Miguel Lavado

Bark drying in a large integrated Finnish pulp mill

Master’s Thesis

Examiners:  Professor, Ph.D. (Tech.) Esa Vakkilainen and M. Sc. (Tech.) Mika Varis

Supervisors:  M. Sc. (Tech.) Mika Varis
             M. Sc. (Tech.) Juha Keltanen
ABSTRACT

LAPPEENRANTA University of Technology
School of Energy Systems
Degree Program in Energy Technology

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2019

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Keywords: Bark, Sludge, Drying, Boiler, Biomass.

In the pulp and paper industry, bark and sludge are commonly burnt in biomass boilers. Often, bark water content accounts for half its mass when it is fired in biomass boilers and sludge moisture is generally over to two thirds of its mass. To maintain combustion temperatures, boilers need a supporting fuel. In the biomass boiler presented in this thesis, flue gas flow from combustion of wet biomass and combustion air demands are limiting its operational capacity. Drying biomass could potentially diminish these flows and the consumption of natural gas. The first will allow biomass boiler to operate at higher loads and the second will reduce the mill’s natural gas costs as well as fossil fuel emission allowances. Several drying technologies such as rotary, flash, superheated steam and conveyor dryers are presented in this work.
ACKNOWLEDGEMENTS

This thesis was done for Stora Enso Imatra mills. The personnel in this mill was great and supported me to understand what I needed to understand for my work but also other areas of the mill when I asked for. In especial, I would like to thank my supervisors Mika Varis, Juha Keltanen, Timo Tidenberg, Hannu Mustonen and Aalpo Pajari for their support and patience explaining me the functioning the whole mill, reporting systems, and in general, how a mill works. They really made me feel like part of the team.

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Last but not least, I want to thank my family. To my wife for her unconditional support during my studies and for being my guide when I needed it. To my kids for understanding that “Papá opiskelee” and giving me strength just by being how they are.

Lappeenranta, 27th of April 2019

Miguel Lavado
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<th>Definition</th>
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<tbody>
<tr>
<td>ar</td>
<td>As received</td>
</tr>
<tr>
<td>CTMP</td>
<td>Chemi-thermomechanical pulp</td>
</tr>
<tr>
<td>d</td>
<td>Dry</td>
</tr>
<tr>
<td>daf</td>
<td>Dry and ash free</td>
</tr>
<tr>
<td>E</td>
<td>Energy</td>
</tr>
<tr>
<td>EG</td>
<td>Ethylene Glycol</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrostatic precipitator</td>
</tr>
<tr>
<td>FGR</td>
<td>Flue gas recirculation</td>
</tr>
<tr>
<td>GWh</td>
<td>Gigawatt hour</td>
</tr>
<tr>
<td>HHV</td>
<td>Higher heating value</td>
</tr>
<tr>
<td>I</td>
<td>Investment cost</td>
</tr>
<tr>
<td>K</td>
<td>Kelvin</td>
</tr>
<tr>
<td>kgH</td>
<td>Kilograms of Hydrogen</td>
</tr>
<tr>
<td>kgdry fuel</td>
<td>Kilograms of dry fuel</td>
</tr>
<tr>
<td>LHV</td>
<td>Lower heating value</td>
</tr>
<tr>
<td>lv</td>
<td>Latent heat of evaporation</td>
</tr>
<tr>
<td>m3n/s</td>
<td>Normal cubic meter per second</td>
</tr>
<tr>
<td>MC</td>
<td>Moisture content</td>
</tr>
<tr>
<td>MH</td>
<td>Hydrogen molar mass</td>
</tr>
<tr>
<td>MH2O</td>
<td>Molar mass, subc water</td>
</tr>
<tr>
<td>MWh</td>
<td>Megawatt hour</td>
</tr>
<tr>
<td>NG</td>
<td>Natural gas</td>
</tr>
<tr>
<td>NOx</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>NPV</td>
<td>Net present value</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operation and maintenance</td>
</tr>
<tr>
<td>P</td>
<td>Power</td>
</tr>
<tr>
<td>PBT</td>
<td>Pay-back time</td>
</tr>
<tr>
<td>RTO</td>
<td>Regenerative thermal oxidizer</td>
</tr>
<tr>
<td>S</td>
<td>Annual net savings</td>
</tr>
<tr>
<td>S0</td>
<td>Current scenario including KK2</td>
</tr>
<tr>
<td>S0+</td>
<td>Current scenario including KK2 and K9-12</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Definition</td>
</tr>
<tr>
<td>--------------</td>
<td>------------</td>
</tr>
<tr>
<td>SSD</td>
<td>Superheated steam</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>t</td>
<td>Tons</td>
</tr>
<tr>
<td>TS</td>
<td>Total solids</td>
</tr>
<tr>
<td>TWB</td>
<td>Temperature wet-bulb</td>
</tr>
<tr>
<td>TWh</td>
<td>Terawatt hour</td>
</tr>
<tr>
<td>Ucr</td>
<td>Critical humidity ratio</td>
</tr>
<tr>
<td>Ui</td>
<td>Initial moisture</td>
</tr>
<tr>
<td>Ueq</td>
<td>Balance moisture</td>
</tr>
<tr>
<td>VOC</td>
<td>Volatile organic compounds</td>
</tr>
<tr>
<td>VS</td>
<td>Volatile solids</td>
</tr>
<tr>
<td>WESP</td>
<td>Wet electrostatic precipitator</td>
</tr>
<tr>
<td>whH</td>
<td>Hydrogen relative mass in fuel</td>
</tr>
<tr>
<td>winter</td>
<td>From September to May both included</td>
</tr>
<tr>
<td>x</td>
<td>Air moisture</td>
</tr>
<tr>
<td></td>
<td>Including currently sold bark</td>
</tr>
</tbody>
</table>

**Greek letters**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>η</td>
<td>Efficiency</td>
</tr>
<tr>
<td>λave</td>
<td>Average stoichiometric air coefficient</td>
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</tbody>
</table>

**Subscript**

<table>
<thead>
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<th>Definition</th>
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<tr>
<td>a</td>
<td>Annual</td>
</tr>
<tr>
<td>air</td>
<td>Air</td>
</tr>
<tr>
<td>aₙ/i</td>
<td>Discount factor</td>
</tr>
<tr>
<td>ash</td>
<td>Ash</td>
</tr>
<tr>
<td>ave</td>
<td>Average</td>
</tr>
<tr>
<td>ca</td>
<td>Combustion air</td>
</tr>
<tr>
<td>d</td>
<td>Dry</td>
</tr>
<tr>
<td>dry</td>
<td>Dry</td>
</tr>
<tr>
<td>dry fuel</td>
<td>Dry fuel</td>
</tr>
<tr>
<td>dryer</td>
<td>Dyer</td>
</tr>
</tbody>
</table>
el Electricity
evaporation Evaporation
flue gas Flue gas
fuel Fuel
glycol ethylene glycol
h Hours
H Hydrogen
H2O Water
hfg Latent heat of vaporization of water or (ls)??
i Interest rate
in Input
independent from fuel Losses that do not depend on fuel input
JA Remaining investment value
losses Losses
m Mass
n Dryer lifetime
out Output
steam Steam
th Thermal
unburnt Unburnt
water Water
wet Wet

Abbreviations

bark-sells Currently sold bark
HE1 Heat exchanger 1
HE2 Heat exchanger 2
K9 Natural gas boiler 9
K10 Natural gas boiler 10
K11 Natural gas boiler 11
K12 Natural gas boiler 12
K9-12 Natural gas boilers 9, 10, 11 and 12
<table>
<thead>
<tr>
<th>Abbr.</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>KK2</td>
<td>Bark boiler 2</td>
</tr>
<tr>
<td>KP</td>
<td>Kaukopää</td>
</tr>
<tr>
<td>LP</td>
<td>Low pressure</td>
</tr>
<tr>
<td>P75</td>
<td>Power capacity is 75% of design</td>
</tr>
<tr>
<td>P90</td>
<td>Power capacity is 90% of design</td>
</tr>
<tr>
<td>SE</td>
<td>Stora Enso</td>
</tr>
<tr>
<td>TA</td>
<td>Tainio</td>
</tr>
<tr>
<td>TU7</td>
<td>turbine 7</td>
</tr>
</tbody>
</table>
1 INTRODUCTION

The mass production of paper and paperboard in the world during the year 2014 was 400 Mt from which 173 Mt was produced from virgin wood pulp and 221 Mt from recovered paper (FAO 2019a). This same year, the Finnish pulp production was 10.8 Mt from which 31.8% mechanical and semi-chemical pulp and 62.5% chemical pulp (FAO 2019b). The energy the Finnish paper and cardboard industry consumed was 75.1 TWh which stood for half the energy consumption of all the industry sector in the country; black liquor accounted for 39.4 TWh whereas bark did it for 6.5 TWh (Tilastokeskus 2015, 4-5). In a smaller scale, sludge streams are also part of the woody biomass the Finnish forest industry uses in energy recovery (Holmberg 2007, 6).

In the year 2015, Stora Enso Imatra mill produced 1.3 Mt of pulp from which bleached pulp 0.9 Mt, unbleached pulp 0.2 Mt and Chemi-thermomechanical pulp (CTMP) 0.2 Mt. As a side product of this production, the mill processed 4.91 Mm$^3$ of barked wood divided into 2.55 Mm$^3$ of birch, 1.6 Mm$^3$ of pine and 0.76 Mm$^3$ of spruce. The mill consumed 6.8 TWh of fuel from which 72 % black liquor, 17 % bark and sludge, 12 % natural gas (NG) and 2 % oil.

In Finland, black liquor is the main fuel in the forest industry and usually it is dried in several stages evaporators. Liquor’s moisture content (MC) can be as low as 15% before it is injected into the recovery boiler furnace (Vakkilainen et al. 2014, 109). However, bark without thermal drying, is commonly of the order of 50% when it is burnt (Alakangas et al. 2016, 62). Sludge MC is of the order of 70% after mechanical pressing (Lohiniva et al. 2001, 26). As black liquor, bark and sludge may also be dried before combustion. In fact, dryers were used before the oil crisis, but after this with the price of fuels falling, investments in dryers made no sense. The general trend is to increase energy efficiency and the increase on fuel and emission allowance prices, could be motivating drivers to this end (Holmberg et al. 2004, 11-12; Motiva 2014, 3).

Bark and sludge drying cases are studied in this work in order to find an eco-environmental solution for this biomass at the Stora Enso Imatra Mills. In order to understand these fuels, their properties, drying possibilities and the change on their characteristics while submitted to a drying process are studied next.
1.1 Bark

In pulp and paper mills, bark is obtained from debarking logs (Werkelin et al. 2005, 451-452). Bark is discarded from the pulp making process because of its chemical composition; it has much less cellulose and hemicellulose than log wood as represented in table 1. The production of pulp relies on the cellulose content in the wood; the larger the amount of cellulose the better the pulp yield is (Vakkilainen et al. 2014, 14). Table 1 depicts the differences on cellulose and hemicellulose from bark and log wood for the three most common tree species in Finland.

Table 1. Main chemical composition of bark and log from pulp wood. Birch (betula pubescens), pine (pinus sylvestris), spruce (picea abies). (Alakangas et al. 2016, 55)

<table>
<thead>
<tr>
<th>Pulp wood type</th>
<th>Cellulose</th>
<th>Hemi-cellulose</th>
<th>Lignin</th>
<th>Extractives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birch bark</td>
<td>10.7</td>
<td>11.2</td>
<td>14.7</td>
<td>25.6</td>
</tr>
<tr>
<td>Birch log</td>
<td>43.9</td>
<td>28.9</td>
<td>20.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Pine bark</td>
<td>22.2</td>
<td>8.1</td>
<td>13.1</td>
<td>25.2</td>
</tr>
<tr>
<td>Pine log</td>
<td>40.7</td>
<td>26.9</td>
<td>27.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Spruce bark</td>
<td>26.6</td>
<td>9.2</td>
<td>11.8</td>
<td>32.1</td>
</tr>
<tr>
<td>Spruce log</td>
<td>42.0</td>
<td>27.3</td>
<td>27.4</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Apart from the difference in cellulose content within log wood and bark, table 1 shows a much higher content on extractives in the bark. Lignin content is also higher per unit of cellulose in bark. Extractives and lignin challenge the pulp-making process reducing brightness and strength qualities of the final product. (Vakkilainen et al. 2014, 41)

After bark is discarded, its MC can be as high as 85% in the case of wet debarking drums (Alakangas et al. 2016, 62). Bark can be crushed and pressed to reduce MC in what is called mechanical drying. Consecutively, bark is commonly burned in boilers at around 50% MC and the energy resultant from its combustion is used to produce steam and electricity that is consumed within the mill or sold if there is excess of it (Holmberg A. et al. 2014, 8-13). In the Finnish forest industry, it is common to burn bark along with sludge streams from different pulp-making processes. Generally, their combustion takes place in fluidized bed boilers (Holmberg et al. 2015, 161).
1.1.1 Bark characteristics

Bark is a biofuel and as such, it consists on a wet and a dry part. The wet part is represented by moisture within the bark. Moisture content may vary from 40% to 60% for fresh bark depending for example on the season of the year the tree is cut. If wood is left to dry during the summer months, MC of bark could decrease to 20-30%. This though, requires time and space. Concentration of moisture can also vary depending on the type of tree, its age, the part of it, the time of the year when this is cut and the moisture at the place of growth. Moisture can also increase or be reduced while bark is stored due to weather conditions. (Alakangas et al. 2016, 60; Holmberg 2007, 7; Werkelin et al. 2005, 547)

Total solid (TS) is the part of the fuel that remains when all the moisture is evaporated at a constant temperature of 103-105 °C. TS can be divided into volatile solids (VS), fixed carbon and ash. Figure 1 represents this graphically. VS are the compounds that become gaseous when the fuel is exposed to heat and they are measured as weight fraction of the dry part lost when fuel is submitted to pyrolysis at (500 °C +/- 50 °C). VS in bark corresponds approximately to 80% of TS weight whereas fixed carbon accounts for most of the rest 20%. The latter is the carbonaceous content of the fuel remaining after pyrolysis. Ash is the solid residue that remains unburned after the complete combustion of a fuel. (Alakangas et al. 2016, 55 and 182; Hagelqvist 2009, 3-4)

Figure 1. Composition of a wet fuel (Alakangas et al. 2016, 24)
Elementary composition of birch, pine and spruce bark from table 1 is represented in table 2. Basic elements like carbon (C), hydrogen (H) and oxygen (O) account for approximately 99% of the dry wood composition. Oxygen is the second most abundant element in bark; its concentration is typically calculated when the rest of the element composition are known. (Alakangas et al. 2016, 8 and 56) At the end of the summer of 2016, bark from Stora Enso (SE) Imatra mill’s debarking drums (bark-mix (SE)) was analysed. The result of this analysis is depicted in the last row of table 2. Half of the analysed bark volume corresponded to birch bark and the rest to pine and spruce bark. Another elementary composition data from Finnish bark is also gathered in the same table. Table 2 also includes information about bark energy content.

**Table 2.** Dry basis elementary composition and energy content of pulp wood bark. *Oxygen calculated from difference.* (Alakangas et al. 2016, 56 and 64). Lowest row is data from SE Imatra mill bark-mix.

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>H</th>
<th>N</th>
<th>O</th>
<th>S</th>
<th>Cl</th>
<th>Ash</th>
<th>LHV [MJ/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birch</td>
<td>56,6</td>
<td>6,8</td>
<td>0,8</td>
<td>34,2</td>
<td>0,00</td>
<td>0,00</td>
<td>1,6</td>
<td>22.7</td>
</tr>
<tr>
<td>Pine</td>
<td>52,5</td>
<td>5,7</td>
<td>0,4</td>
<td>39,7*</td>
<td>0,03</td>
<td>0,01</td>
<td>1,7</td>
<td>20.0</td>
</tr>
<tr>
<td>Spruce</td>
<td>49,7</td>
<td>5,9</td>
<td>0,4</td>
<td>41,4*</td>
<td>0,03</td>
<td>0,03</td>
<td>2,6</td>
<td>18.6</td>
</tr>
<tr>
<td>Bark-mix (SE)</td>
<td>53,4</td>
<td>5,7</td>
<td>0,3</td>
<td>38,1*</td>
<td>0,00</td>
<td>0,00</td>
<td>2,5</td>
<td>19.1</td>
</tr>
</tbody>
</table>

Two of the most abundant elements in bark are carbon and hydrogen. The energy content of bark depends mainly on these elements; the highest their concentration, the more energy per unit mass the fuel has. (Alakangas et al. 2016, 55-56) These elements are the most abundant in birch and the least in spruce. This is the reason why birch bark has the highest energy content and spruce the least. Ash percentage in spruce bark is the highest; this also contributes to the lower energy content in spruce. Compared to the other bark types from table 2, SE Imatra ash content in bark is higher. It could be that SE bark might have extractives from the collection of the logs, however, in a study performed by Werkelin et al. (2005, 455), it was concluded that the stem bark on pine, birch and spruce contained on average of 2.4%, 2.5% and 2.6% of ash respectively which is similar to SE Imatra mills bark average ash content.

### 1.2 Sludge

Various processes in the production of pulp and paper generate residues like rejects, green liquor sludge, dregs, lime mud, wastewater treatment sludge, chemical flocculation
sludge, deinking sludge, scrubber sludge, ash and other wood processing residuals (Karls-
son 2010, 14). The difference in the way the pulp mass is produced will determine in great
measure the amount of wastewater sludge produced with respect to the production of
bark. If the pulp is produced from chemical mass, the mass ratio of sludge to bark is
smaller than in the mechanical pulping due to the differences in the yield output. Yield in
chemical pulping is between 46-53% and for the mechanical 95-98%. The higher the yield
the more pulp produced with the consequent increase in sludge residues for the same
amount of bark. (Holmberg et al. 2015, 162)

A frequent way to treat waste water in the pulp and paper industry consists of three steps
represented graphically in figure 2. The first step is primary clarifying by sedimentation
or flotation of the wastewater and the products coming from it are called primary sludge.
The second step is the biological treatment of the first process overflow. At this point, the
organic material in the overflow is aerobically or anaerobically degraded and the product
is called bio-sludge. In some cases, ultra-filtration, ozonation, adsorption and/or coagula-
tion can be used as a tertiary treatment for the overflow coming from the biological step.
(Karlsson 2010, 15; Hagelqvist 2009, 2-3)

![Figure 2. Representation of sludge production in the forest industry. (Hagelqvist 2009, 2)](image)

Primary sludge tends to have a greater quantity of ash than bark as can be seen from the
difference between tables 2 and 3. This type of sludge is easy to dewater mechanically,
and it can reach a TS content that is appropriate for incineration. (Hagelqvist 2009, 2-3)

Secondary sludge production volume is lower than the one from primary sludge but more
difficult to dewater due to high microbial protein content. In order to improve dewatering
and combustion properties of secondary sludge, this is mixed with primary sludge before
mechanical dewatering. (Bajpai 2015, 10; Vaxelaire 2004, 2216)
1.2.1 Sludge characteristics

As a woody biomass fuel, sludge also consists of a wet and a dry part. The dry part also be divided into VS, carbonaceous and ash fractions. Table 3 shows that sludge is a wetter fuel with a larger ash fraction than bark in table 2. As a result, sludge energy content is lower. Elementary compositions and energy content of different sludge streams are collected in table 3.

Table 3. Characteristics of sludge in pulp and paper mills in %. (Lohiniva et al. 2001, 26)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Pulp mill sludge-mix</th>
<th>Primary sludge</th>
<th>Paper mill sludge-mix</th>
<th>Bio-sludge</th>
<th>Deinking Sludge</th>
<th>Debarking sludge</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>75 - 80</td>
<td>70</td>
<td>85</td>
<td>60</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Concentration in dry basis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ash</td>
<td>13-21</td>
<td>25-60</td>
<td>12-20</td>
<td>16</td>
<td>30-60</td>
<td>2.5</td>
</tr>
<tr>
<td>Carbon, C</td>
<td>40-42</td>
<td>44</td>
<td>44-46</td>
<td>47</td>
<td>25-45</td>
<td>50</td>
</tr>
<tr>
<td>Hydrogen, H</td>
<td>4.5-5.0</td>
<td>6</td>
<td>5.5-6.0</td>
<td>5.2</td>
<td>4-5.5</td>
<td>6</td>
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<tr>
<td>Sulphur, S</td>
<td>0.4-1.3</td>
<td>0.1</td>
<td>0.05-0.1</td>
<td>1.2</td>
<td>0.1-0.3</td>
<td>0.02</td>
</tr>
<tr>
<td>Nitrogen, N</td>
<td>1.3-2.9</td>
<td>0.4</td>
<td>0.5-0.7</td>
<td>1.6</td>
<td>0.1-0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Oxygen, O</td>
<td>25-29</td>
<td>25</td>
<td>6-7</td>
<td>30</td>
<td>22</td>
<td>34</td>
</tr>
<tr>
<td>Chlorium, Cl</td>
<td>0.1-0.8</td>
<td>0-0.1</td>
<td>0.04-1.5</td>
<td>0.2-0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy content [MJ/kg]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHV,d</td>
<td>14-18</td>
<td>2.3</td>
<td>17.4</td>
<td>8-13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHV,d (SE)</td>
<td>19.3</td>
<td></td>
<td></td>
<td></td>
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</table>

1.3 Fuel drying process

Fuel can be mechanically and/or thermally dried. In mechanical drying the fuel is usually presses or submitted to centrifugation and its MC may be reduced up to 50%. Consequently, the overall efficiency of a mill could improve but maintenance demands, and electricity consumption should be well considered. (Ross 2013, 6)

Thermal drying is the process of evaporating MC from a fuel. (Motiva 2014, 7) This process may occur before combustion or during it. In the latter case, fuel drying is the first of the three combustion phases. The other two being the gasification of VS from the fuel and the combustion of fixed carbon (Wimmerstedt 1999, 441). However, this work focuses on drying possibilities before combustion.
Drying process consist on 3 phases represented graphically in figure 3. The warming-up, the constant rate, and the falling rate periods. In the warming-up period, the temperature of the fuel particles rise until its temperature reaches the web-bulb temperature of the drying medium ($T_{WB}$). This phase is the shortest of the three and only needs a fraction of energy the other two phases need. (Holmberg 2007 16; Holmberg et al. 2015, 57)

When the temperature at the surface of the fuel particle reaches $T_{WB}$ the constant rate period is reached. The moisture and temperature during this phase stay constant and water is evaporated only from the surface of the particle. At the beginning of this phase, the surface has free moisture but at the end and due to the evaporation of this moisture, additional moisture must be withdrawn from the inside of the particle to the surface. This happens mainly owing to capillary forces that carry moisture from the inside of the fuel particle to its surface to compensate for the evaporated moisture. As moisture in the fuel is low enough, the critical humidity ratio ($U_{cr}$) is reached. Resistances owed to the fuel particle characteristics and mass transfer resistances in the fuel particle boundary layer slow the rate at which moisture from the inside of the particle rises to the surface. As less moisture reaches the surface, this lacks cooling; the temperature starts to rise. The falling rate period has started. Reaching this point depends on the fuel particle characteristics, thickness and evaporation speed. Then, when the difference in moisture pressure from the inside the fuel particle and the pressure outside of this is insufficient as to overcome the resistance the moisture encounters on its way to the surface, the drying procedure stops. (Holmberg et al. 2015, 57-59)

**Figure 3.** The three phases of drying. (A-B) Initial period, (B-C) constant rate period and (C-D) falling rate period. $u_0$ initial moisture, $u_{cr}$ critical moisture, $u_{eq}$ balanced moisture. (Holmberg et al. 2015, 60 modified)
1.4 Drying effects in bark and sludge

Dried biomass burns better and more efficiently than wet biomass. The latter may leave hydrocarbons unoxidized went in combustion increasing this way emissions (Holmberg 2007, 8; Holmberg et al. 2015, 163)

Additionally, the energy density of dried fuel increases which in turns, decreases transportation cost (Boren, 5). Stored dried biomass might be less prompt to microbiological degradation which is usually activated when MC is 15%-30%, depending on the source; storage temperature also affects. (Lohiniva et al. 2001, 61; Motiva 2014, 19; Ross 2018, 2)

In the other hand, storing large amount of dried biomass over long periods of time could increase the risk of explosion and thus the drying process should be controlled and followed. (Motiva 2013, 9) Also, in the case of sludge, there exist a risk that fine particles can provoke high peaks in CO and VOC emission after the boiler. However, this may be solved by pelletizing fines before combustion. Dried sludge can create scaling problems at certain levels of MC (Hagelqvist 2009, 11).

1.4.1 Energy value

Drying biomass improves heating value. Fuel energy value can be expressed as high heating value (HHV) or lower heating value (LHV). The first represents the combustion energy of the fuel assuming the flue gases are cooled to 25°C, recovering this way the energy used to evaporate fuel water plus the vapor molecules that were formed by the oxidation of fuel hydrogen. In LHV, water vapor escapes the system and so, its evaporation energy. In Europe, LHV is often used. (Holmberg et al. 2015, 166; Alakangas et al. 2016, 28)

Equation 1 can be used to calculate LHV on dry basis; this can be done, once HHV is known. This last value was obtained from a recent analysis of the mill’s bark and sludge. Though the fuel is completely dry, the second part of the equation accounts for evaporation latent heat. This is because the Hydrogen in the fuel will react with Oxygen to form water vapor. As in LHV calculations, flue gas scape the system non-condensed, the evaporation energy is subtracted to the HHV.
Equation 1. Lower heating value in dry basis. (Holmberg et al. 2015, 164)

\[ LHV_d = HHV_d - l_v \cdot \left( \frac{M_{H_2O}}{M_H + 2} \right) \cdot w_H \]  

\( l_v \) Latent heat of evaporation (25°C, isobaric) [MJ/kg]

\( M_{H_2O} \) Water molar mass [kg/mol]

\( M_H \) Hydrogen molar mass [kg/mol]

\( w_H \) Hydrogen relative mass in dry fuel [kg H/kg dry fuel]

LHV on wet basis, or as received, (LHV<sub>ar</sub>), can be calculated from equation 2. LHV<sub>ar</sub> values increase for dry fuels and mass decreases. For this reason, it is important to remember that when LHV in wet basis increases, the fuel energy does not increase directly proportional to the increase in LHV wet value. (Holmberg et al. 2015, 166)

Equation 2. Lower heating value in wet basis. (Holmberg et al. 2015, 165)

\[ LHV_{ar} = LHV_{dry} \cdot \left( 1 - \frac{MC}{100} \right) - l_{vap} \cdot \left( \frac{MC}{100} \right) \]

Both equations were used to calculate values of the analyzed Stora Enso Imatra mill bark, sludge and a mix of both (fuel-mix) as a function of MC. The results of these calculations are represented in figure 4.
Figure 4 shows that dried fuel can provide with more energy to a boiler. The amount of fuel needed in kilograms to achieve a MWh of bark, sludge and fuel-mix is less when this is dried. Values from 10-60% MC depict the exponential behavior of the results.

1.4.2 Environment effects

Part of the drying process emissions are volatile organic compounds (VOCs). When the temperature of the drying media is approximately 100 °C or more, see figure 5, emissions increase heavily. When drying gases are above 100 °C, these need to be treated. Gases are generally sent to combustion in a boiler (Holmberg et al. 2004, 517). When the drying media is superheated steam, emissions can be easily recovered by condensing the exhaust steam. VOCs contained in the steam also condense. The insoluble part of these can be then collected from the condensate. However, some of the compounds of these condensate can cause issues in the sewage. A solution for pulp mills is separating these compounds by evaporation and burning them in a recovery boiler along with black liquor. (McCoy 2014, 30; Wimmerstedt 1999, 444)
When drying sludge, small particles, ammonia and mercury can concentrations may be high in the exhaust. Cyclones are commonly used to collect particles whereas scrubbers and filters are used to trap other emissions. Also, exhaust gases can also be incinerated. (Lohiniva et al. 2001, 61)

1.5 Technical solutions for drying

Driers can transfer heat from heating source directly or indirectly to the drying material. In direct drying, heat is provided through convection. The drying media moves through the wet material rising its temperature and evaporating its moisture. In indirect drying, heat is transferred from the heat source to another fluid heating it. This heated fluid is the one that later will dry the drying material. (Ross 2018, 7; Worley 2011) Direct dryers tend to be simpler and perform better (Ahtila 2010, 42). In this work, dryers are known by their mechanism.

Power plant biomass drying technologies are amongst others, rotary, conveyor, SSD and flash dryers (Motiva 2014, 9). This section presents these dryer technologies in which directly and indirect drying may be possible.

1.5.1 Rotary dryer

Rotary dryers count with an extend history in drying applications and are in fact, the most commonly used dryer for industrial purposes including solid biofuel drying. These robust
and reliable dryers are best suited for drying granular material of at least 10 mm. Materials that are sensible to high temperature or prompt to dust should be avoided. Industrially, rotary dryers are used for drying food, biomass, pharmaceutical products, fertilizers, concentrates products, etc.

These dryers can reach the highest drying capacity amongst the ones discussed in this work (50 t\(\text{H}_2\text{O}/\text{h}\)) while drying the product up to 10 % MC but they require very high temperature heat sources to operate. The most common heating source is flue gas, but hot air can also be used in direct drying as well as steam in indirect drying. Working gas temperature varies from 200 °C to 600 °C at the inlet and at least 100 °C at the outlet to avoid condensing of acids and resins. High exhaust temperatures affect negatively in the energy efficiency of the dryer. Typical heat consumption is 4600-9200 kJ/kg\(\text{H}_2\text{O}\). (Holmberg et al. 2015, 142; Li et al. 2011, 2; McCoy 2014, 20; Motiva 2014, 19-20)

VOC emissions are high with rotary dryer due to the elevated drying medium temperatures and intensive mixing. However, concentration of VOC is low due to the large flow of drying medium used in the process. Typical emission control equipment is cyclone followed by a wet electrostatic precipitator (WESP) to collect particles and a regenerative thermal oxidizer (RTO) to incinerate gases. Dust and gas collection can also be achieved by using an exhaust gas cleaner or scrubber as depicted in figure 6. A scrubber will reduce odorous emissions while it will recover most of the heat used in the evaporation of moisture inside the dryer. Recovered warm water product may be used for other processes. However, WESPs, scrubbers, RTOs, and other equipment, add on investment costs of new rotary dryers. (GEA Barr-Rosin (b), 6; Wimmerstedt 1999, 443; Worley 2011, 8; Yliniemi 1999, 7)
Figure 6. Rotary dryer diagram with, dried fuel cooling, flue gas recirculation (FGR), combustion chamber, cyclon and RTO or scrubber. (GEA Barr-Rosin (b), 6)

Drying in rotary dryers takes place in a 2-8 rpm rotating and slightly inclined cylinder such as in figures 6 and 7. The dimension of the cylinder can be up to 90 meters long and 5 meters on diameter. Fuel is fed to the highest end of the cylinder and is discharged after drying from the lowest extreme. Owing to the inclination of the cylinder, gravitation force helps fuel to move away from the feeding point. As fuel advances, this is continuously lifted by circumferentially assembled lifters or flights located inside the inner walls of the cylinder as figure 7 depicts. (Motiva 2014, 20; Worley 2011, 7-8; Osman et al. 2011, 7; Holmberg et al. 2015, 142)

Flights are a crucial component in rotary dryers. As flights lift the drying material, they also improve mixing and contact with the drying medium improving heat transfer from this to the material. This lifting action also prevents sticking particles from gluing to the inner walls and additionally avoid “dead zones”. (Osman et al. 2011, 7)
Flights profile, drying material density and shape, rotational speed, and drum inclination affect the particle flow and cascading patterns which in turn affect retention time. Smaller particles dry faster and are pushed out of the drum by the drying media flow whereas larger ones spend more time inside the cylinder losing moisture and thus density as they dry. (Osman et al. 2011, 7; Wimmerstedt 1999, 443)

Direct drying rotary dryers use most commonly flue gas as energy source, but hot air can also be used. Drying can happen in counter or parallel flow to the direction of the progressing fuel. The latter is the most commonly used for biomass drying. In parallel flow, flue gas is the hottest when fuel is the wettest and evaporation of moisture in the fuel particles prevent them from overheating which in turn reduces biomass self-ignition. (Motiva 2014, 20; Worley 2011, 6; Holmberg A. et al. 2014, 9) Flue gas recirculation (FGR) increases drying medium moisture at the inlet which in turn diminishes the risk of fire and at the same time improves heat transfer to the fuel (McCoy 2014, 22).

Indirect drying is the less common version of rotary dryers. This uses saturated steam at 6-10 bar pressure. Steam passes through a structure of tubes inside the cylinder onto which heat transfer disks are assembled to gain on heating surface area. The disks structure is fixed to a rotor that spins forcing the wet fuel to enter in contact with the hot surface
of the disks drying the fuel by conduction. Fuel rests on the stator part of the cylinder and can also be lifted by flights as in indirect drying. (Osman et al. 2011, 11)

In comparison, indirect rotary dryers are less efficient dryers and residence time is longer. Investment and operation and maintenance (O&M) costs are higher and yet availability is lower. It must avoid drying sticky materials and it is susceptible to plugging. On the good side, they produce less emissions and do not need emission controlling systems like electrostatic precipitator (ESP), baghouse filter, cyclone or scrubber to remove particulates. They can dry smaller size materials and dusty ones. Additionally, their risk of fire is less than in the direct technology and energy recovery from the working fluid is easier since it is condensed steam. (Motiva 2014, 21; Worley 2011, 9; Ross 2013, 8; McCoy 2014, 23)

Rotary dryers use high temperature energy sources for drying and drying material suffer attrition due to intensive mixing. Due to these conditions, VOC, particulates and dust emissions are high. Exhaust gas control system is needed; this increases investment cost for new rotary dryer installations. Material moisture is hard to control. Sensible to over-drying/heating particles with lower moisture at the inlet. Their high operating temperatures derive in great fire hazard. Energy recover from these high temperature gases is however, hard to recover unless for indirect drying or costly emission control devices are in place for the direct drying version of rotary dryer. Relatively large footprint. (Motiva 2013, 9; Motiva 2014, 21; Osman et al. 2011, 7; McCoy 2014, 23)

1.5.2 Flash dryer

Flash dryers are a type of pneumatic dryer that requires drying material to be small enough before entering the drying process. For this reason, drying materials might need to be pre-treated, crushed or ground prior to drying. The applications of flash dryers are sludge, filter cakes, slurries, crystals, granules and pastes, among other materials which final product can be a granulate or powdered state. Drying medium used can be flue gas, hot air or steam. Wet particles are fed into the lower part of a duct or corridor into an upward flow of drying gas such as the drying column from figure 8. Fluidizing velocity of the drying medium is enough so that the wet particles dry in suspension all over the ducts.
High drying gas velocity increases heat and mass transfer characteristics and allows materials to dry rapidly with retention time below 1 min. During this time, the particles can dry from an initial 70% MC to a final 10% MC using temperatures that vary from 150 °C to 700 °C. Specific heat consumption ranges from 4500 kJ/kg\(\text{H}_2\text{O}\) to 11500 kJ/kg\(\text{H}_2\text{O}\). (GEA Barr-Rosin (b); Holmberg et al. 2015, 144-145; Worley 2011, 13-14; Wimmerstedt 1999, 443)

Additional centrifugal classifiers can be installed in the drying zone to aid separating heavier particles from lighter ones allowing the first ones to stay in the dryer until their density allows them to move forward. When particles are dried, they leave the drying duct along with the drying gas which has already lost temperature and gained on moisture. After this, the mix enters a cyclone where dust particles are separated from the gas. The gas is cleaned in a scrubber to remove smell. (Lohiniva et al. 2001, 62; Van Deventer 2004, 4).
Figure 8. Flash-dryer diagram where hot air is the drying medium and scrubber the emission control device. (GEA Barr-Rosin (b), 4)

Flash dryers need high temperature energy sources to operate and so, alternative dryers might be considered to increase energy efficiency. In the other hand, drying with a flash dryer can result in very high product quality with constant MC all over the product. Fuels dried with flash dryers may be suitable for processes that demand a certain fuel quality, such as gasification or pyrolysis. (Motiva 2014, 22)

The main advantages and disadvantages flash dryers have with respect to rotary, superheated steam dryers (SSD), flash and conveyor dryers are as follows. (Worley 2011, 13-14; Holmberg et al. 2015, 144–145; GEA Barr-Rosin (b); Motiva 2014; Wimmerstedt 1999, 444; Ross 2013, 9)
Advantages.

- Footprint of flash dryers is the smallest compared with rotary and conveyor dryers.
- Their carbon footprint is the smallest compared with rotary or conveyor dryer.
- Risk of fire is smaller than rotary dryers though larger than conveyor driers.
- They are easier to control than rotary type.
- Exhaust gas is more saturated than the one from rotary dryers.
- Short retention time decreases the amount of VOC emissions in the exhaust.
- Flash dryers are of simple design, reliable and their availability is good.

Disadvantages.

- Pre-conditioning of drying material and keeping fluidizing velocity increases electricity consumption.
- Elevated drying gas velocities force small particles against the inner walls of the duct eroding it; this increases O&M costs.
- Energy costs are high owing to the demanding temperatures of the energy sources needed for drying.
- Flash dryers are cost effective only for large installations.

1.5.3 SSD dryers

Steam dryers are best suited for when they are integrated and their exhaust heat from their condensate can be used in another process (Wimmerstedt 1999, 441). Superheated Steam Dryers operate in a similar way as flash dryers. In this case, steam is used for drying instead of flue gas or hot air, see figure 10. Steam is enclosed in a loop that can be pressurized (1-5 bar). If the steam is pressurized, fuel must be fed into the duct by a tight feeder, like a plug-screw or similar. As drying system is enclosed in a loop, evaporated fuel moisture is continuously been added to the superheated steam decreases its temperature. The result is a slightly superheated steam which mass, after completing one drying loop, is larger than the steam mass at the beginning of the loop when steam was heated in the super heater. To maintain the same amount of steam within the loop, some of this is continuously discharged from the system at the slightly superheated stage, figure 9.
Slightly superheated steam mass pulled out of the system is typically 10% of the drying steam mass flow at the beginning of the loop. (Worley 2011, 16)

The steam remaining in the system is indirectly superheated with higher pressure steam, flue gas or thermal oil in a heat exchanger as figure 10 depicts. Drying medium is typically over 200 °C, nevertheless, there is no fire or explosion risk since the atmosphere is inert. After the material is dried, this is separated from the remaining slightly superheated steam in a cyclone. Dried materials are extracted from the system through a pressure tight valve. (GEA Barr-Rosin (a); Motiva 2014, 22; Holmberg A. et al. 2014, 9-10; Van Deventer 2004, 4)

The energy of the steam pulled from the system can be used either directly mixing it in a flow of water to be condensed or indirectly using a heat exchanger. As much as 90% of the energy used for drying can be reused in another process which in turn decreases the amount of net energy used for drying. (GEA Barr-Rosin (a), 7; Worley 2011, 17; Motiva 2014, 22; Van deventer 2004, 18).

Net specific heat demand of an SSD can be reduced up to levels of (400-1000 kJ/kgH₂O). Such a low energy demand is only possible when there is another process that can use the recovered energy in the form of hot water. Dryer economic performance will this way be affected positively. (Holmberg A. et al. 2014, 9; Mujundar 2014, 439-440)

![Figure 9. Schematic of SSD process with direct and indirect use of discharged steam. (Van Deventer 2004, 4)](image-url)
In superheated steam drying there are no emissions to the air. Instead, most emissions can be found in the condensate removal as a resultant of the condensation of the continuously discharged steam in figure 9. Liquid state emissions facilitate their control while it will avoid additional investment on expensive emission control accessories. Amongst the VOC coming out of the system with the condensate, several terpenes are of special interest. These can be separated or distillated from the condensate since they are but slightly soluble in water. Unreacted gases can be burnt while soluble organic compounds can be sent to a water treatment plant. Issues with the condensate can appear since they may difficult the denitrification process of sewage plants. (Holmberg A. et al. 2014, 9; Osman et al. 2011, 25; Van Deventer 2004, 19; Wimmerstedt 1999, 444)

In SSD the drying material can be dried at higher temperatures than flash dryers that use flue gas or hot air for drying. This is owed to the inert quality of the drying medium; drying material is not oxidized and thus cannot ignite inside the ducts. Specific heat of steam is higher than the one from flue gas or hot air thus, SSD drying rates increases with steam drying. The result could be a smaller dimensioned SSD and faster drying process than for flash dryer using flue gas or hot air. (Van Deventer 2004, 19)

The advantages and disadvantages flash dryers have when comparing with the other dryers in this work are as follows. (Holmberg et al. 2015; Mujundar, 439-440; Van Deventer 2004, 19; Worley 2011, 15-18)

- Null fire and explosion risk.
- Drying material is not oxidized since steam is used for drying.
- Smaller dryer size due to higher specific heat capacity of steam over the one from flue gas or hot air.
- Emissions are easily controllable since they are mainly found in the steam condensate.
- Heat recovery from the slightly superheated steam is easier and needs less expensive equipment to be achieved. Up to 90% recovered. If heat is recovered, SSD energy consumption could be in the range of (400-1000 kJ/kg\(_{\text{H}_2\text{O}}\)).
- Smaller exhaust flow when using RTO.
Disadvantages.

- SSD has steam leakage and fuel in- and output problems.
- Condensate is corrosive and must be treated.
- Certain compounds in the water from the condensate might produce problems in the water treatment plant.
- Pressure vessel and in/output feeding systems are costly.
- Higher O&M costs than flue gas flash dryers.

**Figure 10.** SSD dryer using flue gas as heating source to superheat process steam inside the loop. Slightly superheated steam energy is recovered and condense sent to sewer. (Worley 2011, 16)

1.5.4 **Conveyor dryer**

Conveyor dryers, also known as fix bed dryers, have a long and proven history in different industries. (McCoy 2014, 14) They are the most commonly used for thermal drying of woody biomass when low temperature secondary heat sources are used. These sources can be low pressure steam, hot water or air and flue gas. (Worley 2011, 9; Ross 2013, 8-9) The heating source can indirectly be used to heat the incoming drying air in a heat
exchanger situated below or on top of the bed as seen in figure 11. Heating can also happen using directly the heat source if this is hot air or flue gas (McCoy 2014, 10).

Figure 11. Conveyor dryer. (Worley 2011, 10. Modified)

In conveyor dryers, a wide variety of biomaterials such as sludge, bark, wood chips, sawdust, wood residues, and bagasse amongst others can be dried. (Motiva 2013, 10; Motiva 2014, 23) However, as drying happens over a perforated conveyor, fine fuel particles must be screened prior to drying and added later to the bed. (McCoy 2014, 14) A feeding screw is used to evenly spread the drying material over the conveyor until it reaches a bed height that is commonly between 0.1 m and 0.2 m. The conveyor, which serves as a transportation bed for the drying material, moves away from the feeding point at around 1 m/min while hot air is blown through the material and the conveyor in an upward or downward direction. Drying air velocities depend on the drying materials but commonly are between 0.25-2.5 m/s. (Motiva 2014, 23; Holmberg et al. 2015, 143)

Conveyor dryer particulate emissions are low compared with flash or rotary dryers since the dryers do not agitate the drying material. Still, dust emissions can be further reduced by dragging the air from the bottom of the conveyor in which case the air will flow in a top to down direction. A drawback for this option is that electricity consumption will increase. Conveyor dryers can have problems due to fine fuel particles dropping through
the holes in the bed and tar formation. (Motiva 2014, 23; McCoy 2014, 14-15; Worley 2011, 11)

Single and multi-pass. Conveyor dryers can dry material in a single or multi-pass stage. In a single-pass, drying material is usually unmixed during the drying process which happens on a single level bed. Product mixing can be improved by adding vibration to the conveyor which in turn will increase mass transfer and a more homogeneous final product could be achieved. Another way to improve mixing, and thus efficient drying, is with multi-pass or stacked conveyor dryers. This is a way of connecting several conveyors in series in which drying material drops from one section of the dryer to the one below. This continues until the material reaches the last section from where it leaves the dryer.

Some of the advantages of multi-pass dryer are that it will save space, investment costs and its footprint is also smaller compared with the one from a single-pass dryer. On the other hand, O&M costs are higher because the dryers are more complex and thus more unreliable. (Ross 2013, 9)

Conveyor dryers suit the best to processes where retention time is long and low temperature heat supply is available. Retention time is easy to control; additionally, if mixing is added and bed height is the appropriate evenly dried final product can be obtained. Drying medium temperatures are reported to be as low as 30 °C and as high as 200 °C depending on the sources consulted. When temperature of drying media is low, VOC emissions are also low. (Motiva 2014, 23; Holmberg 2007, 10; Ross 2013, 9)

Conveyor and rotary dryer investment costs are similar, however as rotary dryers need costly air pollution control equipment, total investment cost for a conveyor dryer and support equipment is typically lower in new installations. (McCoy 2014, 19; Motiva 2014, 24) Investment cost are even lower with multi-stage conveyor dryer. In the other hand, O&M costs are higher in conveyor dryers, and in especial multi-stage type, due to the larger number of parts to maintain. (McCoy 2014, 32; Ross 2013, 9)
2 BARK DRYING AT STORA ENSO IMATRA

There are several energy boilers in Stora Enso Imatra. Two of these are recovery boilers, one is a bubbling fluidized bed boiler and four natural gas (NG) boilers. The first is called KK2 and its fuel is a mix of bark with sludge. In this work we will refer to the bark and sludge mix as fuel-mix. Additionally, KK2 also burns NG as ancillary fuel to maintain combustion temperature when fuel-mix is too wet and for starting and stopping KK2. NG boilers are called K9, K10, K11 and K12, and from now in this work they are referred as K9-12. Steam produced in these boilers is used to generate electricity in turbines 6 and 7 and to provide the mill with process steam. This chapter explains the reasons why a dryer is advantageous for the energy production of the mill and in special for the operation and performance of boiler KK2.

Biomass LHV increases when dried, it burns better and with less unburned particles in the flue gas or in the ash streams, and also helps controlling the amount of energy input to the boiler since the final MC of the fuel is known (Holmberg et al. 2015, 170). There are, however, other reasons to consider for the Imatra mill. The most important is avoiding issues in boiler KK2 related to the combustion of wet biomass. Also, improving boiler KK2 efficiency and reducing NG consumption for steam generation are reasons related to the economy and studied later in this work. The latter reduces direct costs of the fossil fuel and costs from CO$_2$ emissions allowances. Other reasons for drying the mill’s own biomass are the gain on energy security since fuel-mix can be store on site and less dependency of NG and fossil CO$_2$ prices fluctuation.

2.1 KK2 capacity limitation

Boiler KK2 operation is limited when reaching 75% of its capacity, here called (P75). This limitation mainly happens during high heat demand periods which tend to coincide with autumn, winter and spring. In this work, the year is split into low and high energy demand seasons, being the lower one the summer and the rest of the year the season accounting for high energy demand season. The latter is here called winter and will account for September-May, both included.

Limitations in boiler KK2 may be due to three factors. The first and most common factor, is the undersized secondary air fan system for the current fuel the boiler burns. These fans
have difficulties supplying sufficient combustion air in situations over P75, especially in winter when the fuel-mix is the wettest. Secondly, as MC of winter fuel-mix is high, the volume flow of flue gas generated while at P75 is too large for the flue gas draft fan to pull. Lastly, this large flow of flue gas can create inadmissible pressure difference in KK2 electrostatic precipitators.

Due to capacity limitations during winter and low summer heat demand, boiler KK2 yearly average capacity is only 53%. If a boiler is designed to burn fuel with a certain MC but incinerated fuel is drier than the one this was designed for, boiler maximum capacity can increase over its designed capacity. This is so because the furnace can fit the same volume of fuel, but its energy content is larger. (Boren, 5) According to this, boiler KK2 maximum operative capacity should also augment if bark and/or sludge was dried. Augmented capacity will indirectly decrease the need for burning NG in K9-12 when high energy demand periods.

The aim of this chapter is to find what the flue gas and combustion air volume flows are currently in a P75 situation and compare them with the ones from several fuel drying scenarios. The idea is to prove that, if biomass is dried, KK2 can operate at P75 or higher capacity. This will only be possible if the flows of exhaust flue gas and combustion air demand for a given capacity is no more than the flows for the current P75 situation with wet fuel-mix. Of course, this may also be possible if some equipment was changed, but this work only deals with drying of biomass and how it can affect KK2.

2.1.1 Data finding process

In order to explain what P75 means in terms of flue gas and combustion air flows, data needed to be obtained. Two sources that gather information about KK2 were examined. Data from these sources as well as perfect calculation data is expressed as in normal temperature and pressure. The first source used was a Stora Enso reporting tool, from which a wide range of measurement and data calculations about boiler KK2 can be studied and compared. The second source was an annual measurement report from the company Pöyry. Every summer, Pöyry measures KK2 flue gas and combustion air flows. According to these measurements, vapour accounts for 19.2-21.1%-v of the flue gas. Along with
Stora Enso tool, yearly average stoichiometric air coefficient ($\lambda_{ave}$) is 1.552. This value is used in perfect combustion calculations.

Perfect combustion calculations were performed for all possible MC possibilities in the range of 10% to 60% MC since these values were going to be useful later for efficiency calculations among others. The results from a perfect combustion of summer fuel-mix (53% MC) were compared with the ones from Pöyry. It was observed that the moisture in flue gas from calculations, 20.5%-v, was like the one from Pöyry measurements, 19.2-21.1%-v. Additionally, the excess Oxygen in flue gas was 8.0%-v dry while the value informed by Pöyry was 7.7%-v on average during their measurements. At this point it was assumed that perfect combustion calculations were, for the purpose of this work, close enough from reality and these could provide with the needed data for calculations later in this work.

The next step was to identify what the flue gas and combustion air volume flows presently are when KK2 capacity is P75. In order to calculate this, the elementary fuel composition of bark and sludge from tables 2 and 3, were used in perfect combustion calculations. The winter fuel moisture content, average 57% MC, was chosen since this is more representative of the season where KK2 is limited.

To maintain boiler temperature, KK2 consumes most of the yearly NG consumption when fuel mix is the wettest. During the winter season of the studied period, the average amount of NG energy to KK2 was 9% from the total. This NG value was got while dividing the amount of NG energy used in KK2 during winter, by the total amount of fuel energy the boiler was fed with during the same time.

In a scenario where only fuel mix is used to fulfil P75, flue gas volume flow is 137 m$^3$/s whereas combustion air demand is 108 m$^3$/s. If 9% of the needed energy comes from NG as it is the average current case, the respective flows are 131 m$^3$/s and 104 m$^3$/s. The latter scenario represents the current situation and so, its flows are used in this work to represent KK2 limitations.
2.1.2 Avoiding limitations

KK2 can avoid having capacity limitation by drying fuel. Perfect combustion calculations for dried bark and/or sludge were performed; their flue gas and needed combustion air flows are compared with the ones from the current scenario. Graphically, figures 12 and 13 depict flue gas and combustion air demand flows as a function of MC for the cases when fuel-mix is burnt with and without NG. Dashed line in these figures represent reference flue gas, 131 m³/h, and combustion air demand, 104 m³/h, flows resultant from the combustion of winter fuel-mix with 9% of the fuel energy from NG and in a P75 situation. If the flow of flue gas or combustion air demand for a given MC is above the dashed line, this indicate that boiler KK2 could have combustion difficulties whereas values below this line, indicate proper KK2 operation.

![Flue gas flow graph](image)

**Figure 12.** Boiler KK2 flue gas flow as a function of fuel-mix moisture content. Dashed line represents the current scenario for P75.

Figure 12 shows that when fuel-mix is dried, the flow of flue gas produced is less than the reference flow. In the case that NG was not desired in combustion for whatever reason such as the use of a dryer that would allow fuel-mix to burn well enough without NG, the maximum fuel-mix MC that is needed in order to avoid combustion issues drops to 54%
For P(90) case, when fuel-mix combustion happens along with NG the maximum recommended fuel-mix MC value decreases to 42% and when fuel-mix only is burnt, the value is 38%.

**Figure 13.** Combustion air flow demand for boiler KK2 to operate at 75% and 90% its nominal capacity.

From figure 13, it can also be noticed that the demand of combustion air is larger when fuel mix only is incinerated. Once again, the reference value, is reached when fuel-mix and NG is burned at 57% MC for P(75). To avoid combustion issues for fuel-mix only, means that the fuel needs to be dried at least until 53% or less MC. In a P(90) scenario without NG combustion, fuel mix MC needs to drop to 14% instead of 38% as in the case of flue gas flow limitation. The incineration of very dried fuel could create problems in the sand bed and increase emissions (Holmberg et al. 2015, 170). If KK2 operated over capacities that would incur in such problems, a secondary air blower upgrade could be the safest option for a good operation.

### 2.2 Fuel quality

Biomass is a heterogeneous fuel which MC can vary considerably depending on the weather and season of the year. (Holmberg 2007, 10 & 40). Drying biomass improves
quality and evens moisture throughout the fuel. As a result, biomass heating value and combustion of unburned organic compounds improve while CO emissions in the flue gas diminishes. (Holmberg 2007, 8; Spets 2001, 1) This chapter only considers the increase on heating value.

There are two types of fuel produced in the mill which can be dried prior to combustion in boiler KK2. The most abundant is bark and the least is sludge. Bark is the reject product of debarking logs in the debarking drums from Kaukopää (KP) and Tainio (TA). During the studied period, bark mass from KP and TA was 177.0 kt and 26.6 kt where their average MC was 49.8% and 60.0% respectively. The total mass of sludge produced and sent to combustion was 44.6 kt and its average MC 67.6%. Additionally, as KK2 steam production is limited, a part of KP bark is usually sold. The dry mass of this part of bark is 30.3 kt and it is not included in the previous mass of KP bark. In this work, the mass of sold bark is called bark-sells and, if considered in calculations, it will be announced with an apostrophe (‘) as for example, it can be seen on the right side of figures 14 (a) & (b).

Available current energy content in bark and sludge during the studied period can be calculated when multiplying each of their masses, by their own heating value at their MC. LHV in dry basis of bark and sludge and for the current scenario (S0), can be read from tables 2 and 3 in chapter 1. Once the mass values were obtained from Stora Enso reporting material, the multiplication could be done and results of annual current available fuel energy gave 824 GWh, 114 GWh, 161 GWh, and 141 GWh for KP bark, TA bark, sludge, and bark-sells respectively. These first three values are depicted in the column to the left of figure 14 (a) & (b). Also, an energy flow representation can be seen in figure 22 of chapter 6. This is a Sankey diagram of the current situation of KK2 and K9-12. Total biomass energy on current scenario (S0) sums 1099 GWh and will be used from now on to compare the present situation with different potential fuel drying scenarios. The energy from bark-sells, is only represented on the columns to the right of figures 14 (a) & (b). Energy content from Tainio bark will remain unchanged in this work.
Figure 14 (a) & (b). Energy input to boiler KK2 during the study period (S0) and at other different MC scenarios. Set of columns to the right, include bark-sells (’).

From figure 14, maximum available fuel energy, 1421 GWh, is given by the scenario 10’ of figure 14 (a), when bark from KP and sludge are dried until 10% MC and bark-sells is also dried. If bark-sells was to be sold as it currently is, the fuel energy will be reduced to 1262 GWh. Compared with S0, potential fuel energy increase of scenario 10’ from figure 14 (a) is 322 GWh which represents a 29.3% increase on fuel energy.
2.3 Boiler KK2 efficiency

Steam energy produced from bark and sludge can be obtained once boiler KK2 efficiency is known. Average present KK2 efficiency is approximately 85%. In order to find what the boiler KK2 efficiency would be at different moisture levels, the indirect efficiency calculation method was used. The method is commonly used for boilers that use biomass and the amount of fuel is not exactly known, see equation 3.

This chapter is divided into two parts. In the first part, power losses are either calculated or obtained internal reporting tools. In the second, energy flows into the boiler are calculated.

**Equation 3.** Indirect efficiency equation.

\[
\eta_{KK2} = 1 - \frac{(P_{\text{losses}})}{(P_{\text{in}})}
\]  

\(\eta_{KK2}\)  
Boiler KK2 efficiency  
\ [%\]  
\(P_{\text{losses}}\)  
Power losses  
\ [MW\]  
\(P_{\text{in}}\)  
Power inputs  
\ [MW\]  

According to internal reports, most of the losses are owed to the flue gas losses whereas in a minor measure, unburnt fuel losses, thermal losses from bed ash and other losses independent from fuel flow also exist. Since flue gas losses are the mayor contributors to equation 3, this work their losses and combustion air power are calculated using perfect combustion calculations. The rest of the losses are gathered from internal reports which consists on real data according with the power output in daily basis. Except by the data referring to losses independent from fuel flow, the rest of the power losses data was scaled to P75 combustion situation. Equation 3 can now be written as equation 4.

**Equation 4.** Indirect efficiency equation by power fractions.

\[
\eta_{KK2} = 1 - \frac{P_{\text{flue gas}} + P_{\text{unburnt}} + P_{\text{independent from fuel}} + P_{\text{ash}}}{P_{\text{fuel}} + P_{\text{ca}}}
\]  \( (4) \)
\[ P_{\text{flue gas}} \quad \text{Flue gas power losses} \quad [\%] \]
\[ P_{\text{unburnt}} \quad \text{Unburnt fuel particle power losses} \quad [\text{MW}] \]
\[ P_{\text{independent from fuel}} \quad \text{Other heat losses} \quad [\text{MW}] \]
\[ P_{\text{ash}} \quad \text{Power losses in the ash stream} \quad [\text{MW}] \]
\[ P_{\text{fuel}} \quad \text{Fuel combustion energy} \quad [\text{MW}] \]
\[ P_{\text{ca}} \quad \text{Combustion air power input} \quad [\text{MW}] \]

Flue gas losses could be calculated only when the mass of fuel needed for P75 was known which could not be calculated without knowing the exact efficiency of KK2 for P75 as a function of fuel MC. Calculations started using present efficiency value for biomass combustion in boiler KK2 and assuming the value as constant for the range of 60-10% fuel MC. After several iterations, the values of flue gas power losses \( P_{\text{flue gas}} \) and fuel-mix mass needed to satisfy P75 were obtained. Flue gas losses are depicted in figure 15.

Combustion air power input calculations also needed the mass of fuel-mix needed for combustion. From perfect combustion calculations, the amount of combustion air needed for each ton of fuel was calculated and this multiplied by the mass of fuel needed, in tons, to obtain the mass of combustion air that would provide sufficient Oxygen to satisfy the combustion of fuel-mix at P(75). To find combustion air power (\( P_{\text{ca}} \)), its enthalpy was also needed. Local weather statistic data was used to find the air temperature and its relative moisture in the air. Air enthalpy was read from a Mollier chart once assumed that the air at the inlet of the boiler KK2’s luvo rises to around 35°C from the average of 4.3 °C during winter. \( P_{\text{ca}} \) results as a function of MC can be seen in figure 13 (Ilmatieteenlaitos 2016).
Figure 15 shows how the drier the fuel is, the least combustion air power is input in the boiler and the least the flue gas losses are. For this main reason, the negative fraction in equation 4 decreases and thus the efficiency in the boiler improves. Though boiler KK2 is not necessarily going to run at P75 all the time after fuel is dried, in this work it is assumed that efficiency values from figure 15 may be close from reality. These efficiency values are used in later chapters for energy calculations. In any case, there could be differences with reality since internal data for “other power losses” was scaled to P75, calculations were performed with perfect combustion calculations and it was assumed that stochiometric rate of air for winter fuel-mix is the same as the yearly average, $\lambda_{\text{ave}}$ equals 1.552, regardless of the moisture level of the input fuel.

### 2.4 Potential natural gas saving

During winter, KK2 often needs to consume NG as support fuel to prevent boiler temperature from decreasing. This is because fuel-mix can reach 65% MC and at these moisture levels, boilers need of a higher quality supporting fuel (Holmberg et al. 2015, 163). When fuel quality improves, need for NG as supporting fuel decreases. NG reduction as a function of final MC of bark and/or sludge, is explained in chapter 6. The aim of this chapter is to define a minimum NG consumption in KK2 and K9-12, and to find what the required
fuel-mix energy is, to produce the same steam energy as currently from KK2 and K9-12 or (S0+).

NG can be saved from KK2 and from K9-12. During the studied period, the first consumed 82 GWh\text{fuel} to produce 75 GWh\text{th}, assuming NG combustion efficiency in KK2 is the same as in K9-12, 91%. K9-12 consumed 310 GWh\text{fuel} to total 393 GWh\text{fuel} in scenario S0+.

Part of the NG energy consumed in boilers KK2 and K9-12 was used for starting and stopping these boilers and for quickly balancing the steam demand of the mill. In this work, it is assumed that the amount of NG use for these purposes are at least 100 GWh and thus independently on the annual energy content of the biomass available, NG consumption must be at least this value which will produce 91 GWh\text{th}. Since currently, S0+ NG consumption is 393 GWh\text{fuel}, the annual potential maximum NG savings from KK2 and K9-12 results in 293 GWh\text{fuel} to produce 266 GWh\text{th}. Future dried biomass would need to provide enough fuel energy to compensate for these potentially maximum NG savings of 293 GWh.

**Figure 16.** Current KK2 boiler scenario (S0), S0 and K9-12 natural gas boilers and potential future KK2 + K9-12 boilers scenario assuming minimum natural gas consumption 91 GWh\text{th}/a.

Scenarios S0 and S0+ correspond to current, pre-drying scenarios. For this reason, there is no difference in steam production from fuel-mix. Now, KK2 and K9-12 are producing 1299 GWh\text{th}/a. If scenario S1+ was ever to be achieved, total production of steam from dried biomass in KK2 would need to be 1208 GWh\text{th}/a. Consequently, KK2 average operation capacity will increase from a current average P48 to P62. NG consumption will
fall to 25% and so will the mill fossil fuel emissions and thus emission credit costs as well as the dependency on NG supply and its price fluctuations.

2.5 Other usage possibilities for dried biomass

Presently, the efficiency in power plants and mills is increasing. This means than the bark generated in the debarking drums might not all be needed to supply heat in which case, the mill might try to use the excess of bark for other purposes such as upgrading it to other forms of fuel or selling it. (Holmberg A. et al. 2014, 8) In the Imatra mill, around 150 GWh of bark is sold every year though the reason is not the excess of energy content from bark but the limitations in KK2. Depending on the economics of a drying system, selling dried bark could be feasible since its energy content increases and so does its energy intensity (Boren, 5). This will reduce transportation cost and a better price for the dried biomass might be obtained. However, as shown before in this chapter, if biomass was dried, it could be incinerated in boiler KK2 to reduce the consumption of NG and to improve environmental performances of the mill.

Gasification of biomass is a form of upgrading wet biomass into a fuel that can also be used by combustion engines, micro turbines, fuel cells and gas turbines (IRENA 2012, 5). Often, biomass needs to be dry before gasification. Most gasifiers will require the fuel to contain no more than 20% moisture such as the downdraft fixed bed gasifiers and in addition they need pelletization of biomass. Other gasifiers such as updraft fixed bed and fluidized bed gasifiers for example can tolerate fuels with MC of 50 % and 65% respectively. (Ross 2013, 1-4) As gasifiers burn the fuel under low Oxygen conditions, some of the gases that evaporate from the fuel leave the gasifier unreacted. The products of gasification are typically CO, H₂O, CO₂, char, tar and hydrogen (IRENA 2012, 5). Depending on the gas yield desired a mill might need a fluidized bed gasifier since the most common downdraft fixed beds are rarely scaled for more than 1 MWth while the fluidized types can produce up to hundreds of MWth.

Fluidised bed gasifiers can be bubbling fluidized boiler or circulating fluidized boiler and can operate at atmospheric pressure or at higher pressure. The material is agitated and mixed with sand or alumina from the bed improving the gasifier performance. These gasifiers can use a wider range of products than fix beds, they produce a higher quality and
homogeneous energy content gas and control of their temperature is good. However, they cost more, they are more complex and their respond to load changes is slow. Gas might need cleaning in which case cyclones or ESP can be used. In order to treat tar, a flue gas wet scrubber could be used to remove up to half its amount. Gasification technologies need more R&D to improve fuel flexibility, removing particulates, alkali-metals and chlorine and removal of tars and ammonia. Also, reducing costs and complexity as well as progressing on performance and efficiency will be satisfactory for the commercial development of these technologies. (IRENA 2012, 11-16)
3 AVAILABLE HEATING SOURCES

This work considers drying before combustion. Since drying can be a very energy intense process, design of a dryer should consider the use of all possible heating sources available (Ross 2013, 11). Choosing the right technology to achieve drying depends on the energy sources available, the drying capacity, the desired final material moisture, and the surface requirements for dryer, supporting structure and equipment, amongst others (Motiva 2014, 19). The aim in this chapter is to find information about the possible energy sources from the Imatra mill that could be used for drying bark and/or sludge; also, to calculate flows for each energy source in several drying scenarios.

Gasifiers and incinerator hot gas streams are potential sources. In the pulp industry, warm and hot streams of energy can also be recovered from paper machines, CTMP, tanks and other effluents. Waste low pressure (LP) steam and turbine exhaust LP steam are also possible energy sources (Ross 2013, 11). The Imatra mill could use their KK2 exhaust flue gas, LP steam and hot water from several sources but for simplicity here, we will use hot water from scrubbers at 60 °C to 70 °C.

3.1 Flue gas

During 2015, the average temperature of flue gas after the ESPs downstream of KK2 was 173°C. According with perfect flue gas calculations, the volume flow of moisture in flue gas was around 20% at normal pressure and temperature which is a similar value to measurements performed by the company Pöyry during the summer of 2015. Flue gas could be used as a direct or indirect energy source. In a case where drying happens directly using the energy source, the flue gas temperature coming out of KK2 stack is lower than the minimum gas temperature requirements for flash or rotary dryers. In the other hand, a low temperature operating dryer could use the energy from flue gas however, as this contains moisture, lowering its temperature will increase relative humidity and thus the possibility of flue gas saturation decreasing drying potential. (Ross 2013, 11)

An important disadvantage that appear when cooling flue gas, for example in a heat exchanger to heat another fluid, is that sulphur trioxide can reach its condensation temperature reacting with water to form sulfuric acid. This could corrode the surfaces of the exchanger increasing maintenance cost or investment costs if corrosion resistant materials
are used. In addition, the combustion of dry fuels will release cooler flue gas. Biomass fuels, however, contain low sulphur concentrations but they are high on alkali ones which might cause chlorine issues. (Castleman 1994, 40; Ross 2013, 15)

The aim of this subchapter is to represent how much flue gas energy could be recovered while using it indirectly. A flue gas scrubber can be used to recover flue gas energy and provide this to a dryer (Boren, 2). Figure 17 depicts the quantity of energy needed to dry fuel-mix prior to its combustion in several scenarios. This figure also represents how much energy is recoverable from the flue gas produced from the same drying scenario. The purpose is comparing how much of the energy needed can be supplied from the flue gas in each drying case.

In order to calculate what is depicts in figure 17, the lowest flue gas temperature needed to be found. In the case of biomass boilers, some scrubbers can let the flue gas leave the system at temperatures below 35 °C. However, the average temperature at which biomass combustion flue gas becomes saturated is 60 °C (Carlsson 2008, 11). In this work, it was assumed that flue gas could leave a scrubber at the same saturation temperature which is very similar to the temperature flue gas exits a scrubber downstream of Imatra mills recovery boilers. For simplicity, all the energy flue gas losses in the scrubber is assumed to be transferred to the drying medium in the dryer.

Flue gas recoverable energy was calculated from the multiplication of flue gas mass, its specific heat capacity and its temperature difference across a scrubber. First, the mass of flue gas from the combustion of fuel-mix was known after perfect flue gas calculations. Second, the specific heat capacity of flue gas as a function of MC was obtained from calculations using the composition of flue gas. Lastly, the temperature difference of flue gas from before and after the scrubber was assumed to be constant in every case with the highest temperature as the average temperature of flue gas exiting KK2 boiler stack in 2015 of 173°C and the lowest being 60 °C which corresponds to the saturation temperature of flue gas mentioned earlier.

Energy demand to dry fuel-mix in each case was obtained by multiplying the mass of water needed to be evaporated by the specific heat consumption also in each case. The
latter, among others, was provided by a dryer manufacturer and can be seen from table 5 in chapter 5.

![Figure 17](image)

**Figure 17.** Comparison of recoverable energy from flue gas and energy needed for drying at different MC.

In figure 17, recoverable energy from flue gas diminishes for higher energy demand cases. As seen from figure 12, this is because the drier the fuel is, the less flue gas produced. Flue gas energy, however, might be enough for a 35% MC fuel-mix drying case.

KK2 was operative over 8300 hours during the studied period. If a flue gas scrubber would be used in the future, this will provide with secondary heat to the dryer during most of the year. However, it must be noticed that when steam demand is low, typically during summer, KK2 runs at minimum capacity producing this way less flue gas. In this case, if fuel-mix final MC is desired to be kept constant through the year, either the dryer would need another source of energy or the quantity of dried fuel would have to be reduced. This in turn would result in an oversized dryer during summer, unless the dryer would be sized for summer in which case not all the fuel-mix combusted during winter could be dried.

### 3.2 Secondary heat and LP steam

There are industrial processes in the forest industry from which secondary heat flows can be recovered and used for electricity or heating production. For example, in CTMP pulping, between 1000-4300 KWh of electricity is used to produce one air dry tone (adt) of pulp. Around 90% of this energy can be recovered as high-pressure steam (40-80%) and hot water (20%). (Vakkilainen et al. 2014, 97 & 112) Stora Enso Imatra has a CTMP plant and, if needed, also has LP steam network.
At SE Imatra mill, two of the sources of secondary heat sources are the evaporation plants and a scrubber that cleans flue gas from the recovery boilers and K9-11. Hot water from these sources is abundant during summer and its temperature can reach 70 °C. However, its availability is very limited in the cold winter months. Besides, temperature of available warm water during this season drops to average 60 °C. These two temperature values are in this work used for energy calculations related to water energy. In the case a dryer would be sourced with hot water through the whole year, this could be a problem which solution could be the combination of good availability of process water energy in summer with the one from flue gas water energy in winter studied in the previous chapter. This could make possible the use of a low temperature operating dryer with the enough energy to dry all the fuel-mix until at least 35% MC.

By recovering energy from secondary heat and flue gas, the dryer can be correctly dimensioned, allowing constant drying throughout the year. The use of only hot water as energy source for drying is further studied later.

Table 4 shows flow masses of hot water or steam needed to satisfy the energy demand of each of the drying scenarios in figure 17. This figure gives the energy demand for each case, and to calculate water and steam masses, the enthalpy difference through the dryer was needed. The masses of steam and water are obtained when energy demand is divided by their enthalpy differences.

In order to obtain water enthalpy difference, water warmest temperature had to be defined. Recovery boiler scrubber water outlet is colder, 60 °C, in winter. After consulting with a dryer manufacturer, this recommended the water outlet of the drying system to be not less than 35 °C; this gives a water temperature drop thought the dryer of 25°C. For LP (5 barg) steam, the inlet temperature is approximately 180 °C and the outlet temperature assumed to be condensate at 140 °C. The enthalpy differences are thus 104 and 2223 kJ/kg for water and steam respectively (Holmgren 1997).
Table 4. Flow mass of steam & water to meet fuel-mix drying energy demand. (’) Bark-sells included.

<table>
<thead>
<tr>
<th>E. Demand [GWh/a]</th>
<th>0</th>
<th>110</th>
<th>164</th>
<th>250</th>
<th>0</th>
<th>120</th>
<th>180</th>
<th>277</th>
</tr>
</thead>
<tbody>
<tr>
<td>m,steam [kg/s]</td>
<td>0</td>
<td>6</td>
<td>9</td>
<td>13</td>
<td>0</td>
<td>6</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>m,water [kg/s]</td>
<td>0</td>
<td>127</td>
<td>188</td>
<td>288</td>
<td>0</td>
<td>138</td>
<td>207</td>
<td>319</td>
</tr>
</tbody>
</table>

From table 4, when fuel-mix and bark-sells are dried until 35% MC, 138 kg of hot water is needed per second. In cold winter months, such amount of hot water could only be possible if steam was condensed to produce hot water or if a scrubber was used to recover energy from KK2 and K12 combustion flue gases. Drying fuel-mix and bark-sells further than 35% of MC would require a second dryer in series or increasing the dryer evaporation power by adding steam to the drying process. Chapter 5 describes several options for conveyor dryers.
4 DRYING FUEL FRACTIONS

At SE Imatra mill, bark is produced in Kaukopää and Tainio debarking drums. KP bark and sludge is sent to the bark pile by conveyors. TA bark is transported to the pile by trucks. Bark-sells remains separated from the other biomass fractions. KP bark and sludge mixing occurs on the transporting conveyors as mechanically dried sludge is dropped over KP bark. The storage site where the fuel-mix is piled, is an open area. Two screw reclaimers drag the fuel-mix from the bottom of its pile and send them to KK2 biomass storage silos.

4.1 Bark and sludge drying case

This first case evaluates the potentials of drying bark and sludge. During the studied period, dry mass of fuel-mix sent to the storage pile was 248.2 kt-d and its average MC 55.1%. Its energy content was 1099 GWh. Additionally, NG was also used in energy production from which boiler KK2 consumed 82 GWh. In total 1181 GWh\textsubscript{fuel} was burnt in KK2. Apart from this, the mill sold 30.3 kt-d of bark, bark-sells, which fuel energy value was 141 GWh.

Several drying scenarios are represented in figure 18. In these, steam is produced from the combustion of dried fuel-mix in KK2. On the columns to the right of this figure, bark-sells are also accounted for. Steam shares are obtained when using fuel energy values from figure 14 (a) and multiplying these values by its correspondent efficiency in the boiler KK2. Efficiency values are represented in figure 15.
In the hypothetical future scenario S1+ from figure 16, it was assumed that the minimum NG combustion should be no less than 91 GWh\textsubscript{th} of steam, this means that 1208 GWh\textsubscript{th} of steam had to be produced from the combustion of fuel-mix. In contrast, figure 18 shows that when drying fuel-mix at 10% MC, the steam produced will only be 1125 GWh\textsubscript{th} which means that NG will have to produce more than 91 GWh\textsubscript{th}. In the other hand, when bark-sells is also dried until 10% MC, 10’ in figure 18, its steam production, 1267 GWh\textsubscript{th}, could satisfy S1+. Fuel-mix combustion from 10’ would produce 326 GWh\textsubscript{th} more than fuel-mix in S0+ from figure 16. This would potentially save 358 GWh of NG. Considering that the maximum NG saving potential was determined in chapter 2.4 to be 266 GWh\textsubscript{th} or 293 GWh\textsubscript{fuel}, drying KP bark, bark-sells and sludge until 10% MC might not be needed unless part of the steam produced was used for supplying the energy demand of the dryer; this is not taken into account in this work yet.

Cases 35’and 25’ from figure 18, would produce respectively 1186 GWh\textsubscript{th} and 1225 GWh\textsubscript{th} which is 244 GWh\textsubscript{th} and 283 GWh\textsubscript{th} more production than the one from fuel-mix in S0+ in figure 16. The second of these, also surpasses the assumed maximum steam production from fuel-mix (1208 GWh\textsubscript{th}) from figure 16 while the first (35’) stays very close from it. If the assumption that the mill at Imatra would have the same steam demand in the future, cases 25’ and 35’ are the closest to meet S1+. 
4.2 Bark-only drying case

In this chapter, bark-only drying is simulated. The mass of dry fuel-mix resultant from drying bark-only is the same than in the previous case of fuel-mix drying. However, the final product sent to combustion is wetter since sludge remains at an average of 67.6 % MC. Steam energy from sludge combustion is the only difference from figure 19 with respect to figure 18.

![Graph](image)

**Figure 19.** Steam energy production in KK2 by fuel fraction. Tainio bark and sludge remain wet. Bark-sells (').

In this case, figure 23 shows that the steam production from the combustion of fuel-mix where bark-only is dried can reach 1167 and 1201 GWh\textsubscript{th} for the cases 25´ and 10´ respectively. This means that they would produce 225 GWh\textsubscript{th} and 260 GWh\textsubscript{th} more than what it is currently produced in S0+ from fuel-mix combustion in figure 16 which is close from the minimum NG combustion target case of S1. Bark-only drying case gets the closest to achieve S1+ when all the bark, except by the one from Tainio, is dried until 10% MC.

4.3 Sludge-only drying case

Sludge accounts for 18% of all the dry fuel mass burned in boiler KK2. For this reason, a scenario where only sludge would be dried, would increase less the total solid fuel energy content. However, relative to its mass, it is the fuel with the largest potential since it
is also the wettest fuel at 67.6% MC. + Comparing figures 18 and 19, maximum steam production difference is 66 GWh th on behalf of the first.
5 APPLICABLE DRYING TECHNIQUES

Choosing the best suited dryer for a certain case can be challenging especially due to the number of different dryer options in the market (Osman et al. 2011, 6). This chapter enhances some of the characteristics and advantages from the dryers presented in chapter 1.

5.1 Dryer comparison

Selection of a dryer should be made after considering factors like fuel properties, O&M requirements, capital costs, environmental emissions, energy efficiency and heat recovery, secondary energy sources available to achieve drying targets, risk of fire hazard, feed and discharge systems, corrosion and erosion, space demand for both dryers and for auxiliary equipment, and marketable byproducts. (Ross 2018, 7 and 14) Security is the priority number one for SE Imatra mill and as such, it is valued as the most important fact affecting the decision of what dryer type is studied in this work. Next, there are some of the factors that should be taken into consideration from the point of view of several dryer types.

Fire hazard. Explosion by dust ignition is possible when there is a source that initiate the fire, dust concentration is dense enough in the air and oxygen is also available. This risk is higher in flash and rotary dryers than in SSD or conveyor dryers. However, when dust is piled on a surface, as it could happen on a conveyor dryer, fire could start at lower temperatures than if dust was spread on the air. Temperatures of 100-125 °C could be enough; moving parts in the mechanisms of conveyor dryers are thus a potential fire hazard. (Motiva 2013, 9).

Environmental emissions. Biomass drying tends to release VOCs to the environment. VOC emissions increase with drying medium rising temperatures. Direct-fired rotary and flash dryers have the worst performance in this case while VOC emissions from low temperature dryers like conveyor dryers is minimal. SSD dryers VOC emissions are mainly collected in the condensate and the rest can be sent to combustion. Additionally, SSD close loop decreases smell and dust in the exhaust (Van Deventer 2004, appendix E page 3). Control of particulate emissions rise dryer cost as in the case of direct-fired rotary dryers or flash dryers.
Energy efficiency and heat recovery. Conveyor dryers are the ones than can use the lowest temperature energy source. This enables fuel drying to use waste heat from industrial processes in the mill, increasing energy efficiency. Chapter 6 studies how much energy several conveyor dryers can recover from secondary heat sources to fulfill their energy drying demands.

Feed and discharge systems. SSD have issues with leakage at the in- and outlet of the dryer due to the feed and discharge systems. These issues can alleviate by using plug-screw feeder, but they often need to be replaced. All in all, SS dryers have good availability, but replacement of plug-screws increase their O&M cost.

Corrosion and erosion. Corrosion and erosion are other issues mainly accredited to flash and SSD dryers. High drying velocity of material with high ash or sand content can wear the interior of these dryers.

Marketable by-products. VOC released from the process of drying biomass can be burned along with the air it is contained in. SSD dryers are best suited for the recovery of marketable oils. These can be used in cosmetics amongst other commercial products.

In conclusion, SSD dryers are safe, have no emissions, and they can be very energy efficient recovering up to 90% of the energy they use for drying if the energy from their condensate can be used in another process for example in a conveyor dryer in series with this. However, except by the coldest months in winter, hot water availability in SE Imatra mill is sufficient for drying purposes; in winter, steam energy would need to be used to support hot water.

Conveyor dryers, however, have low of fire risk, cause little VOC and dust emissions and can recover energy from very low temperature sources. Additionally, issues with the fuel in-and output operations or erosion are not as common as with SSD. For this reason, conveyor dryer seems to be a good dryer choice to be studied in this work if only one dryer is chosen. Nevertheless, it could be interesting using two dryers, one conveyor dryer and one SSD type. The first could use the condensate energy from the second, increasing this way the energy efficiency of the system and the mill as well as fuel quality. Part of the output from the first could be used to burn in KK2 and maintain burning temperature...
without using NG and the output from the second could be used for other purposes like gasification. Next chapter briefly explains how the combination of both dryers integrated in a mill could be beneficial.

5.1.1 **Flash dryer**

Due to the advantages of SSD, this chapter briefly discuss about the installation of SSD and conveyor dryers as an integrated system in the mill. The combination of both dryers, in either parallel or series, could allow the energy from the SSD condense to be recovered for the conveyor dryer. Conveyor dryer could be dimensioned according with the recoverable energy from the SSD condense. Conveyor dryer could be over-dimensioned compared to the SSD output energy to use the mill waste heat from hot water too.

Drying in series could allow drying fuel until for example 35% MC in a conveyor dryer that used only hot water energy, and its output could be the input of SSD which could dry until 10-25% MC.

5.1.2 **Conveyor dryer**

Two types of conveyor dryers were introduced in chapter 1.5.4, single- and multi-pass dryers. Some of the disadvantages the multi-pass has over single-pass dryers are that they have higher complexity and maintenance needs which reduces availability and increases O&M cost. The advantages are that they produce a more homogeneously dried final product, require less space for erection and investment cost are less. Space faces the fact that there is enough available space for a full sized single-pass conveyor dryer by the stockpile. A multi-pass dryer might need to be of higher evaporation power to compensate for the lack of availability compared to the single-pass dryer. A biomass dryer manufacturer was contacted during the study of this thesis and information about a single-pass conveyor dryer was retrieved.

5.2 **Drying stages and energy efficiency**

Conveyor dryers can also be differentiated by the number of drying stages in which the different heat sources used transfer their energy to the drying medium. These can be sin-
Single-stage or multi-stage drying. Multi-stage drying can be used to increase energy efficiency. In every drying stage, air can be warmed by hot water and steam. The stage is completed when air is exhausted from the fuel bed. Figure 24 shows how the exhaust air from the first drying stage leaves that stage’s drying bed and heads for reheating at the beginning of the second stage in heat exchangers (5-6, 6-7 and 7-8) before it is sent to dry fuel at a later stage of the conveyor. Reheating is needed because after each stage, air is close to its saturation point and thus its capacity of absorbing moisture is close to zero. Depending on the initial values, an optimized drying stage might not necessarily need more than one heat source. Using several drying stages reduces energy consumption and air demand for drying since the same air is used after it is reheated. Compared to single-stage, multi-stage drying systems need less drying temperature to reach the same outlet air humidity. (Holmberg 2007, 23)

**Figure 20.** Two stage dryers. “t” stands for temperature, “x” for air moisture, “mda” for dry mass of air and “u” for fuel moisture. (Holmberg 2007, 24)

Next, part of two authors work related to conveyor dryers are described. In the first case, Rajala (2013) tested various changes in parameters while using all the time a hot water-only sourced single drying stage conveyor dryer. In the second case, Holmberg (2005) studied about the economic and energy efficiencies of using multi-stage drying with both hot water and steam as heat sources.
Rajala (2013) made three tests from which he got different values of final fuel MC and dryer specific energy consumption. The parameters he tested were drying temperature, bed height, and bed speed.

In his first test, he used hot water to heat a dilution of water-glycol that consequently heated the drying air. Glycol temperatures were from 60-72°C. He observed that when the temperature of glycol was 60-66°C, the specific energy consumption of the dryer was approximately 9000 kJ/kgK but this dropped to 5400 kJ/kgK when the temperature of glycol reached 68°C. However, after 68°C, the reduction in specific energy consumption was almost unnoticeable. In his first test, final MC of biomass remained at around 35% for glycol temperatures between 60-66°C and decreased remarkably to 20% only after glycol temperature reached 68°C.

Rajala’s second test consisted in changing the bed height from 120 mm to 180 mm with increasing intervals of 20 mm while keeping constant the biomass volume flow. This would cause the bed velocity to increase when the bed became thinner. For bed heights of 140-180 mm, the energy consumption of the dryer and the final biomass MC were similar, however, for the thinnest bed layer of 120 mm the specific energy consumption rose considerably and so did the final MC of the biomass. The explanation for this could be the lower residence time of the fuel in the bed and inefficient drying due to the energy loss of exhausting air far from saturation point.

In his last test, bed velocity stayed constant having to decrease biomass drying volume flow accordingly to the change in bed height. Bed height would change in the same way as in the previous test. Even though less biomass was dried in the 120-160 mm settings, these would fail drying biomass until as dry as in the 180mm setting. Specific energy consumption was once again the lowest when the bed height was the thickest. As a way of synthesis, from the results in it could be deduced that when only using hot water as heat source, biomass drying should happen at temperatures of around 70 °C for glycol and bed thickness of 180 mm at least.

Holmberg (2005, 9) studied about the increase of energy efficiency and economic performance of multi-stage conveyor dryers for drying birch bark. In his calculations, he used a secondary heat source to heat incoming air until 70 °C and sometimes also steam for
rising drying temperature more. Other base parameters he used were initial MC of 60 %, price of secondary heat 0.5 €/MWh, price of marginal fuel 14 €/MWh, economic lifetime 10 years, interest 5 % and O&M 3 % of the overall investment cost amongst others. In a scenario with basic parameters, the best economic performance was achieved when bark was dried until 23 % MC using 70 °C air and 2-stage drying system. Specific heat consumption for 1, 2, and 3-stage drying was 5860, 4360, and 3890 kJ/kgK respectively which indicates that a 3-stage system is the most energy efficient.

In a sensitivity analysis, Holmberg (2005) studied the economic performance of this dryer when changing parameter such as dryer’s economic lifetime and prices of marginal fuel, electricity and secondary heat source. If lifetime of the dryer is 7 years or less, a single-stage dryer using 70 °C air makes more economic sense. For long dryer lifetime, a 2-stage drying system that uses only secondary heat source to dry bark until close to 20 % MC is optimal. When marginal fuel price is low, 6-10 €/MWh, the use of steam energy to heat drying air over 70 °C is the best option. However, when fuel price increases, and thus does steam price, the use of only secondary heat in a 2-stage system quickly increases the dryer economic performance. In the case where electricity prices change, the results are the same as in the base scenario except by when the price is at least 50 €/MWh, in which case, a 1-stage system that uses steam outperforms the base scenario. When secondary heat price is 0.5 €/MWh a 2-stage dryer is the best option but when secondary heat source price changes to over 1.5 €/MWh or drops to 0 €/MWh, respectively 3-stages and 1-stage systems becomes more profitable. In every occasion, when using steam to heat air over 70 °C, a single-stage drying system was more economically profitable.

From the tests from Rajala (2013) and the study from Holmberg (2005) it can be deduced that when only hot water is to be used to dry biomass, the drying air should at least be 70 °C and probably a 2-stage system will perform better while a single-stage might be a more optimized system for a dryer that uses both hot water and steam. As it was discussed in chapter 3, only energy from secondary heat sources could be insufficient to cover the energy demand of a dryer that would dry all the bark from SE Imatra mill and thus steam use is a must. For these reasons, a single-stage drying conveyor seems like the most reasonable dryer to study in this thesis.
5.3 Drying cases

This chapter describes five future possible scenarios, here called cases 1’-5’ that would use dryers with a drying capacity for 200 m$^3$/h. In these cases, secondary heat and steam may be used to dry bark-only from SE Imatra mill. These heating sources transfer their energy to a water with Ethylene Glycol (EG) dilution (60/40). Table 6 shows that energy is first transferred in heat exchanger (HE1). This is a water to EG exchanger. Then in the dryers that use steam, second exchanger (HE2) heats EG (T$_{EG_{out}}$) with steam until to 119 °C. EG is used to prevent water from freezing in winter during downtime. The dilution is maintained under 5 bar pressure to make sure it stays in the liquid phase even in the cases where its temperature rises over its boiling temperature which for the given concentration is 105 °C at 1 bar (Dowtherm 2008, 35). The heated dilution is assumed to reach 119°C of temperature as it leaves the HE2 and it is used to heat ambient air until 110 °C.

In this work, all the cases studied are assumed to dry the same amount of bark from KP and/or bark-sells to different final bark MC. Due to the better environmental and economic results of the cases which include bark-sells in the drying and combustion processes, these are the only ones presented in this thesis. Some of their initial data is gathered in table 5. Cases 1-3 use both heating sources whereas case 4 only uses hot water. Case 5 only uses hot water as heat source during winter but uses both sources during summer with the aim of simulating a dryer that could recover energy from whatever excess of steam production during warm months and thus a summer steam that should at first be less costly than cold season steam.

The total mass of dried bark in the 5 cases is 207 kt a year. This corresponds to an average volume flow of 159 m$^3$/h and mass flow of 24.8 t/h of dry bark. MC of bark is on average 48.0 % during summer and 49.8 % during winter. Also, represented in table 6, each drying case has a desired final bark moisture (Final MC). The difference from initial and final desired moisture gives the amount of water that needs to be evaporated. Once the conveyor dryer manufacturer provided the specific energy consumption per unit of evaporated water, the annual energy demand of each dryer case could be obtained. In chapter 6 table 7, the annual energy demand of each of the five drying cases is shown. In table 6, evaporating power of the final desired MC $P_{dryer}$ of each case is represented; this is the
result of dividing annual energy for drying by the number of hours the dryer is operative. The dryer is assumed to work at full capacity all the hours of the year boiler KK2 does which in the studied period was 8352 h/a; the dryer stops for maintenance whenever KK2 stops. Dryer power is the greatest the drier the fuel is at the outlet of the dryer which in this case is 10 % MC in case 3´ during winter since ambient air and fuel temperatures are both colder than during summer.

In each of the five cases, the quantity of energy provided by each of the heating sources depends on these sources mass flow through the heat exchangers and their temperature drop over the exchangers. Warmest hot water and steam temperatures were already given in chapter 3.2 and coldest possible water temperature at the outlet of each case’s heat exchanger was provided by the conveyor dryer manufacturer. Table 6 depicts the temperatures of the different fluids, heat sources and EG dilution, for the each of the different five cases.

Hot water availability from industrial processes at SE Imatra mill might not be enough to cover their mass flow demands from table 6, especially in cases 3´-5´ from which around 100 kg/s are required. Depending on the outside temperature during winter cold months, hot water availability could also be insufficient, even for the less hot water demanding cases from table 6. In this work, it will be assumed that hot water is available.
Table 5. Five drying cases parameters.

<table>
<thead>
<tr>
<th>Case n°</th>
<th>1'</th>
<th>2'</th>
<th>3'</th>
<th>4'</th>
<th>5'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel dried</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel in</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m_dry</td>
<td>[kg/h]</td>
<td>Winter</td>
<td>Summer</td>
<td>Winter</td>
<td>Summer</td>
</tr>
<tr>
<td>m_wet</td>
<td>[kg/h]</td>
<td>24831</td>
<td>24826</td>
<td>24831</td>
<td>24826</td>
</tr>
<tr>
<td>MC</td>
<td>[%]</td>
<td>49,81</td>
<td>47,98</td>
<td>49,81</td>
<td>47,98</td>
</tr>
<tr>
<td>Fuel out</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m_wet</td>
<td>[kg/h]</td>
<td>38201</td>
<td>38194</td>
<td>33108</td>
<td>33101</td>
</tr>
<tr>
<td>Final MC</td>
<td>[%]</td>
<td>35</td>
<td>35</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Energy source</td>
<td>[Steam/water]</td>
<td>Both</td>
<td>Both</td>
<td>Both</td>
<td>Both</td>
</tr>
<tr>
<td>Evaporation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>m_evaporation</td>
<td>[kg/h]</td>
<td>11274</td>
<td>9527</td>
<td>16367</td>
<td>14620</td>
</tr>
<tr>
<td>E_specific evaporation</td>
<td>[MWh/t_H_2O]</td>
<td>1,24</td>
<td>1,09</td>
<td>1,21</td>
<td>1,07</td>
</tr>
<tr>
<td>P_dryer</td>
<td>[MW]</td>
<td>13,7</td>
<td>10,2</td>
<td>20,7</td>
<td>16,3</td>
</tr>
<tr>
<td>Heat exchangers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>P_H_2O_glycol</td>
<td>[MW]</td>
<td>0,9</td>
<td>0,6</td>
<td>1,3</td>
<td>1,0</td>
</tr>
<tr>
<td>P_steam_glycol</td>
<td>[MW]</td>
<td>12,8</td>
<td>9,6</td>
<td>19,3</td>
<td>15,4</td>
</tr>
<tr>
<td>q_m_H_2O</td>
<td>[kg/s]</td>
<td>46</td>
<td>40</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td>q_m_steam</td>
<td>[kg/s]</td>
<td>5,8</td>
<td>4,3</td>
<td>8,7</td>
<td>6,9</td>
</tr>
<tr>
<td>q_m_glycol</td>
<td>[kg/s]</td>
<td>53,4</td>
<td>46,9</td>
<td>81</td>
<td>75</td>
</tr>
<tr>
<td>Electric power</td>
<td>[kW]</td>
<td>278</td>
<td>283</td>
<td>356</td>
<td>364</td>
</tr>
<tr>
<td>Active drying surface</td>
<td>[m_2]</td>
<td>224</td>
<td>308</td>
<td>408</td>
<td>408</td>
</tr>
<tr>
<td>Case n°</td>
<td>Heat Exchanger 1 (water/glycol)</td>
<td>Heat Exchanger 2 (steam/glycol)</td>
<td>Heat Exchanger in dryer (glycol/air)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------</td>
<td>--------------------------------</td>
<td>----------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q&lt;sub&gt;m&lt;/sub&gt;water [t/h]</td>
<td>46,0</td>
<td>40,4</td>
<td>69,6</td>
<td>8,7</td>
<td>97,2</td>
</tr>
<tr>
<td>T&lt;sub&gt;steam in &lt;/sub&gt;[°C]</td>
<td>5,8</td>
<td>4,3</td>
<td>8,7</td>
<td>6,9</td>
<td>12,2</td>
</tr>
<tr>
<td>T&lt;sub&gt;steam out &lt;/sub&gt;[°C]</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>T&lt;sub&gt;EG in &lt;/sub&gt;[°C]</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
<td>140</td>
</tr>
<tr>
<td>T&lt;sub&gt;EG out &lt;/sub&gt;[°C]</td>
<td>57</td>
<td>67</td>
<td>57</td>
<td>67</td>
<td>57</td>
</tr>
<tr>
<td>T&lt;sub&gt;air out &lt;/sub&gt;[°C]</td>
<td>119</td>
<td>119</td>
<td>119</td>
<td>119</td>
<td>119</td>
</tr>
<tr>
<td>T&lt;sub&gt;EG in &lt;/sub&gt;[°C]</td>
<td>48</td>
<td>59</td>
<td>48</td>
<td>59</td>
<td>48</td>
</tr>
<tr>
<td>T&lt;sub&gt;EG out &lt;/sub&gt;[°C]</td>
<td>33</td>
<td>64</td>
<td>33</td>
<td>64</td>
<td>33</td>
</tr>
</tbody>
</table>
5.4 Drying before storing or before combustion

In chapter 4, it was agreed that conveyor dryer will only dry bark. This means that transporting conveyors that currently carry bark and sludge at the same time will have to do so separately. If no additional investment on conveyor is made, in the future the mill could send bark and sludge with the same conveyor as it uses currently by alternating the type of fuel the conveyors. Sludge can be stored in its own sludge pile. Bark could be sent to its own wet bark pile in the current bark pile area to wait for drying or could be sent straight to the dryer’s silo if this has enough volume.

The dryer’s maximum capacity is 200 m$^3$/h of loose bark, thus if the dryer was only supplied with wet bark from the debarking drum conveyors, dryer’s silo storage capacity should at least be 200 m$^3$ for an hour of fuel buffer permitting this alternate bark and sludge every other hour with a minor change on the current fuel-mix conveyor just before the biomass storage area. In the other hand, if all the bark from the debarking drums was sent to the wet bark pile and this feed to the dryer from this, the dryer’s silo could be smaller. A combination of both supply paths might also require a smaller silo. In the case that part or all the bark supplied to the dryer’s silo came straight from the debarking drum conveyor a new conveyor system should divert the wet bark from going to the biomass storage area so this wet bark could be poured into a dryer’s silo instead.

5.4.1 Drying before combustion

When KK2 is on, bark could be dried in the amount needed by the boiler at that moment and then sent to combustion. Sludge and Tainio bark may be mixed with dried bark on a conveyor after the dryer and prior to their brief storage time in KK2 silos. The mass of wet Tainio bark and sludge mixed with dried bark sent to KK2 silos should be controlled to achieve the desired MC of the fuel-mix that is going to combustion. When KK2 is off, the conveyor dryer will only dry wet bark until KK2 silos are full and then it will stop. Though KK2 is operative most of the time, this drying option will only dry the amount of bark needed by the boiler and thus dimensioning the dryer for winter operations will incur in over-dimensioning for warmer months whereas dimensioning for summer will only dry part of the bark that is produced at the KP debarking drums.
This work is more inclined towards the possibility of saving as much NG and use as much secondary heat sources as possible to improve energy efficiency and environmental performance; so, dimensioning a dryer that can dry as much bark as it is produced is more in line with this work. In the five cases earlier presented, dryer capacity, 200 m³/h, allows it to dry as much bark as it is produced and regardless of the operating capacity of KK2, the dryer will dry at full capacity. If more bark that the one KK2 would need at a certain moment was dried, the excess of it could be stored in a dried bark pile.

Excess of dried bark could occur when the steam demanded from KK2 is less than the steam that this boiler could produce from the combustion of all the dried bark the dryer outputs at that exact time, including sludge and Tainio bark in the balance. Dried bark pile could act as a high-quality, or at least higher quality than currently, fuel buffer; it may be consumed during high steam demand season and dryer downtime.

In this case, the whole fuel storage should be comprised of four areas; already dried bark, wet sludge, wet TA bark and possibly some wet KP bark that would be taken to the open storage area during dryer downtime. The first will become larger during the low steam demand season and will start diminishing as high steam demand season enters. Dried bark pile could use the same space fuel-mix sits in currently over the screw reclaimers and be dragged towards the conveyors which currently carry fuel-mix to KK2 silos.

5.4.2 Drying before storing

Dried bark is always sent to the dried bark stockpile where at its bottom, screws reclaimers send it to KK2 silos before combustion. There is no direct connection from dryer to KK2 silos and thus conveyor length might be saved. In this option, dried bark is sent to KK2 silos indirectly through the dried bark stockpile as it is done in the present. Additionally, Tainio bark and sludge will not need a conveyor to take them to the mixing point with dried bark, instead they can be mixed with the dried bark stockpile before the mix is taken to combustion.

Though this last option seems to save on conveyor length, it might incur in more fuel mixing and handling running costs. Drying bark and sending it to combustion has an advantage which is that the bark is hotter when it is input in KK2 than when this is taken
from the stockpile. If an option dries more bark than the one needed at that moment by KK2 at lower than 30 % MC and sends it to the dried bark to storage, that bark will preserve better in storage than if it stayed in it wet and then sent to drying.

At this point it is worth mentioning that this work considers that neither dried bark can get wet nor it dries while in storage. This is mainly because most of the excess dried bark is produced during the low steam demand period of the year which coincides with the dry and hottest season while during the colder and wetter seasons all the incoming wet bark might be send to the dryer and combusted within a short period of time or even straight away as it comes from the dryer.
6 ENERGY AND SAVING RESULTS

Chapter 2 demonstrated how the energy content of fuel and its combustion efficiency in KK2 may improve. The drier the fuel is, the better these parameters are. However, according to (Holmberg et al. 2015, 170), combustion temperature and NOx emissions increase with dried fuel. Also, in bubbling fluidized boilers, when the temperature is too high, the sand on the bed could melt and create agglomeration of it. Mechanism such as controlling the air input to the bed or reusing flue gas can help prevent these problems. But such mechanisms are already in place in KK2 and thus they might not be enough to prevent bed temperature issues if the MC of all the bark from KP would change from around 50 % to 10 %. On the good side is the fact that dried bark must be mixed with sludge and wet Tainio bark before combustion and this will increase the final fuel-mix MC. This work, however, considers the possibility of drying all the bark from KP and bark-sells until several final bark MC limiting this at 10 % in case 3’ as seen in table 6. The reason for this is to show how does the economic performance of a large dryer that uses steam compares with smaller dryers that also uses steam, cases 2’ and 3’, or dryers that use only hot water while maintaining the same size, case 4’.

6.1 Case results

Five different single pass conveyor drying cases have been simulated in this chapter. These cases contemplate the possibility of drying more fuel that what it is needed at a certain moment and assumes the rest of the dried fuel is stored in the bark pile area for later combustion.

In table 7, energy demand corresponds to the water and/or steam energy used to achieve drying of bark from KP and bark-sells. This is obtained from the multiplication of the mass of water needed to evaporate and the specific energy consumption of each drying case. Specific energy consumption for each drying case were consulted with a conveyor dryer manufacturer. Energy benefit stands for the gain on steam energy from the combustion of dried biomass compared with the one from the current biomass from present scenario S0 in figure 16. Values from this column are greater than the ones from energy demand because they include the share of steam that combustion of bark-sells would pro-
duce. NG savings are obtained when assuming that all the energy benefit can reduce energy from NG combustion and dividing this by the combustion efficiency of NG from chapter 2.4 of 91%. Steam energy from fuel-mix, in the last column, represents the summation of energy benefits and the steam energy from fuel-mix in the current scenario S0, from figure 16 this is 941 GWhₜₜ.

**Table 7.** Comparison of data related to the operation of the 5 drying cases.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1'</td>
<td>35,0</td>
<td>107</td>
<td>191</td>
<td>210</td>
<td>1132</td>
</tr>
<tr>
<td>2'</td>
<td>25,0</td>
<td>163</td>
<td>223</td>
<td>245</td>
<td>1165</td>
</tr>
<tr>
<td>3'</td>
<td>10,0</td>
<td>231</td>
<td>258</td>
<td>284</td>
<td>1200</td>
</tr>
<tr>
<td>4'</td>
<td>40,0</td>
<td>88</td>
<td>171</td>
<td>187</td>
<td>1112</td>
</tr>
<tr>
<td>5'</td>
<td>34,5</td>
<td>122</td>
<td>193</td>
<td>212</td>
<td>1134</td>
</tr>
</tbody>
</table>

Case 4’ uses the same size dryer as in case 3’, but it only uses hot water as heat source. With sufficient hot water, this dryer could dry the same amount of bark until 33-35 % MC. However, as hot water source availability is insufficient during winter, the final bark MC of case 4’ was set to 40 % MC.

In case 5’, the same dryer uses hot water energy during the whole year, but compliments this with available and inexpensive steam during low heat demand season. In other words, the dryer operates as case 3’ dryer in summer and as case 4’ dryer during winter to obtain a bark average MC of 34.5 %.

The last column of table 7 is represented graphically in figure 21. In this figure, the steam energy produced in every case is subdivided by fuel fractions. Bark-sells is not included in the first two scenarios, S0+ and S1+. In the actual scenario, S0+, this is so because bark-sells is sold as can be seen in figure 22 and in the future scenario, S1+, because this scenario only created for the guidance of other cases simulated in this work. This last only reflects the steam energy that needs to be produced from biomass, independently of the fuel fraction, to reduce the production of steam from NG combustion in KK2 to 91 GWhₜₜ.
In Figure 21, all cases are limited to the production of 1299 GWh th. To this point, it was assumed that future steam demand will remain as it is in the present. The share of steam that is not produced from the combustion of biomass, dried or not, must be covered by NG addition to the boiler. Future case 4’ will need the most NG for providing enough steam to the mill whereas case 3’ will need to use the least NG, almost as in the optimal future production commented in Chapter 2.4. Steam energy that could be produced from the combustion of dried bark in KK2 ranges from 884 GWh th in case 4’ to 971 GWh th in case 3’. Along with Table 7, the gain in steam production in case 3’ comes with an extra energy demand of 142 GWh th, from which most of it is steam.

6.2 Effects of using steam or secondary heat

In the current scenario, KK2 and K9-12 produced 1299 GWh th of steam per year, see from Figure 22 electricity and steam energy flows exiting turbine 7 (TU7). However, if a dryer would use steam energy to dry bark, this quantity of steam should also be provided by the mill to the dryer. One solution could be that the mill bought additional biomass to cover for the additional steam demand of the future dryer.
The steam energy used for drying bark will be taken from the exhaust of the turbine. This means that part of the steam energy from additional bark is used to produce electricity and part will be used by the dryer as LP steam. Additional mass of bark must account for both, electricity production from this share of additional biomass, from which the mill will benefit, and LP steam energy to allow KP bark and bark-sells drying. In figure 23, future scenario case 3′ with additional biomass flow is represented.

Now, figures 22 and 23 may be compared. From the difference in energy flows out of turbine 7, it may be noted that steam and electricity have increase in 231 GWh\(_{\text{th}}\) and 42 GWh \(_{\text{el}}\)/a respectively in figure 23. This energy is provided by additional biomass. The first is used in the dryer which has losses. The increase on energy value for the dried bark is the additional production of steam from additional biomass minus the dryer losses, 121 GWh in case 3′. As the Imatra mill needs to buy electricity from the grid, all this additional electricity would easily be used within the mill, diminishing electricity cost. Additional biomass costs disregarded in this work because the dryer is treated as a customer of the mill and so in calculations, the dryer buys steam from the mill. For the same reason, electricity savings are then not in the scope of this study.
Figure 22. Energy flow diagram of the present scenario with no dryer. Bark-sells fraction is sold presently.
Figure 23. Case 3’ energy flow diagram. NG is only burned in K9-12. Bark-sells is dried and burns in KK2. Additional biomass is sent to KK2 without drying.
7 ECONOMIC PERFORMANCE

This chapter presents the economic performance of the five drying cases from chapter 5.3 including a sensitivity analysis for several parameters. Data used for calculations, include investment cost of dryer, cost of auxiliary equipment, and operating cost. The last costs are divided between fixed annual and variable annual cost. Variable annual cost is further studied as a function of final bark MC whereas the rest of the costs are assumed fix for the period of 10 years of dryer’s lifetime.

7.1 Investment and operating costs

The goal of this chapter is to represent graphically the economic performance of each of the 5 dryer cases from chapter 5.3, using net present value (NPV) and pay-back time (PBT) calculations. Dryer investment and operating costs needed to be investigated.

Investment cost consist on dryer, heat exchangers for water to glycol and steam to glycol depending on the drying case, foundation work, piping and pumps, new fuel conveyor systems, crushing equipment to reduce oversized bark, sheltering, 200 m$^3$ wet bark silo, sprinklers, fire alarm system, connections, etc. Cost information about each of the five dryers studied was obtained from a conveyor manufacturer and from the company Efora Oy, maintenance operations at the Stora Enso mill. Since at this early stage the exact installation location for the future dryer is uncertain, parts of the equipment costs were only approximated, for example the costs of the modifications for the bark conveyor.

Dryer operating costs are divided between fixed annual cost and variable annual cost. Fixed annual cost include O&M, bark-sells cost since the dryer is assumed to buy this bark from the mill, and electricity consumption cost. Along with Holmberg (2007, 34-35), O&M cost are around 3 % of the overall investment cost and price of marginal fuel is 14 €/MWh$_{fuel}$; in this work, bark price is the same as marginal fuel. For LP steam, its price is 16.2 €/MWh$_{th}$. Lastly, electricity cost is constant due to the assumption already made in chapter 5 that the dryers operates at maximum load for as long as KK2 does.

Variable annual parameters include costs of hot water and/or LP steam energy demand, NG saving in positive, and carbon allowances saving also in positive. Additionally, a system that replaces fossil fuel by a renewable fuel may be considered as a cost-effective
system and be entitled to possible incentives. (Ross 2013, 16) This, however, is disregarded in this work.

Price of hot water energy and costs for pumping this until the heat exchanger in the dryer is often null (Holmberg 2007, 36). This work uses prices of hot water energy 3 €/MWh during winter and 1 €/MWh during summer and no costs for pumping water electricity. Steam price is 16.2 €/MWh during the whole year which, for the purpose of case 5’ is a disadvantage since the idea of this dryer is to use steam when its price is low. Savings are also accounted for in equation NPV, where NG price, 27 €/MWh\textsubscript{fuel}, is taken from the average price of NG during the winter of 2015 because it is then when most of NG was consumed in KK2 and K9-12 boilers (Statistics Finland 2019). Regarding fossil CO\textsubscript{2} emissions allowances, the price used is 8 €/tCO\textsubscript{2}. Figure 24 shows these costs for case 3’ where values from 10 % MC are the ones calculated from former data given in tables 6 and 7.

![Figure 24](image_url)

**Figure 24.** Variable and fixed price data for dryer case 3’ as a function of fuel MC.

Figure 24 starts from 49.8 % MC since this is the average MC of KP bark during the studied year. In table 5, dryer case 3’ steam power demand is 15 times greater than hot water demand. Additionally, the price of steam per unit of energy is higher than the one from hot water. This makes case 3’ very dependent on steam energy price. Economic impact on steam energy price variations is further studied later in this chapter. The largest
parameter in fix annual cost is the purchase of bark-sells by the dryer. For this reason, these costs start from figure 24 at 2.3 M€ when bark is barely dried. In the other hand, as bark-sells will be dried and send to combustion in KK2, this diminishes NG consumption. For this reason, NG savings with a price per unit of energy of 27 €/MWh\textsubscript{fuel}, start in figure 24 with a value of 3.6 M€. NG saving can be considerable, but their quantity is greatly dependent on the fossil fuel price. For this reason, NG energy price is also studied later in the sensitivity analysis chapter 7.3.

In figure 24, values of steam production from biomass, correspond to the steam produced from the combustion of sludge, dried KP bark and bark-sells, and TA bark. At 10 % MC, the sum of these values is 1200 GWh\textsubscript{th} and it is the same value than the one from biomass steam production in figure 21 of the same case 3’. CO\textsubscript{2} allowance savings look rather modest compared with the ones from NG saving because the price of CO\textsubscript{2} allowances in calculations is only 8 €/t\textsubscript{CO\textsubscript{2}}; however, these prices are increasing rapidly (Statistics Finland 2019). Sensitivity analysis chapter also investigates the impact on CO\textsubscript{2} allowance prices variation to the economics of the each of the five dryers studied in this work.

### 7.2 NPV and PBT methods

Net present value (NPV) and pay-back time (PBT) as a function of MC, are calculated here to study the economic performance of each dryer case at designed MC or less. Studying each of the dryer performances when these only operate partially to what they are designed for, is done to understand how they will perform in case of disturbance conditions. Here, calculations for both methods were done using base prices mentioned before in this chapter. NPV method equation 5 is presented next.

\textbf{Equation 5.} Net present value equation.

\[ \text{NPV} = \sum_{t=1}^{n} \frac{S_t}{(1+i)^t} - \left( I - \frac{J\alpha_n}{(1+i)^n} \right) > 0 \] (5)

- \( S \) : annual net savings [k€/a]
- \( i \) : interest rate [%]
- \( t \) : time after commissioning [a]
- \( I \) : investment cost [k€]
Annual net savings remain constant through the lifetime of the dryer, 10 years. This includes the prices of hot water, steam, NG and CO₂ emissions. After dryer lifetime, the remaining value of the dryer, \( JA_n \), is considered negligible. Now equation 5 can be written as equation 6.

**Equation 6.** Simplified NPV equation

\[
NPV = a_{n/i} \cdot S - I
\]

\( a_{n/i} \) discount factor

Discount factor may be expressed as in equation 7. Final NPV equation used in calculations is equation 8. This is got after discount factor from equation 7, is substituted in equation 6. Interest rate used here is 7%.

**Equation 7.** Discount factor equation.

\[
a_{n/i} = \frac{(1 + i)^n - 1}{i \cdot (1 + i)^n}
\]

**Equation 8.** NPV equation with discount factor

\[
NPV = \frac{(1 + i)^n - 1}{i \cdot (1 + i)^n} \cdot S - I
\]

The results of these calculations are represented in figure 25. In this figure, case dryer 4′ is the most economically efficient. The rest of the cases performance are expressed as percentages of case 4′.

PBT is found when the investment is paid back, NPV equals 0. Then for NPV value 0, equation 8 may be expressed as equation 9. After using logarithm to lower exponent \( n \), equation 10 is obtained. PBT results are also represented in the same figure 28.
Equation 9. Finding PBT from NPV equation with discount factor

\[
\frac{(1 + i)^n - 1}{i \cdot (1 + i)^n} = \frac{I}{S} 
\]  

Equation 10. PBT equation

\[
n = \frac{-ln\left(1 - \frac{I}{S} \cdot i\right)}{ln(1 + i)}
\]

Figure 25. NPV and PBT results for case dryers 1´-5´. NPV performance in percentage of case 4´ performance.

NPV lines from figure 25 show two different behaviours. The slope in these lines show that dryers that use steam to dry bark such as cases 1´-3´ dryers, have a weaker performance than cases 4´ and 5´ dryers. The most powerful dryer, and the most energy intensive, is case 3´. This dryer performance is less than half the one from case 4´. Case 4´ perform is owed to only using hot water as heating source for drying; hot water is inexpensive and thus net saving in equation 5, 6 or 8 will grow larger than in the other cases. Case 5´ uses only hot water during winter, but it also uses steam during summer and thus,
its performance line is slightly flatter than the one from case 4’. Case 3’ shows steam energy for drying bark more than 16 % MC is very costly and its performance line starts decreasing. Case dryer 4´ performs the best and its product has approximately one third of moisture. Further study on how to recover energy from hot water or condensates could give grounds to a future investment as the dryer in case 4’. PBT for dryer case 4´ is 2.4 years whereas the worst performance at design values is 4 year from dryer case 3’.

7.3 Sensitivity analysis

Variations of three parameter prices are studied in this last part of this work. The aim is to find how a future investment of a conveyor dryer could perform when prices of energy, NG and fossil CO₂ emission allowance change. These price variations are studied for each of the five drying cases from chapter 6 are analysed here.

The analysis estimates that once the price of a parameter is changed, this remains constant until the end of the period analysed. The results from calculations while using basic prices are represented in figures 26 and 27 with continuous lines. These prices are increased and then diminished 20 % from the basic prices. The basic price for fossil emissions tax changes differently; minimum price for this is 0 € and maximum 20 € though for case 3’ also the value of 50 € is represented. Cases 1´ and 2´ are omitted to help reading the following figures 26 and 27.

It could be considered that when NG prices rise, so does steam prices. However, in the Imatra case, only a fraction of the steam energy is attributed to the energy released from the combustion of NG. Besides, if a dryer was used, consumption of NG in KK2 should diminish. For this reason, in sensitivity analysis, the increase on NG prices does not affect steam prices.
Figure 26. Sensitivity analysis with parameters “energy”, “NG”, or “CO₂ emission” prices. NPV values in percentage of case dryer 4’ with base prices.
Figure 27. Sensitivity analysis with parameters “energy”, “NG”, or “CO₂ emission” prices. PBT values.
Figures 26 and 27 show how NG price variations affect the most the economic performance of every drying case whereas cost of energy does it the least. Negative values of vertical axis in figure 26 were needed to allow visualization of what -20 % NG energy price would do to a case 3´ dryer. Also, in figure 27, PBT axis had to be modified to represent case 3´ values. On the other hand, if the energy became costlier, case 3´ dryer would perform better than case 4´ with basic prices. Once again, case 4´ dryer performed the best lowering its PBT below 2 years for 20 % pricier NG in figure 27.

When price of CO₂ emissions varies in figures 26 and 27, the changes are also noticeable. When the price of emission tax is 50 €/tCO₂, case 3´ dryer performs as well as case 4´ at its best. With base price for CO₂ emissions allowance, case 3´ gives a 4-year PBT whereas for 20 €/tCO₂ and 50 €/tCO₂, PBT are 3 year and less than 2 years respectively.

Energy price changes affect the most in the cases where steam energy is used as a heating source. Case 4´ performance will barely be affected since the energy it uses to operate is inexpensive. Investing in either case 5´ or in especial case 4´, could be less risky since they are less dependent on one of the three parameter this sensibility analysis studies. Case 5´ can always stop using steam if this is costly and will become as efficient as dryer 4´ except for the fact that the investment on this dryer is larger than for the one in case 4´.

NPV results of sensitivity analysis calculations can also be represented as in figures 28-32. Here, the performance value for each of the 3 changing parameters are shown in every one of these figures at their maximum design drying capacities. The design capacity is the reference point at center of the figures (0 %-0 %), which for example in case 1´ is bark drying until 35 % MC. Horizontal axis represents the rate of change in the price of the three parameters. In this case, +10 and -10% values are added to the figures. CO₂ allowance prices are the same as before, 0 €/tCO₂, 8 €/tCO₂, 20 €/tCO₂ and 50 €/tCO₂ and they are represented in values -10 %, 0 %, +10 % and +20 % respectively in figures 28-32 below. Rising NPV 100 % means that NPV value is double the one from basic scenario at design capacity.
Figure 28. Minimal drying capacity dryer. Lower investment cost. It mainly uses steam energy for drying bark.

Figure 29. Similar dryer than in case 3’ but less drying capacity dryer. It mainly uses steam energy for drying bark.
Figure 30. Maximum drying capacity dryer. It mainly uses steam energy for drying bark.

Figure 31. Minimum drying capacity dryer. It only uses hot water energy for drying bark.
From figures 28-32, it can also be seen how cases 4′ and 5′ are much less dependent on energy price change, even at their design capacities. NG price affects the most in case 3′ since it is the case where the most NG can be saved. For this reason, the rate of NPV change is the fastest for in this dryer. At the same time, cases with less potential to save NG also save less CO₂ emissions and so rate of change of NPV with this parameter is slower.

NG prices fluctuate rapidly (Eex 2019). Its price during the summer of 2012 was over 38 €/MWh and by the spring of 2016, the price halved. At the end of 2016, the price rose again until 25 €/MWh. Base price of NG is 27 €/MWh and here, calculation are made with +/-20 % price change which is 32.4 €/MWh and 21.6 €/MWh respectively. Price of CO₂ allowance has risen recently vigorously. If both prices would rise, any dryer could become a lucrative investment. However, the opposite might also be possible. An investment on a dryer should be decided carefully and further assessment on the potential behavior of the most affecting parameters could be needed.

**Figure 32.** Dryer that operates as case 3′ during summer and as case 4′ during winter.
8 SUMMARY

Combustion of only mechanically dried bark and sludge in biomass boiler KK2 at 75% of its design capacity, generates too large flue gas flows for the boiler equipment; also, the demand of combustion air at this point is greater than what the boiler fan system can provide. Perfect combustion calculations were made to find if drying biomass could allow KK2 to operate over 75% of its capacity. If biomass was dried until 38%, the boiler could operate at 90% load and will generate the same amount of flue gas as if operated at 75% load without drying biomass. However, when combustion air supply is the limitation, biomass will need to be dried until 10% moisture. This indicates that investing in KK2 combustion air system could be an asset for the operability of the boiler.

Additionally, when drying biomass, its LHV will increase, its combustion will maintain boiler temperature and KK2 will output more steam without having to use natural gas to support combustion. Consequently, the mill natural gas bill will diminish and so will the fossil CO2 emission which in turn will also save on emission allowance.

Economic calculations are made to find how feasible five possible conveyor dryers would be. Two groups are differentiated; hot water and steam energy usage for drying bark. In the drying case of only hot water energy usage, the dryer would perform the best whereas the dryers that use steam are negatively affected by steam prices. A sensitivity analysis is made to find how each dryer could perform under price variation of energy for drying, natural gas and CO2 allowance.

When a dryer only uses hot water for drying, its net present value is over double the one from the dryer that mainly uses steam to dry bark until 10% moisture content. Decreasing energy prices by 20% causes the performance from the steam energy dryer to increase NPV by 50%, but still below the first dryer. Changing natural gas prices in the same percentage that energy prices, affects substantially more the economic performance of any of the five drying cases. In especial, the one from the dryer that uses steam energy to dry bark until 10% since this increases bark LHV the most, therefore saving more natural gas to the mill than the other four dryers. However, its NPV value when natural gas increases 20% is 30% lower than the one from only hot water energy dryer. The last factor studied in sensitivity analysis is the price variation of emission allowances. These are also
to be considered since, recently, their price trend has noticeably risen. The more bark is
dried, the best performance for a dryer when emission allowance price increases.

All dryers are affected by the changes in prices of energy, natural gas and emission al-
lowance but in the case of the dryer that uses only hot water to dry bark, the first parameter
affects considerably less than in the other drying cases. This could be seen as an advantage
an inexpensive waste energy conveyor dryer could have over higher drying capacity and
high temperature energy source dryer. Of course, if it was known that natural gas and
emission allowance price would surely increase in the near future, a higher drying capac-
ity dryer could be a more lucrative option. However, the opposite might also happen.
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