the other kilns. This demonstrates how important the displacement in time is between the different kilns, considering the heat recycling. In general, many dryers are started simultaneously, often due to simplicity, which renders effect in an unnecessary peak load at the heating system. The heat recovery system, explain in this paper, can be used among small drying systems in sawmills but will serve best for larger systems, with at least 10 kilns. I.e., sawmills with a production capacity of about 70 000 m³ lumbers. At these sawmills a heat recycling scheme between the kilns can be made with less sensitiveness of a specific kiln malfunction.

**References**


Paper C
Improved energy efficiency in sawmill drying system

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Abstract

The worldwide use of biomass has drastically increased mainly because of the large tax benefits which were authorized on the usage of renewable energy resources in order to make them more competitive at the market. Swedish sawmills use 56% of the total domestic wood supply for their lumber production and about half of that are transformed into by-product (biomass). A large part of this biomass is consumed for internal heat production, 80% of it being consumed during lumber drying with forced drying technique. The characteristics of the lumber drying process result into large energy losses due to the high amount of evacuation air. Available state-of-the-art technologies can be implemented into the existing drying systems to make use of the heat associated with the evacuation air exiting the drying kilns. Different technologies will be beneficial depending on the characteristics of the sawmill and of the drying process. A calculation program has been developed to evaluate their impact on the sawmill energy demand, lumber quality being ensured by the use of drying schemes to be implemented as boundary conditions reflecting given drying settings. The comparison among the technologies points out some significant outcome and the national impact on the biomass market is evaluated according to each combination of sawmill and drying process.

Keywords: Biomass, Drying technology, Sawmill, Kiln, Timber, Energy efficiency.

¹ Corresponding author
1 Introduction

A sawmill produces lumbers from the entering timber with the help of the sawmill processes; timber handling, barking, sawing, sorting, drying, packaging, and in some cases a grinding process is necessary. In these processes a lot of biomass is produced as by-products from the lumber production. About one tenth of the incoming timber is used for the internal supply of heat. The sawn lumber needs to be dried to a desired end moisture content to prevent cracks, shrinking, and mould issues. The supplied heat is mainly used for the drying process, which is a large energy and time intensive process. The drying process is done in a facility called drying kiln; dry outside air is heated and circulated through the lumber packages to carry away the moisture in the lumber. The additional part of the produced biomass is nowadays sold.

When producing lumber the lead time and wood quality are prioritized before the energy consumption. The reason for the high thermal energy requirement in the drying processes is that the evaporation heat is normally difficult to recover usefully, due to the low temperature. Heat recycling in the kilns is quite uncommon. In some few cases the heat is recovered with air/air heat exchanger [1]. The research devoted to increased energy efficiency when drying of lumber has been low prioritized in the past decades, due to the large supply and the historical low prices of biomass. Different software has been developed during the last decades to ensure correct kiln air conditions in order to attain adequate lumber quality [2-4]. Several experiments were made to evaluate the different variables’ effect on the energy efficiency when drying lumber for different drying conditions. [5-12]. That method is very time consuming and costly, especially if each drying condition needs to be tested for each type of recycling technology. It has been found that the heat consumption is possible to decrease by about 60% if available state-of-the-art technologies are used in the drying kiln [1, 5, 9-10, 13].

The main objectives of this work are to compare different technologies for increased energy efficiency hour by hour based on certain drying schemes. The focus is on wood types, lumber dimensions, and kiln types that are most commonly used in Sweden according to earlier work [1, 5, 14]. To ensure high lumber quality the drying scheme is constructed with the help of a simulation program called Torksim [15, 16]. Torksim was developed by the Technical Research Institute of Sweden. It is regularly used by sawmills to predict the drying scheme, to obtain a specific lumber end moisture content with a secured lumber quality and lead time, for the specific drying conditions.

2 Background

2.1 Swedish sawmills

In sawmills today only 47%wt [1, 14] of the entering timber becomes lumber. Except for timber the production processes needs electricity and heat to fulfil their purposes. The heat is often supplied by the sawmills own biomass fired furnace; otherwise the heat is purchased from nearby industries. The heat and electricity demand for each process is shown in Table 1. The main part of the energy used by the sawmill is heat and the drying process uses the majority part of it, while additional heat is used for
local heating. About 12%wt [2] of the entering timber is used to supply the sawmill with heat.

Table 1, Usage of heat and electricity between the lumber production processes [5, 6, 8, 17].

<table>
<thead>
<tr>
<th>Process</th>
<th>Electricity [kWh/m³ lumber]</th>
<th>Heat [kWh/m³ lumber]</th>
<th>Temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barking</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sawing</td>
<td>23</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Sorting</td>
<td>2</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Drying</td>
<td>31</td>
<td>299</td>
<td>75</td>
</tr>
<tr>
<td>Dry handling</td>
<td>4</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Grinding</td>
<td>13</td>
<td>5</td>
<td>30</td>
</tr>
<tr>
<td>Office</td>
<td>15</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>77</strong></td>
<td>339</td>
<td></td>
</tr>
</tbody>
</table>

The drying process is necessary to prevent unwanted mold, cracks and lumber modifications. A lumber drying process is a struggle among sufficient quality, low lead time and low energy usage. The quality and the lead time are always prioritized before the use of energy. To decrease the lead time forced drying technique is applied (in drying facilities called drying kilns), which gives rise to the high use of heat. The most common type of dryer is the progressive and batch kiln. The main difference between these kiln types is that the air state inside the batch kiln changes over time corresponding to the planned drying scheme. Compared with the progressive kilns, with several air zones of different air state, were the lumber package changes zones when travelling through the kiln. This gives rise to different energy uses and lead times, which is advantageous for different types of drying conditions.

Conventional drying technique uses outdoor air as moisture transport medium of evaporated water from the lumber. The moisture in the air has a lower partial pressure compared to the air close to the lumber. The equilibrium principle forces a moisture transport from the lumber into the air close to the lumber and further to the circulation air in the surroundings, which results in a drying effect. The bound and free water between and inside the wooden cells will be transported towards the surface. A large difference in partial pressure will cause a faster moisture transport; if this is done too fast an ununiformed distribution of the water can result in cracks and large lumber deformation, i.e. an unwanted low quality of the lumber (the amount of stored bound water compared to the amount of free water makes the structure more sensitive to these forces in the fiber structure). On the other hand a low difference in partial pressure will lead to unwanted slow drying. However, before the circulation air becomes saturated it needs to be evacuated from the dryer and exchanged with outdoor air with lower humidity. The dry but cold outdoor air needs to be heated until the drying temperature is achieved.

This contributes to the largest energy losses called evacuation losses, which stands for about 78% [10] of the total losses in a drying kiln, see figure 1. Other losses when
drying lumber in kilns can be divided into the following parts: transmission losses through the envelope, leakages that mainly arise when the kiln has been open during lumber loading. Lumber heating arises in the beginning of the drying processes to warm up the lumber to the drying temperature and melting heat, which arise when the lumber has been stored in degrees below zero. The high amount of evacuation losses, see figure 1, would give a high possibility to recover the heat in it. Still kilns with heat recovery are quite uncommon, but in those cases where the heat is recovered, the most popular type is the air/air heat exchanger.

![Figure 1, Magnitude of typical losses in a kiln [10]](image)

The majority of the lumber is dried to 18%wt end moisture content, and the remainder is often dried to 12%wt and 6%wt respectively. The wood types that are used in Sweden are Norwegian spruce and Scotch pine (with some minority part of broad-leaf trees). [2] The drying of the two different tree species is similar but not the same. This is because of the difference in start moisture content, density and the cell structure of the wood itself. The dimensions of the lumber board and the part of the timber log it is sawn from will of course affect the moisture content and the cell structure even further, which will give reason to choose different types of drying schedule and dryer depending on the specific conditions. The dimensions of 50 x 150 mm and 22 x 100 mm are a reasonable average of the most common sizes.

### 2.2 Available state of the art technologies

The fact that sawmills give higher priority to achieving sufficient quality and lead time before the energy efficiency has forced the analysis to guarantee that none of the technologies set up will affect the drying climate, this is ensured by letting the air state before and after the lumber package to be fixed, independently of which type of technology was used. Please, make clear that with the identical drying climate satisfied in the kiln the technologies will only affect the magnitude of the evacuation losses, i.e. other losses; transmission losses, leakage, melting losses etc. will be the same regardless of the used technology. For the same reason the need for electricity and heating period at the beginning of a drying scheme for a conventional kiln will be identical and therefore independent of the analysed technology. A branch marked questionnaire for Swedish sawmills with production of at least 50,000 m³ was produced to analyse their heating systems, drying setups, potential heat sinks and used technologies to clarify the criteria for the technologies to be used. The questionnaire also showed that heat recovery is seldom used at Swedish sawmills today. In the article
technologies were selected to be analysed concerning their potentials to decrease the usage of energy and increase the profit for sawmills. The criteria of available technologies selected were: existing state-of-the-art technology and its possibility to be used in an industrial site for drying. Analysis of possible technology that could be used was made through published literature, branch and patent registry in the technical area. An additional criterion was that they need to have a larger impact than the standard air/air heat exchanger from an energy recovery point of view. Some of the technologies were rejected because they were not possible to use in an industrial situation, or were inappropriate for use in this kind of contaminated air or had too low heat recovery impact etc. All these technologies are then compared with the reference case: conventional kiln, i.e. drying without heat recovery.

2.3 Chosen technologies implemented in the analyze

An extensive literature study resulted in three different technologies that had potential to achieve a sufficient impact for the sawmill industries, each compared with the reference case: conventional dryer without heat recycling technologies. Heat exchanger is the most commonly used recovery technology for the industrially used kiln dryer. It is well known and after installation it has very low operation costs. The heat exchanger uses the thermal energy in evacuation air, taken from the hot stream to heat the cold entering air. The advantages are low investment and variable operation cost with disadvantages of low overall efficiency. The mechanical heat pump uses a part of the circulation air to flow through the evaporator, the air is cooled and water is condensed and then recirculated into the dryer. By use of electricity powered compressor, the energy from the evaporator and compressor is set free as heat in the condenser. In terms of an effective technology, the disadvantage is the large electrical usage because of the compressor. The open absorption system consists mainly of three parts, absorber, generator and condenser, see figure 2. Water evaporates from the lumber in the kiln and is transported by the airflow to the absorber, water vapour in the humid air is absorbed by the absorption solution and the air is dried. The dry air is brought back to the kiln and therefore the supply of outdoor air can be excluded. The diluted solution is pumped to the generator. There the water is separated from the solution medium by evaporation using primary heat supply. The concentrated solution is transported back to the absorber. The water vapour is condensed in the condenser, giving latent heat at a temperature that is determined by the pressure in the device. The condensed and cooled water is drained from the system after the condenser; only the solution medium is recirculated in the system.

![Figure 2, Open absorption system installed at a sawmill](image)
3 Methodology

To ensure the quality of the lumber and normal lead time, a simulation program, Torksim, was used to predict the drying schemes. Each drying scheme is constructed with dry and wet bulb temperature and the lumber moisture content in the middle of the lumber package over time. Calculations were made for the two most used kiln types in the market; progressive kilns and batch kilns and with most commonly used tree species and lumber dimensions according to earlier work [1, 14]. A calculation program, IGOR Pro 4.0.9.1, was used for the calculation procedure through thermodynamic and psychrometric relationships to obtain the air state in the drying kiln. Input data was the result from the Torksim simulation. The air states before and after the lumber package are the same for each drying scheme, independently of the type of technology that was studied. The quality of the lumber was therefore ensured to be the same between the comparisons of the technologies. Please, make clear that with the identical drying climate produced in the kiln, the analysed technologies will not affect the magnitude of the other heat losses (transmission losses, leakage, melting losses etc.) except for the evacuation losses. For the same reason (constant air flow, temperature and pressure drop) the need for electricity for fans in a conventional kiln will be identical and therefore independent of the analysed technology. In the comparison among the different technologies these heat and electrical demands were excluded.

Six cases were chosen, three for a batch kiln and three for a progressive kiln, see table 2. In all cases the outdoor air temperature was set at +3°C and a relative humidity of 70% for the batch kiln; a relative humidity of 80% RH was used for cases with the progressive kiln. Dry lumber density for Scotch pine was set to 430 kg/m³ and for Norwegian spruce 385 kg/m³. Heartwood and sapwood were set to 50% each for the program Torksim. The progressive kiln was a two zones type of kiln, where the airflow is in one direction in the first zone and in the opposite direction in zone two. In the program IGOR one direction was simulated and constant air conditions in the kiln were set neglecting the lumber heating time period for this type of kiln. For the batch kiln a heating period and in some cases steam treatment at the start of the drying scheme were included in the simulations. Calculations for the progressive kiln with the different technologies implemented follow the batch kiln procedure but only for steady state conditions. Further explanations of procedure are therefore omitted.
Table, 2 Conditions for selected cases.

<table>
<thead>
<tr>
<th>Case nr</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln type</td>
<td>Batch</td>
<td>Batch</td>
<td>Batch</td>
<td>Progressive</td>
<td>Progressive</td>
<td>Progressive</td>
</tr>
<tr>
<td>Tree species</td>
<td>Scotch pine</td>
<td>Scotch pine</td>
<td>Norwegian spruce</td>
<td>Norwegian spruce</td>
<td>Scotch pine</td>
<td>Scotch pine</td>
</tr>
<tr>
<td>Lumber dimension (mm)</td>
<td>50x150</td>
<td>22x100</td>
<td>50x150</td>
<td>22x100</td>
<td>22x100</td>
<td>50x150</td>
</tr>
<tr>
<td>Drying scheme time (h)</td>
<td>70</td>
<td>44</td>
<td>65</td>
<td>45</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Lumber heating period (h)</td>
<td>4</td>
<td>7</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass flow of dry air in kiln (kg/s)</td>
<td>30</td>
<td>35</td>
<td>25</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Initial moisture content (%wt)</td>
<td>70</td>
<td>90</td>
<td>70</td>
<td>90</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>End moisture content (%wt)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>Dry bulb temperature, wet end (°C)</td>
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<td></td>
<td></td>
<td>63.5</td>
<td>63.2</td>
<td>62.5</td>
</tr>
<tr>
<td>Wet bulb temperature, wet end (°C)</td>
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<td></td>
<td></td>
<td>62.0</td>
<td>62.0</td>
<td>62.0</td>
</tr>
<tr>
<td>Volume of lumber in kiln (m³)</td>
<td>150</td>
<td>100</td>
<td>150</td>
<td>250</td>
<td>250</td>
<td>250</td>
</tr>
</tbody>
</table>

3.1 Theoretical calculation model

To evaluate the heat demand in a batch kiln for different technologies the air states (1) to (4) need to be known, see figure 3. The variables from Torksim (1) and (3b) are not enough to establish each air state in the drying cycle. Therefore, additional variables are needed to be calculated, such as: dry bulb temperature in points (2), (3) and (4), absolute air humidity and enthalpy from points (1)-(4), shown in Figure 4. The air circulation is schematically explained in figure 3 and the corresponding air state in a Mollier diagram in figure 4. For a batch kiln without heat recovery technology the cold
outdoor air with lower water content replaces some of the circulation air with higher water content. The air mix (2) is heated through the heating coil and a fan circulates the air through the lumber package, air states (3)-(4).

Figure 3, Air flow in a batch kiln without heat recovery.

Figure 4, Air state in a Mollier diagram for a batch kiln without heat recovery.

Torksim gave the temperature and relative humidity for the outdoor air. To calculate the air state in point 1, the partial water pressure was defined with Eq. 1; the saturation pressure for the dry bulb temperature can be calculated through a polynomial equation.

\[ P_w = (\theta / 100)P_{w\text{et}} \]  \hspace{1cm} (Eq. 1)

The absolute humidity in the air was calculated through Eq. 2, hence the partial water pressure and the absolute pressure were known.

\[ x = \frac{N_w}{M_d}P_w / (P_{\text{tot}} - P_w) \]  \hspace{1cm} (Eq. 2)

The enthalpy was calculated through Eq. 3 when the temperature and the absolute humidity are known in the calculated point.

\[ h = C_{p,d}T_d + x(r + (C_{p,v}T_d)) \]  \hspace{1cm} (Eq. 3)

The outdoor air state, point 1, is now defined. With the dry and wet bulb temperature
known in point (3b) (from Torksim), the absolute humidity can be calculated assuming an adiabatic saturation process. The absolute humidity at the wet bulb gauge ($x_{wet}$) was calculated with Eq. 2 (saturated state) and for the point (3b) the absolute humidity was calculated in accordance with Eq. 4, and the specific heat for water (liquid) and evaporation heat was calculated through a polynomial correlation at actual temperature. The enthalpy was determined through Eq. 3.

$$x = \left(C_{p,d}(T_w - T_d) + x_{wet}r\right)/(r + C_{p,v}T_d - C_{p,w}T_w)$$  \hspace{1cm} (Eq. 4)

The air states in points (1) and (3b) are now defined. But to analyse the energy demand due to the interchange of outdoor air, the air states in the other points need to be known. Between points 3 and 4 the air state is only affected by absorption of moisture from the lumber in accordance with presumptions.

The mass of evaporated water to the circulation air can be calculated by considering the decreased wood moisture content hour by hour (from Torksim) and the air state in point (3b) by using Eq. 5.

$$\dot{m}_{evap} = V_{wood} \rho(u_t-1 - u_t)$$  \hspace{1cm} (Eq. 5)

By implementing a constant mass flow rate of the dry air circulation in the kiln, valid for these types of drying conditions, a fixed value was used for all techniques, Eq. 6–8 can be used to determine the absolute humidity in points (3) and (4).

$$x_{diff} = \dot{m}_{evap}/(3600\dot{m}_{air})$$  \hspace{1cm} (Eq. 6)

$$x_3 = x_{3b} - x_{diff}/2$$  \hspace{1cm} (Eq. 7)

$$x_4 = x_{3b} + x_{diff}/2$$  \hspace{1cm} (Eq. 8)

The enthalpy in point (3) and (4) can be defined with Eq. 9 and 10.

$$h_3 = h_{3b} - (C_{p,w}T_w \dot{m}_{evap}/(3600 \ 2\dot{m}_{air}))$$  \hspace{1cm} (Eq. 9)

$$h_4 = h_{3b} + (C_{p,w}T_w \dot{m}_{evap}/(3600 \ 2\dot{m}_{air}))$$  \hspace{1cm} (Eq. 10)

A test was then implemented to ensure that the conditions in point (4) did not exceed saturated conditions. This was done by calculating the absolute humidity in point (4) with a polynomial correlation, $x_4 = f(h_4)$ created from saturated conditions, see Eq. 11.

$$x_{4, test} = -2.06745 \times 10^{-17} \times h_4^5 + 9.60207 \times 10^{-14} \times h_4^4 - 1.72423 \times 10^{-10} \times h_4^3 + 1.52956 \times 10^{-7} \times h_4^2 + 2.99162 \times 10^{-4} \times h_4 - 4.23359 \times 10^{-3}$$  \hspace{1cm} (Eq. 11)

The absolute humidity, $x_4$, determined by Eq. 8 was then compared with the absolute humidity at the saturation point, $x_{4, test}$. If the absolute humidity was lower than the saturated point, $x_{4, test}$, earlier calculations (Eq 7-10) was valid. Otherwise the absolute humidity was recalculated through Eq. 12 and 13.

$$x_4 = x_{4, test}$$  \hspace{1cm} (Eq. 12)
With enthalpy and absolute humidity known, the dry bulb temperature in points (3) and (4) was possible to calculate using Eq. 3. The partial pressure in these points was established with Eq. 2. Using a polynomial expression for determining the saturation pressure made it possible to calculate the relative humidity in each point using Eq. 1. The complete states for points (3) and (4) were thereby established.

The absolute humidity between points 2 and 3 is the same \( x_2 = x_3 \), hence the air is only influenced by heat transfer from the heating coil. With a mass balance for water vapour and absolute humidity known in points (1), (2) and (4), a mixing rate for the outdoor air could be calculated, see Eq. 14, i.e. how much air enters the kiln in relation to the circulation air.

\[
L_1 = \frac{(x_4 - x_2)}{(x_4 - x_1)} \quad \text{(Eq. 14)}
\]

An energy balance gives the enthalpy in point (2) according to Eq. 15 when the mixing rate is known.

\[
h_2 = L_1 h_1 + (1-L_1) h_4 \quad \text{(Eq. 15)}
\]

To get the total state for point (2) the dry bulb temperature and relative humidity were established in the same way as described earlier for points (3) and (4). The heat demand for the kiln was calculated with Eq.16.

\[
Q = \dot{m}_{air} (h_3 - h_2) \quad \text{(Eq. 16)}
\]

The calculations presented were made every hour during the drying scheme, excluding the heating period at the start of the scheme. This period was established as the time from the beginning of the scheme and until the moisture content in the lumber starts to decrease. The heating period was set equal to the conventional system for all the different techniques. Summing up the heat demand for all hours in the scheme gives the total heat demand for the kiln (see Eq.17), i.e. the heat demand to cover the evacuation losses.

\[
\dot{Q}_{tot} = \sum_{i=1}^{n} \dot{Q}_n \quad \text{(Eq. 17)}
\]

Specific heat demand was calculated by dividing the total heat demand with total amount of water evaporated from the lumber during the drying scheme, see Eq. 18.

\[
\dot{q}_{tot} = \frac{\dot{Q}_{tot}}{\sum_{i=1}^{n} \dot{m}_{evap,n}} \quad \text{(Eq. 18)}
\]

### 3.2 Heat exchanger

By combining the drying kiln with an air/air heat exchanger the heat in the exiting air can be used to heat the cold but dry outdoor air entering the kiln. The drying cycle with a heat exchanger is explained in figure 5, schematically and in a Mollier diagram in figure 6. The humid air (4) preheats the entering air from air state (1) to (1b). The preheated air is mixed with the remaining circulation air, creating point (2). This
causes the enthalpy difference between air states (2) and (3) to decrease, i.e. less heat is needed to be supplied through the heating coil. The remaining part and the drying cycle are the same as for the regular kiln working without heat recovery.

Figure 5, Air flow in a batch kiln with an air/air heat exchanger.

The air states in point (3) and (4) were calculated as explained in Ch. 3.1. The temperature efficiency for the air/air heat exchanger was set constant at 68%. The air state in point (1b) was calculated as earlier explained for heating. The air state in point (4out) was also calculated in order to investigate if condensation occurred. The mixing rate, air state point (2), and heat demand were calculated as before, given the specific heat demand using a heat exchanger for the drying scheme in question. The heat exchanger causes a higher electricity usage due to increased air pressure loss over the heat exchanger. This pressure difference was assumed to be 100 Pa for the air entering the kiln and 200 Pa for the air exiting the kiln. The fan efficiency was set at 75%, and the maximum airflow to/from the heat exchanger was assumed to be valid throughout the total drying period when calculating the electricity supply. Multiplying by the hours for the drying period and dividing by the total evaporated water from the lumber gave the specific electricity demand for the air/air heat exchanger and the drying scheme in question.

Figure 6, Air state in a Mollier diagram for a batch kiln with an air/air heat exchanger.
3.3 Mechanical air pump

A mechanical heat pump was connected to the batch kiln. A partial flow of the circulation air (state 4) was cooled and dried (water condensed) in the evaporator, and thereby no outdoor air was needed. The drying cycle is explained in figure 7 and figure 8. In the calculation procedure a COP=4 was used for the heat pump. One third of the circulation air was assumed to flow through the evaporator (points (4)-(5)). By placing the condenser in the total air flow it is possible to decrease the maximum working medium temperature, i.e. lower maximum pressure for the heat pump. A disadvantage is increased electricity usage for the fans due to higher air flow through the condenser.

The air state (3) and (4) were the same as for the conventional kiln. The absolute humidity in point (5) was calculated from the evaporated amount from lumber for the hour in question in the drying scheme. The air state (2VP) was calculated as mixing, explained earlier in Ch. 3.1. Heating of the circulating air occurs when passing through the condenser, point (2VP) to (6). If that state, points (6) was higher than needed, point (3) the original heating coil works as a cooling coil in the calculations. Increased electricity supply compared to conventional technique was applied because of the compressor and to cover the pressure drop in the evaporator and the condenser, this has been assumed to be 100 Pa each. The heat pump has been assumed to be in work during the hours evaporation from lumber take place.

![Figure 7, Air flow in a batch kiln with a mechanical heat pump.](image-url)
Figure 8, Air state in a Mollier diagram for a batch kiln with a mechanical heat pump.

In the calculation procedure the total heating obtained by the condenser contributed to the circulating air, which caused the ordinary heating coil to decrease the temperature in the kiln climate to acquire the drying temperature. In normal cases only the desirable heat to acquire the wanted drying temperature will be supplied; the surplus heat is used at another heat sink for other purposes.

3.4 Open absorption system

Installing an open absorption system as a heat recovery technique will affect the drying cycle in the following order, schematically shown in figure 9 and 10. A partial flow (one third) of the circulation air (4) enters the absorber, a part of the moisture in the air is absorbed by the absorption medium to achieve air state (5), according to the working line for the absorption medium. The air temperature increases due to the vaporisation heat being set free for the absorbed water. The dried air (state (5)) after the absorber is mixed with the circulating air (state (4)) gives state (2). The achieved air state is the same as the air state in point (3), i.e. no heat supply is necessary from the heating coil. To compensate the pressure drop in the absorber, assumed to correspond to 200 Pa, an extra electricity supply for a fan was calculated.
The absorbed water in the absorption solution needs to be separated from the system, in the generator, see chapter 2.3. For the comparison of the different techniques, the total energy supply for the open absorption system has to be calculated. The generator was assumed to separate 10,000 kg of water each hour, i.e. several drying kilns included at the sawmill. The generator works with three heat effects (absolute pressure 1, 3.5 and 10 bar in the respective effect), for which reason the heat demand decreases to about 40% compared to a one effect apparatus. The water exiting the generator (originally from the humid air in the kilns) has a temperature of +95 °C. The electricity demand consists of electricity to two pumps in the absorber, pumps for the transportation of the solution to the generator and from the generator, three pumps to distribute solution to each heat effect, three pumps for internal solution flow in each heat effect and a condensation pump for the water leaving the generator. The electricity demand was taken from the manufacturers’ data by calculated solution flow and pressure height for each pump. To include the partial load of the generator, the specific electricity demand for the generator was increased by 33% compared to full load. The heat output from the generator and thereby from the open absorption system was calculated as one part steam (3500 kg/h), liquid water cooled from 100°C to 75°C in the kilns (to cover other losses than evacuation losses) and finally cooling from 75°C to 45°C used for heating in buildings at the sawmill.
4 Result and discussion

The result of the previous sections provides some interesting outcomes if considering the difference between each studied technology from an energy usage point of view. Heat and electricity were separated because of the high difference in price.

4.1 Drying perspective

Please make clear that calculation was made by using drying schemes suggested by Torksim as boundary conditions from the three most commonly used drying conditions for each type of dryer: batch and progressive kiln [1]. The drying conditions for each case are shown in table 2. The use of electricity and heat for each type of technology tends to be similar for the cases. For this reason only case 1 is shown schematically, see figure 12; specific values for all cases are shown in tables 3-4. To compare the different technologies only the heat to cover for the evacuation losses is presented. This value is divided by the total amount of evaporated water during the scheme and the specific energy usage is obtained.

During the initial time of the drying scheme for a batch kiln the lumber is heated until the desired drying temperature is reached. During this phase steam is added into kiln to decrease the strain in the lumber to prevent cracks and lumber modifications. This period was determined by comparing the lumber moisture content hour by hour; when it starts to decrease the heating period is over. During this period the heat supply was taken directly from the Torksim program. The moisture extraction during the drying cycle for case no. 1 can be seen in figure 11, where the heating time of the first four hours is visualized. The maximum evaporation of water is about 780 kg/h. During the total drying cycle 38758 kg of water is evaporated from the lumber package to be carried away with the circulation air.

Figure 11, Evaporation of water from lumber to circulation air for case no. 1.
In figure 12, the specific energy uses of each technology are compared to each other: Conventional kiln (i.e. kiln without heat recovery) Heat exchanger, Mechanical heat pump and Open absorption system. The energy supply covers for heating periods and evacuation losses. The heat used for heating the lumber until the actual drying starts is identical for each technology since the climate is the same.

![Figure 12: Specific energy usage depending on type of technology, case no. 1.](image)

For case 1 the total specific energy usage for conventional technology is 3.5 MJ/kg of evaporated water. If using a heat exchanger the heat usage is decreased by 7% (heating period excluded). The marginal decrease of heat usage is due to only a small part of the energy in the evaporated water being recovered. (If a temperature efficiency of 90% was used, the heat demand decreased by 9.4%). The need for electricity will increase slightly.

The heat pump alternative shows a surplus of heat produced by 1.30 MJ/kg of water (the temperature for the working medium in the condenser, about +90°C) and a drastically increased electricity usage mainly used in the compressor. The use of the open absorption system will also result in a heat surplus (heating period excluded) and an increased electricity usage. The main difference to the mechanical heat pump is that the primary energy supply is heat and therefore decreases the electricity demand strongly. In tables 3 and 4 the specific energy usage is shown for the different drying cases, bath kiln and progressive kilns respectively. The specific heat supply during the heating period for the batch kiln cases was 0.89, 0.36, and 0.92 MJ/kg evaporated water for cases 1, 2 and 3 respectively.
Table 3, Specific energy usage for investigated technologies, batch kiln.

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat</th>
<th>Heat Exchanger</th>
<th>Mechanical Heat Pump</th>
<th>Open Absorption System</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MJ/kg water)</td>
<td>(MJ/kg water)</td>
<td>(MJ/kg water)</td>
<td>(MJ/kg water)</td>
</tr>
<tr>
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<td>-1.02</td>
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<td>2.40</td>
<td>-1.35</td>
<td>-1.02</td>
</tr>
</tbody>
</table>

Table 4, Specific energy usage for investigated technologies, progressive kiln.

<table>
<thead>
<tr>
<th>Case</th>
<th>Heat</th>
<th>Heat Exchanger</th>
<th>Mechanical Heat Pump</th>
<th>Open Absorption System</th>
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<tr>
<td></td>
<td>(MJ/kg water)</td>
<td>(MJ/kg water)</td>
<td>(MJ/kg water)</td>
<td>(MJ/kg water)</td>
</tr>
<tr>
<td>Case 4 Heat</td>
<td>2.73</td>
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<td>-1.23</td>
<td>-1.02</td>
</tr>
<tr>
<td>Case 5 Heat</td>
<td>2.73</td>
<td>2.48</td>
<td>-1.22</td>
<td>-1.02</td>
</tr>
<tr>
<td>Case 6 Heat</td>
<td>2.72</td>
<td>2.47</td>
<td>-1.20</td>
<td>-1.02</td>
</tr>
</tbody>
</table>

The impact of the heat exchanger as a heat recovery technology will only have a marginal effect on the heat usage (a decreased heat demand of 0.15-0.45 MJ/kg water). This can be compared with the heat decrease when using a mechanical heat pump with 3.9-4.3 MJ/kg water, but with an increased electricity usage of 1.0-1.1 MJ/kg water. This is similar to the heat usage with the open absorption system installed, which will decrease the heat consumption by 3.6-4.1 MJ/kg water with an increased electricity use of 0.05 MJ/kg water (which is considerably lower than the use of electricity of the heat pump). To compare the different technologies one needs to go back to the biomass input to the sawmill furnace (in heat supply units) due to the fact that some techniques create a surplus of heat at the kiln.

According to figure 1 heat losses in a drying kiln with conventional technique (evacuation losses excluded) constitute 22% of the total heat demand; thereby it is
possible to calculate these losses using tables 3-4. The heat demand for the total sawmill (kiln excluded) can be calculated using table 1 (13.4 % of the heat demand for the kilns). The overall heat demand for the sawmill can now be determined by adding these three values. Assuming 10% losses in the furnace during heat production gives a final value for the heat input to the furnace.

Using the heat exchanger decreases the evacuation losses according to tables 3-4, and the magnitude of other losses is the same as earlier. The total heat input can be compared to the conventional system and the heat recovery for the sawmill using this technique is presented in table 5.

The mechanical heat pump creates a surplus of heat larger than the total heat demand at the sawmill; no furnace is needed and the heat recovery in table 5 is hence 100%. An external heat sink is needed to be able to use all the heat produced in the condensers; the possible maximum temperature of the secondary system is about 80-85 °C. In reality a furnace will be needed to cover the heat supply during periods with large heat demand and for steam production during the heating period in batch kilns.

For the open absorption system heat produced in the generator is used to cover losses in the kiln (evacuation losses do not arise) and to cover other heat demands at the sawmill. Assuming another 5% heat losses in the generator (to cover transmission losses and culvert pipes’ heat losses) gives the heat demand to the generator. This heat is produced in the furnace and including those losses gives the heat supply to the furnace. To cover the remaining heat demand at the sawmill another heat supply (with furnace losses included) has to be calculated. Adding these two values gives the total heat supply to the sawmill using this technique; the heat recovery compared to the conventional system is shown in table 5.

Table 5, Heat recovery for investigated technologies compared to total heat demand for a sawmill using conventional drying system.

<table>
<thead>
<tr>
<th></th>
<th>Conventional Heat exchanger</th>
<th>Mechanical heat pump</th>
<th>Open absorption system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MJ/kg water)</td>
<td>(% reduction)</td>
<td>(% reduction)</td>
</tr>
<tr>
<td>Case 1</td>
<td>4.23</td>
<td>5.0</td>
<td>100</td>
</tr>
<tr>
<td>Case 2</td>
<td>4.93</td>
<td>10.2</td>
<td>100</td>
</tr>
<tr>
<td>Case 3</td>
<td>4.12</td>
<td>4.1</td>
<td>100</td>
</tr>
<tr>
<td>Case 4-6</td>
<td>4.41</td>
<td>6.3</td>
<td>100</td>
</tr>
</tbody>
</table>

Applying the results to the entire national Swedish lumber production at sawmills on a yearly basis can be done as follows. Assuming a start moisture content of 90%wt and 70%wt for Norwegian spruce and Scotch pine respectively and an end moisture content of 18%wt. Including the dry density for each wood type makes it possible to
calculate an average value for evaporated water per cubic lumber. From earlier work the annual production of lumber in Sweden was 17.3 Mm$^3$ per year 2008 [1, 21]. Multiplying these values gives a total annual amount of water evaporated from lumber. 60% of all lumber dried in batch kilns (1/3 for each case 1-3) and 40% dried in progressive kilns, gives the evaporated water annually for each case [1, 14]. Using values from table 5 it is possible to calculate the annual heat reduction on a national basis compared to the conventional system, assuming that all sawmills in Sweden were to implement the technology. Calculation of the increased annual electricity supply for each technology uses values from tables 3-4. The result is presented in table 6.

<table>
<thead>
<tr>
<th></th>
<th>Heat exchanger</th>
<th>Mechanical heat pump</th>
<th>Open absorption system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat reduction (TWh/year)</td>
<td>0.33</td>
<td>5.56</td>
<td>3.44</td>
</tr>
<tr>
<td>Electricity supply (GWh/year)</td>
<td>2.4</td>
<td>996.2</td>
<td>49.2</td>
</tr>
</tbody>
</table>

If the heat exchanger is adopted for the heat usage, it will decrease corresponding to a small amount of biomass to be saved, with an additional electricity consumption of 2.4 GWh annually. If instead the mechanical heat pump is used, biomass corresponding to 5.56 TWh will be saved, and a surplus of 0.62 TWh heat will also be available for the external heat sink. The drawback is the large increased electricity usage, almost 1 TWh annually.

Using the open absorption system for heat recovery at the Swedish sawmills industry will result in a large reduction of the heat demand and a more moderate electricity increment. The open absorption system has a higher freedom at the return water temperature for the surplus heat than the heat pump, which makes the usability easier for a larger amount of possible heat sinks for further use of surplus heat.

Additional heat sinks for surplus with the mechanical heat pump could be external heat uses, e.g. district heating, heating of pelleting plants, ORC (Organic Rankine Cycle) power plants or other industrial process heating.

The heat reduction potential on the national level presented for the different technologies assumes steady state conditions. The simulations performed with IGOR show for instance that the heating period lasts only for a few hours but during this time the heat supply is large. It is therefore not certain that the produced heat surplus from the mechanical heat pump technology or the open absorption system is sufficient to cover the heat demand. The outcome depends on the sawmill configuration and operation mode. The assumption of steady state conditions is therefore not totally correct. The actual heat recovery on the national level will consequently decrease to some extent.
5 Conclusions

A substantial quantity of biomass could be saved and used for other purposes in society, if available energy recovery technologies were implemented in the sawmill industry. Use of heat exchanger technology to recycle the heat in the evacuation air leads to only a marginal increase of the efficiency, between 4-10% (depending on the drying scheme and sawmill conditions). In a national system aspect for the sawmill industry in Sweden this corresponds to 0.33 TWh, with an additional use of electricity consumption of 2.4 GWh. The low impact on the drying kiln’s efficiency that is possible to achieve is due to the fact that only a small part of the energy in the available evaporated water in the evacuation air is recovered.

The mechanical heat pump is an effective technology that can decrease the energy usage considerably and result in a large heat surplus if implemented in the drying system. The disadvantage of the technology is the high consumption of electricity due mainly to the compressor. In a national perspective the mechanical heat pump can decrease the internal biomass usage corresponding to 5.56 TWh and also create a surplus of heat, the negative effect is the large electricity demand, almost 1 TWh on annual basis The fact that the price of electricity is much higher compared with the biomass price is a large drawback from the point of view of profitability.

The open absorption system will decrease the heat usage by 67.4% on average if implemented in the drying kilns. In a national perspective this technology will decrease the annual use of biomass in the sawmill industry by 3.44 TWh, lower than the mechanical heat pump but with significant lower electricity consumption, 49.2 GWh.

The heat reduction potential presented for the different technologies assumes steady state conditions. The high correlation of the specific heat load at the dryer affects the heating system, and where in the drying period the dryer is located will affect the possible usage of surplus heat from these technologies. It should therefore be clear that how the dryers are operated will have an impact on the possible received effectiveness of the system.

Additional heat sinks for surplus heat purposes should in those cases therefore be implemented in the overall heating system to increase the usage of surplus heat, e.g. district heating, pelleting plants, ORC (Organic Rankine Cycle) power plants or other industrial process heating.

6 Further studies

Further studies are needed to show the impact of the studied technologies in a system approach. A suggestion would be to make a process integration of a reference sawmill to be implemented to show how the system requirement of heat is changed depending on what kind of technology is used to recover the heat.
7 Acknowledgements

The research is funded by the Swedish Energy Agency and is the first part of a research project that will analyse the energy use among sawmill drying facilities.

Nomenclature

<table>
<thead>
<tr>
<th>Term</th>
<th>Symbol</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass flow</td>
<td>( \dot{m} )</td>
<td>[ kg/s ]</td>
</tr>
<tr>
<td>Absolute moisture content</td>
<td>( x )</td>
<td>[ kg water/kg dry air ]</td>
</tr>
<tr>
<td>Pressure</td>
<td>( P )</td>
<td>[ kPa ]</td>
</tr>
<tr>
<td>Enthalpy</td>
<td>( h )</td>
<td>[ kJ/kg ]</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>( \theta )</td>
<td>[ % RH ]</td>
</tr>
<tr>
<td>Lumber moisture content</td>
<td>( u )</td>
<td>[ kg water/kg lumber ]</td>
</tr>
<tr>
<td>Volume</td>
<td>( V )</td>
<td>[ m(^3) ]</td>
</tr>
<tr>
<td>Density</td>
<td>( \rho )</td>
<td>[ kg/m(^3) ]</td>
</tr>
<tr>
<td>Temperature</td>
<td>( T )</td>
<td>[ °C ]</td>
</tr>
<tr>
<td>Latent heat</td>
<td>( r )</td>
<td>[ kJ/kg ]</td>
</tr>
<tr>
<td>Specific heat</td>
<td>( C_p )</td>
<td>[ kJ/kg K]</td>
</tr>
<tr>
<td>Molar mass</td>
<td>( M )</td>
<td>[ g / mol ]</td>
</tr>
<tr>
<td>Heat</td>
<td>( \dot{Q} )</td>
<td>[kJ/s]</td>
</tr>
<tr>
<td>Specific heat</td>
<td>( \dot{q} )</td>
<td>[kWh/kg]</td>
</tr>
<tr>
<td>Mixing rate</td>
<td>( L )</td>
<td></td>
</tr>
</tbody>
</table>

Subscript

1 door, point 1
2 before the heating battery, point 2
3 middle of lumber package, point 3
3d before lumber package, point 3b
4 after lumber package, point 4

t time \( t=0 \)
t-1 time \( t=-1 \)
i initially
n interval number
w water
v vapor
d Dry air
s Saturated
test test
tot total
wet saturated conditions
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