LAPPEENRANTA–LAHTI UNIVERSITY OF TECHNOLOGY LUT
School of Energy Systems
Department of Environmental Technology
Sustainability Science and Solutions
Master’s thesis 2021

Petra Rissanen

INTENSIFICATION OF MECHANICAL PULP’S DRYING PROCESS AND ITS IMPACTS ON GREENHOUSE GAS EMISSIONS – CASE JOUTSENO

Examiners: Professor, D.Sc. Risto Soukka

Laboratory engineer, Lic.Sc. (Tech.) Simo Hammo

Instructor: Operations manager, M.Sc. (Tech.) Mika Nieminen

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems
Degree Programme in Environmental Technology
Sustainability Science and Solutions

Petra Rissanen

Intensification of mechanical pulp's drying process and its impacts on greenhouse gas emissions – case Joutseno

Master's thesis

2021

98 pages, 25 tables, 16 figures, 2 appendices

Examiners: Professor, D.Sc. Risto Soukka
Laboratory engineer, Lic.Sc. (Tech.) Simo Hammo
Supervisor: Operations manager, M.Sc. (Tech.) Mika Nieminen

Keywords: BCTMP, twin-roll press, greenhouse gas emissions, energy efficiency

This master's thesis was ordered by Metsä Board Joutseno. The goal was to assess the impacts which the new roll press would have on pulp's dry matter content, flash drying process' energy consumption and greenhouse gas emissions. In addition the most optimal operation model for the mechanical drying process was built. In the theory part of the thesis the production process, environmental impacts and important properties of mechanical pulp were gone through. In empirical part the case mill in Joutseno was presented and test drives and energy balance were used to analyse the functioning of the roll press.

As results of the test drives it was found out that the roll press managed to both improve the dry matter content of the pulp and to reduce the energy consumption in flash drying process. Annual consumption of natural gas reduces averagely 20 %. Total specific energy consumption of the flash drying process reduces about 17.8 % on the drying line 1 and 12.4 % on the drying line 2. In total natural gas consumption reduces about 3.28 million m^3 per year, which accounts for 6 608 tons CO_2-equivalent each year. It was also found out that the drying capacity of the roll press is at its highest when the production rate is between 500 – 550 ADt/d and the torque is at the same level or slightly higher, measured as Nm. The two twin-wire presses operate at their best when their production rate is around 250 – 275 ADt/d. Thus the total production rate would be 1 000 – 1 100 ADt/d, at which the dry matter content would be at its highest and the specific energy consumption of the flash drying decent.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
School of Energy Systems
Ympäristötekniikan koulutusohjelma
Sustainability Science and Solutions

Petra Rissanen

Mekaanisen massan kuivausprosessin tehostaminen ja sen vaikutukset kasvihuonekaasupäästöihin – case Joutseno

Diplomityö

2021

98 sivua, 25 taulukkoa 16 kuvaa, 2 liitettä

Työn tarkastajat:	Professori, TkT Risto Soukka
	Laboratorioinsinööri, TkL Simo Hammo
Työn ohjaaja:	Käyttöpäällikkö, DI Mika Nieminen

Hakusanat: BCTMP, telapuristin, kasvihuonekaasupäästöt, energiatehokkuus

Tämän Metsä Board Joutsenon tilaaman diplomityön tavoitteena oli määritellä uuden telapuristimen vaikutukset massan kuiva-aineeseen, hiutalekuivauksen energiankulutukseen sekä maakaasun poltosta muodostuviin kasvihuonekaasupäästöihin. Lisäksi määriteltiin optimaalisin ajotapa mekaaniselle kuivausprosessille. Työn teoriaosassa käsiteltiin mekaanisen massan ominaisuuksia, tuotantoprosessia ja sen ympäristövaikutuksia. Kokeellinen osa alkoi Joutsenon tehtaan tuotantoprosessin läpikäymisellä, jonka jälkeen käytiin läpi koeajot ja energiatase sekä niiden avulla saadut tulokset.

Koeajojen ja energiataseiden avulla selvisi, että telapuristin vähentää maakaasun kulutusta noin 20 %. Kokonais-ominaisenergiankulutus tulee arvioiden mukaan vähenemään noin 17.8 % kuivauslinjalla 1 ja 12.4 % kuivauslinjalla 2. Kokonaisuudessaan maakaasun kulutus tulee vähenemään noin 3.28 miljoonaa m^3 vuodessa, mikä vastaa noin 6 608 hiilidioksidiekvivalenttitonnia. Koeajoista selvisi myös, että telapuristimen poistosakeus on korkeimmillaan kun sen tuotantovauhti on noin 500 – 550 ADt/d ja momentti samalla tasolla kunkin hetken tuotannon kanssa tai hieman korkeampi. Kaksi viirapuristinta puolestaan yltävät korkeimpaan kuiva-aineeseen kun niiden kuormitus on noin 250 – 275 ADt/d. Täten tehtaan kokonaistuotanto olisi välillä 1 000 – 1 100 ADt/d. Tällä tasolla massan kuiva-ainepitoisuus on korkeimmillaan hiutalekuivauksen energiankulutuksen pysyessä kohtuullisena.

ALKUSANAT

Haluan kiittää Metsä Board Joutsenoa mielenkiintoisesta ja sopivan haastavasta diplomityöaiheesta. Työn tekeminen opetti minulle paljon koeajojen järjestämiseen liittyvistä käytännöistä ja siitä, millainen prosessi uuden laitteiston käyttöönottaminen teollisessa ympäristössä voi olla. Erityiskiitokset kuuluvat Risto Soukalle ja Simo Hammolle työn ohjaamisesta ja tarkastamisesta, sekä Mika Niemiselle, joka ohjasi työtäni tehtaan puolesta.

Erityisen suuri kiitos kuuluu myös Kaisa Mutikaiselle sekä koko Joutsenon tehtaan porukalle, jonka apu koeajojen aikana ja yleinen kiinnostus diplomityötä ja sen etenemistä kohtaan oli korvaamatonta työn loppuun saattamiselle. Lisäksi haluan kiittää ystäviäni niin yliopistossa kuin sen ulkopuolella, poikaystävääni ja perhettäni tuesta niin lopputyön kuin koko yliopisto-opintojenkin aikana.

On ollut unohtumaton matka opiskella ympäristötekniikkaa juuri LUT-yliopistossa, missä opittu Skinnarilan Henki, uteliaisuus ja oppimisen halu jäävät varmasti osaksi minua myös opintojeni päätyttyä.

Lappeenrannassa 12. helmikuuta 2021

Petra Rissanen

TABLE OF CONTENTS

APPENDICES

LIST OF SYMBOLS

CSF	Canadian standard freeness	[ml]
h	enthalpy	[J/kg]
m	mass	[g]
p	pressure	[Pa]
Q	lower heating value	[J/m^3]
SEC	specific energy consumption	[Wh/t]
T	temperature	[°C], [K]
V	volume	[m^3]
v	incoming volume	[m^3/h]
w	consistency, dry matter content	[%]

Subscripts

0	before processing
1	after processing
dm	dry matter content
n	NTP conditions (Normal Temperature and Pressure)
ng	natural gas
rp	roll press
tw	twin-wire press

Abbreviations

ADt	Air-dry ton
BCTMP	Bleached chemi-thermomechanical pulp
CD	Conical disc refiner
CMP	Chemi-mechanical pulp
CO$_2$eq.	Carbon dioxide equivalent
COD	Chemical oxygen demand
CSF	Canadian standard freeness
CTMP	Chemi-thermomechanical pulp
DD	Double-disc refiner

DTPA	Diethylenetriaminepentaacetic acid
GDP	Gross domestic product
GHG	Greenhouse gas
GWP	Global warming potential
EDTA	Ethylenediaminetetraacetic acid
ETS	Emission trading system
HC	High consistency
M	Middle part of the twin-wire press
MC	Medium consistency
MS	Maintenance side of the twin-wire press
NECP	National energy and climate plan
OS	Operating side of the twin-wire press
PGW	Pressure groundwood pulp
RMP	Refiner mechanical pulp
SD	Single-disc refiner
SEC	Specific energy consumption
SGW	Stone groundwood pulp
TMP	Thermomechanical pulp

Chemical compounds

CO_2	Carbon dioxide
H_2O_2	Hydrogen peroxide
$NaHSO_3$	Sodium bisulfite
$NaOH$	Sodium hydroxide
Na_2SO_3	Sodium sulfite
$Na_2S_2O_4$	Sodium dithionite
OOH^-	Hydroxide ion

1 INTRODUCTION

Reducing the greenhouse gas emissions and increasing quantity of carbon sinks are the most important methods in mitigating the climate change. Carbon sink is a term used for any process or ecosystem, which bonds more carbon to itself than it releases to atmosphere. In Finland forests are the most important carbon sinks. (Lakanen 2011, 13.) Other carbon sinks are for example oceans, fossil fuels and soil (Ocean & Climate Platform). Being carbon neutral means that there is a balance between emitting carbon dioxide (CO_2) to atmosphere and storing it into carbon sinks (European Parliament 2019).

European Union has an ambitious goal of being carbon neutral by 2050 and on national level Finland desires to achieve the same goal already in 2035 (Finnish Government). This goal has raised conversation about how to achieve a balance between preserving and utilizing our forest reservoirs in a sustainable manner. An aspect which further increases the importance of this conversation is that about 75 % of the land area of Finland consists of forests. This has created optimal conditions for the growth of forest industry, which utilized approximately 63.7 million m^3 of wood in 2019. This corresponds about 87 % of the total felling amount. Despite of the large felling numbers, it is estimated that Finland’s forest reservoirs grow by 107 million m^3 annually, which exceeds the felling amounts by 30 %. (Natural Resources Institute Finland 2019; Ministry of Agriculture and Forestry of Finland.)

Large economic importance of the forest industry can also be concluded from the report of The Research Institute of the Finnish economy (2016, 3), which lists the 10 most important corporations in terms of their impacts on gross domestic product (GDP) in Finland. From these 10 corporations 3 are forest industry companies (UPM, Metsä Group and Stora Enso). In 2019 the sector of forest industry accounted for 19.2 % of Finland’s goods exports, which corresponds 12.5 billion euros (Finnish Forest Industries 2019). A large economical role of forest industry creates demand also for energy efficiency and sustainability.

1.1 Drivers for energy efficiency in forest industry

European Union has created plans and frameworks which aim to mitigating climate change and to keep global temperature rise below 2 °C, possibly even on 1.5 °C. Currently actions concentrate on EU’s climate and energy framework for 2030, which sets goals for greenhouse gas emission reductions, share of renewable energy and energy efficiency. (European Commission.) Previous goal of 40 % reduction in greenhouse gas emissions was criticized and more strict actions were demanded, so in December 2020 EU raised the emission reduction goal to 55 % compared to 1990 levels (Deutsche Welle 2020). At the same time EU started to form legislatives means for achieving the emission reduction target. To ensure that the member states commit to these goals, EU required every country to form their national energy and climate plans (NECPs) on how they’re going to achieve the targets. (European Commission 2020.)

In Finland’s NECP the theme of carbon neutrality is well presented in addition to the main goals corresponding to EU-level goals. These goals include reducing the GHG emissions by 39 % among the functions in emission trading system (ETS) until 2030, increasing renewable energy share of final energy consumption to 51 % and keeping final energy consumption under 290 TWh in order to ensure energy efficiency. In the NECP Finland has defined different energy and climate policies which aim for achieving the goals stated earlier. These policies are defined for the sectors of energy supply, industry, transport, residential and services, waste and agriculture. For industrial sector these policy measures include for example energy and carbon dioxide taxes, energy audit programme and energy efficiency agreements. (Ministry of Economic Affairs and Employment of Finland 2019, 17-18.)

Since Finland is one of the largest pulp and paper producers in the world (Fracaro et al. 2012, 3553) and forest industry is the largest industry and employer in Finland, its role in working on national climate goals cannot be ignored. In Finland forest industry’s share of electricity consumption was 23 % in 2017, which is more than double compared to other industries (Finnish Forest Industries 2018a). Even if majority of forest industry’s energy comes from renewables, it still gets approximately 14.6 % of its energy from fossil fuels, of which 6.1 % originates from natural gas (Finnish Forest Industries 2018b).

In addition to the above mentioned drivers for energy efficiency, the structural changes of forest industry can be seen as a motivator for more efficient pulp and paper production. Since new technologies are emerging and conquering the markets from traditional products like newspapers, it is clear that forest industry needs to be even more energy and cost efficient to remain competitive. In Finland efficiency demands create pressure especially on the area of South-Karelia, since there the forest industry is most dense and it is one of the biggest consumers of industrial energy (Statistics Finland 2018).

1.2 Metsä Group and Metsä Board Joutseno

Metsä Group is a global forest industry company which consists of 5 subsidiaries: Metsä Wood, Metsä Forest, Metsä Tissue, Metsä Board and Metsä Fibre. The parent company of Metsä Group is Metsäliitto Cooperative. (Metsä Group.) Main products and financial numbers of each subsidiaries are presented in the table 1 below.

Table 1. Financial numbers of Metsä Group's subsidiaries (Metsä Group 2019).

	Metsä Forest	Metsä Wood	Metsä Fibre	Metsä Board	Metsä Tissue
Product	Forest services	Wood products	Pulp and sawn timber	Board, pulp	Tissue, grease-proof papers
Sales [EUR billion]	2.0	0.4	2.2	1.9	1.0
Personnel	840	1 500	1 300	2 400	2 700

The numbers presented in the table 1 are from 2019. During 2020 the Corona-virus pandemic has had its impact on global economy, including the sector of forest industry. The biggest negative impact the pandemic has had on the demand of sawmill products, papers and furniture, while demand of pulp has remained relatively steady (Biotalous 2020).

In addition to the financial numbers, Metsä Group also transparently informs its stakeholders about their sustainability objectives. Among many other goals, Metsä Group wants for example to increase carbon intensity of forests and their products by 30 % from 2018 levels and to secure the biodiversity of forest environments. In addition Metsä Group aims to ensure that their factories are fossil free by 2030. (Metsä Group a.) This is done both by modernizing the existing factories and investing in new, fossil free ones. Two examples of large investments in Finland are a modern sawmill in Rauma and a bioproduct mill in Kemi, which will both be completely fossil free. (Metsä Group b.) One example of modernizing an existing factory, and the topic of this thesis, is the intensification of pulp's drying process at Metsä Board's mill in Joutseno.

Metsä Board Joutseno mill was established in 2001 and it produces bleached chemi-thermo-mechanical pulp (BCTMP) which is used as raw material in paperboard production at Metsä Board mills in Finland (Metsä Board). To improve energy efficiency and the dry matter content of the pulp, Metsä Board has decided to renew the drying process by installing a new twin-roll press dryer. The new dryer is a part of the mechanical drying phase with the two existing twin-wire press dryers. Second drying phase consists of flash drying which will be presented later in the report. The main goal of the investment is to increase the pulp's dry matter content after the mechanical drying phase and thus reduce the natural gas consumption in the flash drying phase.

1.3 Goal and scope of the study

This thesis is ordered by Metsä Board Joutseno for assessing the impacts of the new twin-roll press which is installed during the autumn 2020. The goal is to define how much the twin-roll press decreases pulp's moisture content, how much the usage of natural gas is reduced after the renewal and how much this reduces the greenhouse gas emissions in the flash drying phase. In addition the thesis aims to find the most optimal way to operate the renewed mechanical drying process so that the lowest possible moisture content can be achieved. Analysis of the twin-roll press' impacts on the process is done with the help of test drives and energy balances.

The thesis consists of theoretical and empirical part. In theoretical part the production process of BCTMP, its properties and energy efficiency of the production are gone through. Also the relevant concepts of empirical part, for example functioning of pulp's drying equipment and other relevant equipment are presented in the theoretical part of the thesis. In the empirical part the production process and its sub-processes at Joutseno mill are presented. After this the test drive plans for the drying process are gone through after which the analysis of the results is conducted. Empirical part will end to conclusions and summary of the report. The empirical part of the thesis focuses on the drying process of the pulp, and thus the energy efficiency of the other sub-processes is not reviewed in empirical part. Estimation of the emissions and their reduction includes only the emissions of burning the natural gas in the flash drying phase.

2 PRODUCTION PROCESS OF BCTMP

Pulp types can be divided roughly into two groups: chemical pulps and mechanical pulps. In chemical pulping processes the lignin is dissolved by cooking, whereas in mechanical pulping the aim is to preserve as much of lignin as possible and to separate the fibres by grinding or refining. Mechanical pulps can be further divided into subcategories depending on if heat or chemicals are used for softening the lignin. (Lönnberg 2009, 18; Seppälä et al. 2004, 57, 75.) In this thesis the focus is on mechanical pulp since it is the final product of the case mill. The abbreviations and descriptions of different mechanical pulp types are presented in the table 2 below.

Table 2. Different types of mechanical pulps (Seppälä et al. 2004, 57).

Abbreviation	Meaning	Description
RMP	Refiner mechanical pulp	No usage of heat or chemicals
TMP	Thermo-mechanical pulp	Preheating of wood chips, pressurized refining
CMP	Chemi-mechanical pulp	Chemical handling of wood chips before refining
CTMP	Chemi-thermomechanical pulp	Chemical handling of wood chips before refining in excess pressure
BCTMP	Bleached chemi-thermomechanical pulp	Bleaching of the pulp before the drying phase

Refiner mechanical pulp was the first type of mechanical pulps being produced. Nowadays production of RMP has been substituted with thermo-mechanical and chemi-mechanical pulps due to higher quality. Typical uses of TMP are newspapers, super calendered (SC) and light-weight coated (LWC) paper, whereas CTMP is mostly used in paperboard and tissue production. CTMP can be used also in SC and LWC papers to substitute some of the chemical pulp to achieve economical savings. (Seppälä et al. 2004, 57, 59.) In this chapter a general production process of BCTMP is described while the empirical part of the study will deal with it on a mill-level.

2.1 Chipping and chip handling

Before the actual production process the wood raw material has to be chipped. Requirements for chipping process differ slightly between chemical and mechanical pulping. For refining wood chips are smaller than for chemical pulping to make refining easier and more efficient. For mechanical pulping chips should also contain as little bark as possible since it deteriorates the quality of the pulp. Additionally the chips for mechanical pulping are usually preferred in slightly higher moisture content compared to chemical pulping. (Seppälä et al. 2004, 31.)

The purpose of chip handling is to prepare the raw material for refining and further processing. Usually chip handling consists of 3 or 4 sub-processes depending on the mill: presteaming, chip washing and dewatering, chip pre-heating and chemical impregnation. Presteaming is used especially in cold climates for de-icing the wood chips. The steam can be acquired for example from the refining process. With the help of pre-steaming it is easier to remove the impurities in the chip washing phase. Washing should be conducted as accurately as possible to remove contaminants like sand, stones and plastic to prevent damaging of refiners and other process equipment. (Lönnberg 2009, 179-180.)

Final phase before refining is preheating of the chips and impregnation of chemicals. The purpose of the preheating is to achieve even moisture content and optimal conditions for refining process. Usually chip preheating does not demand high temperatures, but it is possible to slightly modify pulp properties with preheating conditions. As a rule of thumb higher temperature leads to better strength properties and lower shive content, whereas slightly lower temperature promotes the optical properties. Achieved benefits should be optimized with the energy consumption of preheating. (Lönnberg 2009, 182.)

Chemical impregnation aims to improve the result of refining by leading to smaller shive content of the pulp. Due to raw material properties usage of hardwood species requires the chemical impregnation to be able to fulfil the quality requirements. Additionally the impregnation phase makes it easier to produce several different pulp grades at the same mill. Usable chemicals in impregnation are Na_2SO_3, caustic soda, NaOH and in some cases H_2O_2.

(Seppälä et al. 2004, 58-59.) Impregnation can be done either by mechanical compression of the chips and expansion in a sulphite solution or by steaming and soaking the chips in a cold sulphite solution. Other methods exist also but these two methods are found to be most effective. (Lönnberg 2009, 260-261.) After the impregnation the chips can be fed to the retention silo to enhance the impact of impregnation chemicals (Ek et al. (ed.) 2009, 78). The temperature of the impregnation varies between 120 – 135 °C and typical retention time is from 2 to 30 minutes. Impregnation conditions depend on the wood species which are being used. (Lönnberg 2009, 260-261.)

2.2 Refining

Refining is the production phase where the wood chips are processed into pulp by separating the fibres from each other (Seppälä et al. 2004, 60). Refining could be thought to correspond the cooking phase in chemical pulping, with the difference of utilizing mechanical forces instead of chemical treatment. Mechanical pulping is known to have higher yield compared to chemical pulping since lignin is preserved to larger quantity in refining (Kivistö & Vakkilainen 2014, 44, 69-70).

Refining is done with disc refiners, which can be roughly divided into single-disc (SD) refiners and double-disc (DD) refiners depending on if there is one or two rotary discs. Single-disc refiners are usually used in mills with smaller capacity, whereas double-disc refiners are suitable for larger production capacities due to a larger differential speed of two rotating discs. In addition to the chips also dilution water is fed into the refiners to ensure constant refiner consistency and thus pulp quality. (Lönnberg 2009, 186, 196, 199.) Another variation of disc refiner is a conical disc (CD) refiner, which consists of a flat inner zone and conical outer zone (Valmet).

Refining can be conducted either in one or two phases. Either way it is the most electricity intensive process phase in mechanical pulping. One property mitigating the energy intensity of the refining phase is that large amounts of steam can be recovered in the process. The steam is taken to heat recovery, from which it can be used for example in the drying phase of the pulp. (Kivistö & Vakkilainen 2014, 72, 97-98.)

2.3 Latency removal

When the wood chips are refined and fibres separated from each other, fibres tend to curl due to the process conditions and heavy mechanical forces which are applied during the process. This fibre curliness and deformation is often referred to as latency of the pulp. In addition to curling the fibres change in terms of surface and length properties. The latency needs to be removed after the refining process since curliness of the fibres increases the freeness of the pulp. In addition the strength properties of the pulp are affected by latency. (Gao 2014, 3, 6, 9.)

There are couple possible methods for the latency removal: hot-disintegration and beating, of which hot-disintegration is more commonly in use (Illikainen 2008, 23). In latency removal mechanical forces and heat are used to detangle and straighten the fibres. The process of latency removal is relatively simple. Usually it takes place in a latency chest, where the pulp is mixed in low consistency and in the temperature of 80 – 90 °C. Retention time of the latency chest is normally between 15 – 60 minutes. In the chest the pulp is mixed steadily in order to detangle and straighten the fibres. (Gao 2014, 8, 10.) After the latency removal the pulp proceeds forward in the production process.

2.4 Sorting and reject handling

After refining and latency removal the pulp is taken to the screening phase, which aims to remove as much impurities and too large particles as possible. Objects to be removed are usually shives or too large fibres, which are taken as reject to the reject handling process. The part of pulp which continues forward in the pulping process is called accept.

The screening technique which is commonly used in pulping processes is pressure screening, which utilizes the pressure difference across the mesh surface. Accept flows through the holes of the screener while reject stays on the other side. Result of the screening depends on several process parameters, like feeding pressure, pressure difference, production rate and consistency of the pulp. (Seppälä et al. 2004, 65.)

The process of reject handling consists of dewatering, reject refining and screening, after which the accept is directed to the production process and reject is removed from the process. Aim of the reject handling is to achieve as high yield of the pulping process as possible by minimizing the amount of the reject. Dewatering is usually done with bow screens, but also equipment like screw press, twin-roll or twin-wire presses can be used. Reject is refined with disc refiners as in wood chip refining and screening can be conducted for example with centrifugal cleaners. (Lönnberg 2009, 330-333; Seppälä et al. 2004, 66.)

2.5 Bleaching and washing

To improve the quality of the printed end product the pulp which is used for printing papers and packaging is often bleached. Purpose of the bleaching phase is to increase pulp's brightness, in other words to reduce its light-absorption and increase the light-scattering ability. Light-absorption ability describes the amount of coloured substances in the pulp, while the light-scattering ability can vary depending on the pulping method. Bleaching of mechanical pulp differs largely from bleaching of chemical pulp, since chemical pulp's bleaching aims to removing the residual lignin, while mechanical pulp's bleaching aims to transforming the colour-causing groups into non-coloured forms. (Lönnberg 2009, 362.)

2.5.1 Wood properties affecting the brightness

Brightness describes the share of blue light which is reflected from the surface of the paper or pulp and it is usually presented in the unit of % ISO (Sappi North America 2017, 1). The standard providing guidelines for brightness measures is SFS-ISO 2470. The standard defines the brightness as a ratio between the reflected radiation and the radiation reflected by the perfect reflecting diffuser in the same conditions (SFS ISO 2470:2003, 5). In mechanical pulping the brightness of the pulp is mainly determined by the wood species which are used as raw material. In wood species colour is mainly caused by lignin, whereas cellulose and hemicellulose are colourless compounds. Small part of the colouring is also caused by extractives. (Lönnberg 2009, 362, 364.) Differences in composition of pine (softwood) and birch (hardwood) are presented in the table 3 below.

Table 3. Typical composition of pine and birch (modified from Vanninen 2009, 6).

	Pine	Birch
Cellulose	40 %	40 %
Hemicellulose	25 – 30 %	30 – 35 %
Lignin	25 – 30 %	20 – 25 %
Extractives	< 5 %	< 5 %

As it can be seen from the table 3, there are no big differences between the two wood species. Largest differences occur in lignin and hemicellulose contents, of which lignin content is an important factor in the bleaching process. Even if there seems not to be large difference between the compositions of pine and birch, the initial brightness of the wood material might vary largely depending on the wood species. Initial brightness of the wood material can vary from 40 % ISO to even 70 % ISO. Storage time reduces the brightness of the wood material so it is important to store wood for as short time as possible. (Lönnberg 2009, 363, 365.)

2.5.2 Methods for bleaching

There are two main methods for bleaching mechanical pulps, peroxide and dithionate bleaching, of which the former one is more commonly in use. The bleaching chemical used in peroxide bleaching is hydrogen peroxide (H_2O_2) and the method relies on the formation of perhydroxyl anion (OOH^-). To ensure the proper functioning of hydrogen peroxide, the bleaching process has to be conducted in alkaline conditions, pH being between 10.5 – 11.5. Other process parameters which affect the bleaching efficiency are the dosage of peroxide, temperature, pH, consistency, retention time and the amount of transition metal ions, which originate from wood material and process water. Transition metals like iron, manganese and copper slow down the bleaching process by increasing the rate of peroxide decomposition and increase the COD (chemical oxygen demand) of the process waters. To minimize this impact the pulp is often treated with substances called chelating agents, like EDTA (ethylenediaminetetraacetic acid) or DTPA (diethylenetriaminepenta-acetic acid). These substances release the metal ions from the pulp so that they can be removed in dewatering phases. (Lönnberg 2009, 367-370, 375-376.)

The above mentioned bleaching parameters vary largely between mills depending on raw materials which are utilized, but some general trends exist. Peroxide dose is the process parameter which has the largest impact on the bleaching process, since 1 % change in the dosage can lead to a 6 – 8 % ISO change in the pulp brightness. Peroxide dose also affects the need of washing after the bleaching stage. Similar connection is observed between the pulp consistency and bleaching result; the higher the pulp consistency is, the more efficient is the bleaching process in terms of the retention time and final brightness. Typical pulp consistency in bleaching stage is between 30 – 35 % and it is mainly limited by emerging challenges in mixing procedure. (Lönnberg 2009, 368, 375-376.)

Temperature and retention time of the bleaching are highly dependent on the mill and process design but both have a positive correlation with bleaching efficiency. Temperature of the bleaching stage normally varies between 70 – 80 °C, even higher if water circulation is efficient enough and chemical doses high. Retention time is dependent on the peroxide dose and temperature; the higher the dosage and the temperature, the shorter the retention time. Typically retention time is varying between two and four hours. (Lönnberg 2009, 376.)

There are three different kinds of bleaching systems which can be used at pulp mill: single-stage medium-consistency (MC) bleaching, high-consistency (HC) bleaching and medium- and high-consistency bleaching (MC-HC). Of these the two latter ones have substituted single-stage medium-consistency bleaching. High-consistency bleaching is conducted in consistency of 30 – 40 %, which is achieved with dewatering equipment before the bleaching tower. To achieve as high brightness as possible, BCTMP mills usually utilize MC-HC bleaching in their production processes. (Lönnberg 2009, 377-380.) A simplified example of an MC-HC bleaching process configuration is presented in the figure 1 below.

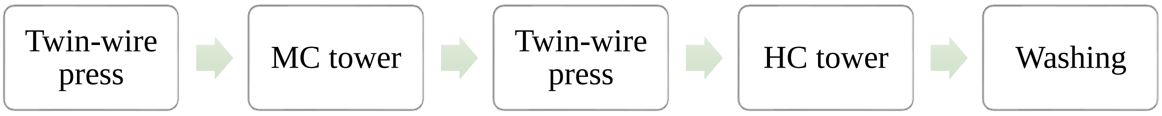


Figure 1. A simplified flowchart of MC-HC bleaching a mechanical pulp (modified from Ek et al. (ed.) 2009, 275).

The bleaching process described in the figure 1 starts with a twin-wire press, which dewaters the pulp for medium-consistency bleaching. Between the bleaching towers the pulp is dewatered again for the high-consistency bleaching. From the HC-bleaching tower the pulp is taken to the washing process.

Another method for bleaching the mechanical pulp is dithionite (sodium hydrosulphite, $Na_2S_2O_4$) bleaching. It is common that mills which utilize this technology produce the bleaching chemical on the mill site. In dithionite bleaching several different bleaching reactions occur, and it requires avoiding the contact between air and pulp to prevent oxidation. There is less knowledge about chemical reactions which occur between dithionite and lignin chromophores compared to the knowledge about peroxide bleaching. However, it is known that mainly the same process parameters affect the dithionite bleaching as peroxide bleaching, even if the process conditions differ largely between the two methods. In dithionite bleaching the optimal pH level is clearly lower compared to peroxide bleaching, being between 4.5 – 6.5. Also temperature is slightly lower because high temperatures make the optimal pH area more narrow. As a benefit compared to peroxide bleaching dithionite bleaching can have a retention time of only 30 – 60 minutes, even 10 minutes depending on the desired brightness level. (Lönnberg 2009, 381-385.)

After the bleaching process a washing phase is essential to remove the residual peroxide and other chemicals from the pulp so that they won’t end up to the final product. Washing is usually conducted in several phases to ensure sufficient purity of the pulp. In practise the washing phase can be implemented so that the pulp is first diluted with water and then dewatered for example with screw or wire presses. (Regional State Administrative Agency of Southern Finland 229/2017/1, 8.)

2.6 Drying and baling

In the mechanical pulp mill the drying process is not necessary if the mill is integrated with a paper factory since the pulp is taken straight to a paper machine. However, in non-integrated mills drying is done to save in transportation costs and to prevent the deterioration of product quality due to moisture. Mechanical pulp is generally dried in two phases: first in mechanical dewatering phase and then in thermal drying phase. (Seppälä et al. 2004, 138, 142.)

Dewatering is often done with twin-wire presses, which can dry the pulp up to 50 % dry-matter content. The main components of a twin-wire press are the wire section and the press section. In wire section pulp's own weight and suction is utilized when removing the water from the product, and in press section water is removed by pressing the pulp between two cylinders. (Kivistö & Vakkilainen 2014, 62.) Structure and functioning of twin-wire press is described more accurately in the chapter 3.

After the mechanical dewatering the pulp is taken to the second drying phase. For the drying there are two methods available, air-borne drying and flash drying, of which flash drying is more commonly in use. In flash drying the pulp is dried with the help of hot gases and normally the drying is done in two or more phases. After the drying the pulp's dry matter content is around 80 - 85 %. The final phase of the production process is baling, where slab presses form tight bales of the pulp. (Lönnberg 2009, 263-264.) The baling line consists of the bale press, wrapper, labelling and tying machine. Usually one bale weighs around 200 kilograms. Baling line groups the bales so that they can be stored and transported to the customers as the units of 12 – 16 bales. (Seppälä et al. 2004, 143.)

3 EQUIPMENT DESCRIPTIONS OF PULP’S DRYING PROCESS

In this chapter more accurate operation principles of the most relevant equipment of the pulp’s drying process are gone through. These equipment are twin-wire press, twin-roll press, flash drying equipment and screw conveyors. These are the equipment which are applied in the pulp’s drying process at the case mill which is why knowing their operation principles is essential for the empirical part of the report.

3.1 Twin-wire press

There are several types of wire presses available for dewatering purposes, of which a twin-wire press is viewed here. First part of the machine is a headbox, which spreads the pulp evenly on the wide wire. One benefit of a twin-wire press is that it can handle wide range of feed consistencies varying from a low consistency of 2 – 6 % to medium consistency of up to 12 %. After a headbox there’s a wedge zone, where the filtrate passes through the wires. A consistency of 12 – 15 % can be achieved at this phase. Third phase of a twin-wire press utilizes pressure in further dewatering, reaching a consistency of 20 – 25 %. In this section the wires are wrapped around the rolls and the pressure is dependent on the roll diameter and wire tension. The final stage of the machine is the press section, in which the final consistency of 50 % is achieved with the help of 1 – 5 nips which press the water out of the pulp. (Lönnberg 2009, 333-334.)

Some of the benefits of a twin-wire press in addition to wide consistency range are for example low specific energy consumption, high throughput (up to 500 t/d), reliable operation and low filtrate load (Andritz; Kilpeläinen 2000, 18). With high production rates wearing and breaking of wires can result in higher maintenance costs. Additionally one drawback is that the outlet consistency of a twin-wire press can be a bit unsteady.

3.2 Roll press

A roll press, or in other words twin-roll press, is a device which has multiple purposes in industrial units. This is because of its high capacity, relatively small size, high automation level and stable production. In pulp industry twin-roll press can be used for example in bleaching, washing and drying of the pulp. (Zhang et al. 2018, 1.) The focus of this chapter is on drying purposes because the roll press installed at the case mill will be used for drying the pulp. A simplified structure of a roll press is shown in the figure 2 below.

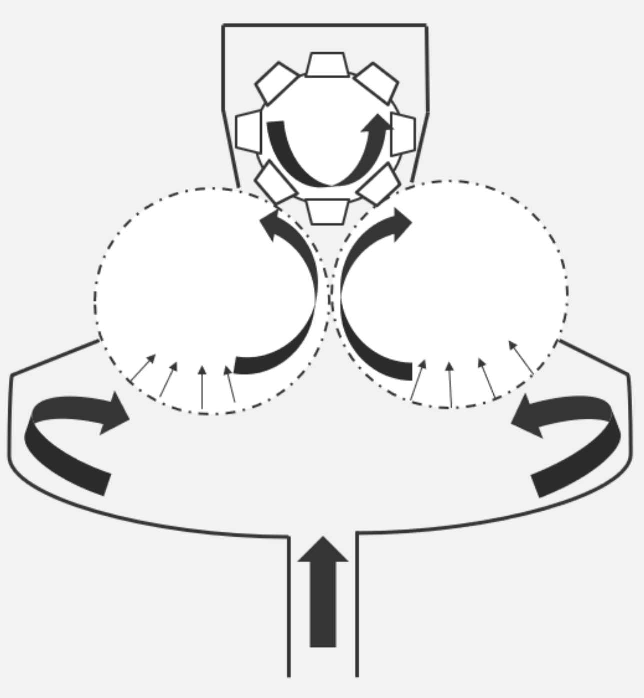


Figure 2. Simplified structure of a twin-roll press (modified from CNBM International).

The figure 2 above shows the main components of a roll press which are two rollers, the vat where the pulp is fed and the screw conveyor which delivers the pulp out of the press. Black arrows in the figure 2 describe the flowing of the pulp and rolling directions of the rollers and the screw conveyor. From the rollers one is stationary laterally and another one is movable so that the size of the nip (nip clearance) can be modified if needed. Pulp is fed to a roll press in a consistency of about 10 % and it is dewatered when passing through the nip between the rollers. (Zhang et al. 2017, 2.) The water passes through the surface of the rollers which has small holes in it and thus the water is removed from the pulp suspension. Dimensions of a roll press depend largely on the intended purpose and the demands created by the process. Most important dimensions are radius of the rolls, size of the nip clearance and height of the vat below the rollers. (Paterson 2020, 90.)

The drying efficiency of a roll press is dependent on several process parameters, like freeness, flow rate, feed consistency and temperature of the pulp and pressure of the vat. Usually target outlet consistency is around 35 – 45 %. (Lönnberg 2009, 331-332.) The roll press at Joutseno mill is designed to achieve even 50 % consistency. Probably with higher feed consistency even higher output consistency could be achieved, but feed consistency is limited by the possible clogging of the feed pipes. Lower consistency also ensures smooth proceeding of the pulp in the machine. Additionally also the nip clearance has an impact on the drying capacity since the smaller the gap between the rollers is, with larger pressure the pulp is pressed and thus more water is removed.

3.3 Flash drying

The main components of a flash drying process are fluffer, drying tower and cyclone separator. The process starts from the fluffer, which shreds the pulp into small flakes. After this the pulp is fed to the dryer, where it is dried with the help of hot gases. Normally a flash dryer consists of two sets of drying towers separated with a cyclone separator. In the first phase the drying gas is usually heated with natural gas or oil, whereas in the second phase circulated process steam is used either on its own or with other energy sources. Drying process itself happens in the drying towers, while in the cyclone separators the pulp and hot gases are separated from each other. (Lönnberg 2009, 263.) A simplified flow chart of a flash dryer is shown in the figure 3 below.

Figure 3. A simplified flowchart of a flash drying process (modified from Mujumdar (ed.) 2015, 793).

The figure 3 does not show the flows of exhaust air, natural gas, process steam and glycol. The exhaust air which contains the evaporated water and greenhouse gases of natural gas combustion is taken to exhaust air cleaners. At the case mill the heating energy of the process steam and glycol is utilized with the help of heat exchanger in the drying phase two, whereas the natural gas burners are available in both drying phases for the case if more drying energy is needed.

The flash drying technology is favoured especially in chemi-mechanical pulps' drying processes because its investment and operating costs are generally lower than for air-borne drying technology. Additionally the flash drying is quick, since the temperatures of the gases are between 150 – 400 °C so evaporation of moisture occurs in seconds. On top of that also high dry matter content of about 82 % can be achieved with flash drying. (Lönnberg 2009, 264.) In addition flash drying process is relatively easy to operate. However, flash drying technology also has some disadvantages, for example risk of fire and high efficiency requirements of flue gas cleaning system. (Mujumdar (ed.) 2015, 382.) The flash drying process at the Joutseno mill consists of two identical flash drying lines, drying line 1 and drying line 2.

3.4 Screw conveyors

Optimal operation manner of the drying process at the case mill is tightly dependent on the operating manners of screw conveyors, which is why knowing the operation principle of the conveyors is essential. Simply described it can be said that screw conveyors transfer volume, which means that with each cycle of the screw a constant volume of the material is conveyed. Thus the capacity of a screw conveyor can be calculated. For example one calculation method takes into account the outside diameter of the screw and the pipe (enclosure), the pitch of the screw and the through loading. Usually these calculations are done by the conveyor manufacturers and delivered with the conveyor device. (Cai & Meng 2010, 37-38.)

Screw conveyor is a long-known technology which is still widely used in industry due to its simple structure and good operability. Size of a screw conveyor can be modified according to the demands so it's suitable for various environments and applications. Other benefits of screw conveyors are safety and low need of maintenance and replacement parts. (Leino 2018, 16.) The two most common types of screw conveyors are the tubular and the U-shaped conveyors, which differ to some extent in terms of usability. The U-shaped conveyor is more usable with low inclinations and low fill ratio, whereas tubular conveyor can handle more elevation and larger fill ratio. (Roberts 2015, 62.)

Even if the structure and operating principle of screw conveyors might seem simple, there are many factors which affect the conveying effectiveness. These factors include for example inclination, rotational speed and fullness of the screw. (Roberts 2015, 63-64.) Ignoring the importance of conveyor design and above-mentioned factors can lead to problems like unsteady flow rates, degradation of the product, high equipment wear or excessive power consumption (Cai & Meng 2010, 37). Operational parameters and their impacts have been modelled in several different manners in literature. In his article Roberts (2015, 63) suggests that conveyor efficiency, in other words throughput, depends for example on a "braking effect", which is caused by the casting friction. This reduces the unwanted vortex motion of the material and thus increases the conveying efficiency. Vortex motion and its impact is also reduced by increasing the rotational speed of the screw. However, this has a limiting value, after which the efficiency is reduced.

4 IMPORTANT PROPERTIES OF MECHANICAL PULP

In mechanical pulping process the wood raw material has one of the largest impacts on pulp properties during the production process (Lönnberg 2009, 70). In this chapter the most important wood and fibre properties influencing the mechanical pulp production are gone through. In addition some pulp properties and their impacts on process controllability are reviewed.

4.1 Wood and fibre characteristics

Estimating the impacts of single wood characteristics is difficult since the influences on pulping process are interrelated. However some of the most important wood properties are considered to be wood basic density, moisture content, fibre properties, chemical composition and amount of impurities. (Lönnberg 2009, 70-71.) Wood properties are affected by several factors, for example geographical growing location, growing pace, tree species and age of the tree. Also different parts of the wood can have different properties, for example inner part of the wood, in other words juvenile wood, is known to have shorter fibres and lower density than other parts of the tree. (Hartler 1986, 1-2; Hietanen 2007, 14-15, 17.)

Wood species is one of the major sources of variation in wood and thus also on pulp properties. Generally wood raw material used in pulping is divided into softwood and hardwood. Hardwood species are for example birch, eucalyptus and poplar, whereas pines and spruces are softwood species. Based on the quality properties Norway Spruce would be the most favoured material for mechanical pulping, since its fibre properties and initial brightness are optimal and it has low extractives content. However, lack of spruce has led to preferring pine as a raw material especially in Nordic countries. Compared to softwoods, hardwoods generally have smaller quantities of lignin and weaker strength properties. These drawbacks are minimized with chemical pre-treatment before the refining process. (Lönnberg 2009, 78-80, 82.)

The most relevant fibre properties which affect the pulping process are fibre length, cross sectional dimensions and share of juvenile wood (Lönnberg 2009, 460). Differences between juvenile wood and mature wood can be explained with the changes in the structure of the tracheids, which are bonded together by middle lamellae. Juvenile wood is formed during the first 5 – 20 years of the tree’s lifetime, during which the transportation of water and nutrients is in important role. This is why tracheids of juvenile wood have a low wall thickness. Wall thickness of the fibres of mature wood is higher, because after the first growing years supporting the trunk becomes more important. When it comes to refining it has been shown that refining juvenile wood demands more energy than refining mature wood to the same freeness level. (Reme 2000, 22-24.)

In addition to the age of the tree also growing pace has an impact on fibre properties. Fast growing pace results in higher lignin content and earlywood proportion than a slow growing pace. Trees which have grown slowly have fibres with thinner walls and contain more heartwood than quickly-grown trees. Terms earlywood and latewood refer to if the wood material is formed in the beginning of the growing season or in the end of the growing season. It has been found out that earlywood has more thin-walled fibres whereas fibres of latewood are thick-walled. (Lönnberg 2009, 458.)

So it has been shown that proportions of juvenile wood and mature wood and heartwood and sapwood have an influence on refining process, which on the other hand has an impact on the rest of the pulping process. The relationships between the different factors are complex which is why there is only little information about how these factors affect the production process of mechanical pulp. However, it has been found out that the share of different fibre types and fines content have an impact for example on how much pulp’s dewatering demands energy. (Lönnberg 2009, 467-468, 471.) For example increase in fine content also increases the dewatering resistance of the pulp, which means that it demands more energy to remove the water. When talking about different fine types it is claimed that secondary fines are the biggest reason for more difficult dewatering of the pulp. Secondary fines are the ones formed in the refining process. (Lamminen 2020, 45, 54, 56.)

4.2 Pulp properties

Several pulp properties can be monitored while producing the pulp. These pulp properties are for example freeness, shive content, density, tensile and tear index, fibre length and extractive content. (Lönnberg 2009, 276.) The most common ones which have also a limit value to maintain required pulp quality are freeness and shives content. Additionally properties like brightness and pH are often monitored as pulp quality factors. Limit values are determined according to the end use of the pulp.

Freeness is used to describe the drainability of the pulp. A common measuring method for freeness is Canadian Standard Freeness (CSF), which presents freeness value as millilitres. In addition to drainability also many other pulp properties can be estimated based on freeness value, for example fine content, degree of refining and specific surface area of the fibres. (Elahimehr 2014, 10, 11.) Limit values for freeness are set depending on the paper type for which the pulp is used. Freeness is generally lowest for LWC and newsprint grades and highest for tissue and board grades. (Lönnberg 2009, 276.)

Other important quality properties of mechanical pulp are shives content (%), brightness and pH. Shives content is kept as low as possible since it has negative influence on paper smoothness and printability. As with freeness, also brightness limit values depend on the end use of the pulp. For example board packaging demands high brightness to ensure good printing properties.

Above mentioned properties do not have an impact only on pulp quality and end use, some of them have an impact also on pulp production process and its operability. It is estimated that at least pulp’s freeness has an impact on dewatering processes. The higher the freeness is, the easier it is to dewater the pulp. (El idrissi et al. 2019, 303, 308.) In addition it has been noticed that properties like pH and temperature have an impact on pulp’s drying process and its efficiency. The impact of these factors is also dependent on the technology which is utilized at a mill, which is why these factors should be examined on a mill-level. The impacts of freeness, temperature and pH on the pulp dewatering are also reviewed in this thesis when investigating the functioning of the twin-roll press.

5 ENERGY AND ENVIRONMENTAL ASPECTS OF BCTMP

Globally the share of mechanical pulp of the total wood pulp production is about 25 % (Houtman & Tapas 2004, 1). In Finland the production of mechanical pulp has been slightly decreasing while the production of chemical pulp has been increasing. In 2019 about 3.3 million tons of mechanical pulp and 8.3 million tons of chemical pulp were produced in Finland. (Finnish Forest Industries 2020.) In general the demand of pulp can be predicted to be growing or remaining on the same level in the future since new ways of utilizing paper board are being invented all the time. This functions as an incentive for forest industry companies to increase their environmental friendliness and energy efficiency since customers are being more and more aware of the environmental impacts of their consumption habits.

In this chapter the energy and environmental aspects of forest industry and mechanical pulp production are reviewed. Also some common means for increasing energy efficiency are presented. It should be noted that both energy consumption numbers and environmental impacts of the industry depend largely on the mill’s geographical location and technology which is utilized. This is why only common trends and approximations can be presented in this chapter.

5.1 Energy efficiency of mechanical pulping

Globally the pulp and paper sector is the 4th largest energy consumer in industrial sector with the consumption of 6 900 PJ in 2007 (Kivistö & Vakkilainen 2014, 86). In mechanical pulp production the electricity consumption is more dominant, whereas in chemical pulping the heat consumption forms the major part of the total consumption (Kähkönen 2019, 66, 68). In mechanical pulping refining is the most electricity-intensive process phase, and mechanical pulp’s specific energy consumption (SEC) has increased lately due to higher quality requirements of the product. The pulp property which is the most important measure of quality is freeness, the lower the freeness target is the more the wood has to be refined. (Kivistö & Vakkilainen 2014, 97.)

In her Master's thesis Kähkönen (2019, 66) researched the energy efficiency of forest industry in Finland and found out that electricity consumption of two BCTMP reference mills was about 2,8 MWh/t, while heat consumption was well below 1 MWh/t. Creating converging trends of pulp mills' energy consumption and efficiency is difficult since it is strongly dependent on the process, pulp grades which are produced, utilized technology and geographical location. However some possible means for increasing the energy efficiency of mechanical pulping can be presented.

Since refining is the largest energy consumer in mechanical pulping, it is also the most researched topic when it comes to energy efficiency improvements. Several studies about chemical and mechanical pre-treatment of wood chips and their impact on refineries' electricity consumption have been done during the latest decades. Sandberg et al. (2017) review in their article some methods for increasing energy efficiency of mechanical pulping and their impact on energy consumption. One of the main findings of the review was that optimising the mechanical forces (refining intensity) with the process conditions like temperature and chemical environment is an important factor in mechanical pulping. In addition they reviewed chip pre-treatment methods like laser and separate processes for defibration and fibrillation. These methods however are not in commercial usage due to either losses in pulp quality or too high capital investments (Sandberg et al. 2017, 615, 619.)

One of the most common ways of reducing the energy consumption of refining is to increase refining intensity. This reduces the retention time and thus lowers the specific energy consumption. In addition to refining intensity also wood raw material has an influence on energy consumption of the refining phase. For example spruce is known to have lower energy demand than pine. In addition properties like chips' moisture content and type of fibres affect the energy demand of refining. For example latewood fibres demand more energy to achieve the same freeness than earlywood fibres and corewood demands more energy than slabwood. (Laitinen 2011, 10, 17, 19.)

Even if refining has been in the centre of researches, also other process stages and their development have been studied. For example for screening phase there are several opportunities which could possibly increase energy efficiency of the process. Some examples of these are combination of screens and hydro-cyclones and interstage screening process, in which screening is done already in primary refining. Even if these methods are complicated and have higher investment costs, they are reported to have a capacity to reduce energy consumption by 10 – 20 %. (Sandberg et al. 2019, 9.)

Changes in process structures or equipment are not the only ways of increasing energy efficiency of mechanical pulping. Also reducing maintenance breaks or improving energy conservation are parts of energy efficiency while they decrease specific energy consumption and down-time of the mill. Even factors like personnel operating the process have an impact on specific energy consumption. This is why the personnel should be educated to operate the mill in the most efficient, but at the same time feasible manner. Another way to pay attention to energy efficiency is energy auditing, which consists of gathering the energy consumption information of the process, defining the most important factors of energy consumption and proposing the most feasible energy conservation methods. (Kivistö & Vakkilainen 2014, 139-140.)

5.2 Environmental impacts of mechanical pulping

As said earlier, forest industry has an important role not only economically but also as an energy producer in Finland. About 70 % of Finland’s renewable energy is produced in forest industry units. In addition to biomass, other important energy sources for forest industry are nuclear power and hydro power, which ensure that energy is available around the clock during all times of the year. Due to an important economical role, large investments in forest industry’s energy efficiency have been made in Finland: in 2000’s over one billion euros have been invested for energy efficiency and bioenergy. This has reduced CO_2 emissions with 40 % per ton of product. (Finnish Forest Industries 2017, 2-3.)

In Finland environmental friendliness is considered well among forest industry operations. Generally emissions during normal operation are controlled well, whereas emissions of special situations like maintenance breaks, production interruptions or equipment breaks are controlled more weakly (Ikonen 2012, 48). So called disturbance emissions can cause problems for example in wastewater treatment plant operations since changes in emissions are difficult to predict. These sudden emission changes should be avoided by preventing surprising disturbance situations. This is done for example with risk assessment and stable control of production process. (Ukkonen 2005, 10, 13.)

Globally the environmental impacts of forest industry vary largely depending on the region and technology. In their study Mingxing et al. (2018) researched environmental impacts of pulp and paper industry in terms of global warming potential (GWP), acidification potential (AP) and eutrophication potential (EP). According to the study production of 1 ton of paper results in about 951 kg CO_2eq. Of this the energy consumption was the most dominant factor, of which pulp making process was responsible for about 62 %. In their study Mingxing et al. (2018, 6) studied also the average emissions of different pulp types and found out that chemi-mechanical pulp was responsible for 512 kg CO_2eq./t, which is slightly higher than Kraft pulp's emissions.

Generally emissions from mechanical pulping are clearly lower compared to emissions from chemical pulping (Ikonen 2012, 47). Gaseous emissions of mechanical pulping are mainly caused by fossil fuel incineration in pulp's drying phase. In addition volatile organic compounds (VOC) originating from wood's extractives and polymers cause emissions in mechanical pulping. (Kallioinen et al. 2003, 21-22.) VOC emission reduction is essential since they decompose NO_2 into NO and O_2 resulting in ozone formation. VOC concentration is dependent on the wood species which are used in the production process. (Lönnberg 2009, 445.) Volatile organic compounds can be removed from exhaust gases for example with biofiltration.

In general technology and production methods have been developing quickly over the last years among the forest industry sectors: flue gas cleaning systems have developed and water circulation of the mills are nearly closed. In Finnish forest industry even 95 % of wood raw material is utilized, 65 % of wastewater sludges is utilized as energy and 30 % of ashes from energy production is used for example in fertilizing. (Seppälä et al. 2004, 169.) By intensifying the sub-processes of the industry the material and energy efficiency can still be improved.

6 CASE MILL PROCESS DESCRIPTION

Metsä Board’s unit in Joutseno locates in South-East Finland by the lake Saimaa. The mill is a part of an industrial integrate in which locates also a mill of Metsä Fibre which produces chemical pulp. (Regional State Administrative Agency of Southern Finland 229/2017/1, 3.) The mills are co-operating in terms of energy and material. In this chapter the manufacturing process of the Joutseno BCTMP mill will be described. First the process phases will be outlined and then the focus is directed to the drying process and its energy balance.

6.1 General process description

As raw material Metsä Board Joutseno utilizes both softwood and hardwood and it produces three different pulp grades, HWE, HWSW and HYPER. Since there is only one production line, there is circulation between the pulp grades so that each one is produced from one to few weeks at a time. The production process at the mill consists of the following main processes: wood and chip handling, impregnation, refining, sorting and reject handling, bleaching, washing and drying and baling. (Regional State Administrative Agency of Southern Finland 229/2017/1, 6-8.) These sub-processes will be gone through next.

In practice the production process at the mill begins with chip handling, because debarking, chipping and screening is done by the mill of Metsä Fibre. Chip material is sorted according to the wood species and is taken to the storage silos on the mill site. From the storage silos the chips are taken to another silo where the material is preheated with steam. Then the chips are washed and the washing water is separated in a screw press. After dewatering the chips are prepared for impregnation by heating, pressing and swelling. Impregnation is done in impregnator screws and reaction silos. Utilized chemicals are oxidized caustic soda, NaOH, $NaHSO_3$ and EDTA. (Regional State Administrative Agency of Southern Finland 229/2017/1, 7.)

At the Joutseno mill refining is conducted as one-phased pressurized refining. Steam which is formed in refining process is taken to heat recovery, purified and then utilized in chip preheating and evaporation in the wastewater treatment process. After the refining the pulp is taken to latency removal, where EDTA is added to the pulp suspension. After the latency removal shives and other unwanted components are removed in pressurized mesh screening which has several screening phases. Reject is taken to the reject handling and accept is taken to the dewatering, which is done with bow screens. In reject handling the reject is refined and screened. (Regional State Administrative Agency of Southern Finland 229/2017/1, 7-8.) If needed, the reject is further screened in centrifugal cleaners, which remove sand and other heavy particles from the pulp. Pulp share which is accepted from the reject handling is returned to the production process in which the next phase is bleaching.

The bleaching method used at the mill is two-phased MC-HC bleaching and the chemicals which are used are hydrogen peroxide, NaOH and stabilators. Bleaching is conducted in MC and HC bleaching towers, after which the pulp is washed several times in screw and wire presses. From the bleaching the pulp is taken to the bleached pulp silo, from where it is directed for drying and baling. (Regional State Administrative Agency of Southern Finland 229/2017/1, 8.) Drying process and its energy balance are described more accurately in the following sub-chapter.

6.2 Drying process and its energy balance

In this chapter the drying process of the Joutseno mill and it’s energy balance components are gone through. Both old and new configurations of the drying process are first presented after which the energy balance components, its goals and scale are viewed. Further analysis of the energy balance and its initial values are gone through later in the report because the results of test drives are needed for composing the energy balance.

6.2.1 Development of the drying process

At the case mill the drying phase of the pulp consists of two drying lines which, before the roll press installation, were identical in terms of equipment. First there is a mechanical drying phase which before the renewal consisted of two twin-wire presses. After the mechanical drying the pulp is taken to the flash drying phase, which utilizes natural gas, process steam and glycol in heating the drying air. The final dry-matter content of the pulp has usually been around 84 – 85 %. (Regional State Administrative Agency of Southern Finland 229/2017/1, 8.) The process chart of the initial drying process is described in the figure 4 below.

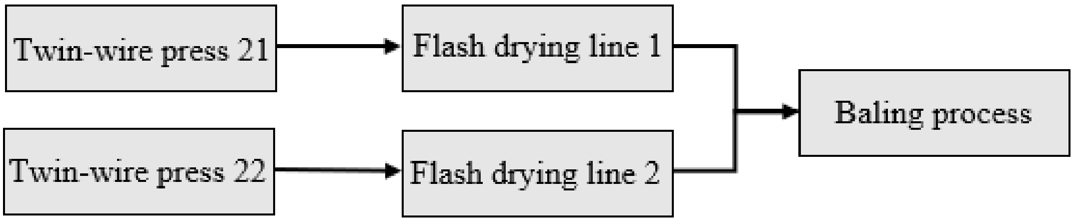


Figure 4. Flow chart of the old drying process

As shown in the figure 4, in the initial configuration of the drying process twin-wire press 21 fed the pulp to the flash drying line 1 and twin-wire press 22 to the flash drying line 2. Installing the roll press changed the drying process so that the drying lines aren't completely separated anymore. The configuration of the present drying process is described in the figure 5 below.

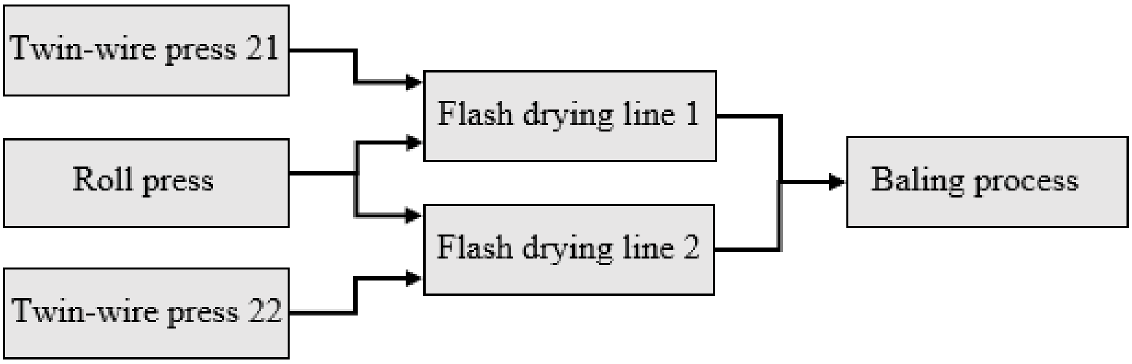


Figure 5. Flow chart of the renewed drying process

As it can be seen from the figure 5, the pulp from the roll press is divided between the two flash drying lines. Dividing the pulp between the drying lines is done with screw conveyors so that first a screw conveyor takes part of the pulp to the flash drying line 1 and then the rest of the pulp is taken to the flash drying line 2. It is possible to direct the excess pulp to the pulper but in normal process conditions all of the roll press' outlet flow is taken to the flash drying process. In energy balance calculations it is also assumed that pulp flow from the roll press divides equally between the drying lines.

6.2.2 Goal and scope of the energy balance calculations

For the flash drying lines 1 and 2 the energy balance is composed in order to estimate the energy consumption after the installation of the roll press. The purpose is to find answers for how much natural gas is consumed per ton of pulp and how much it causes emissions. One goal is also to find out how much the roll press reduces natural gas consumption in the flash drying process. Energy balances are built based on DNA View process tracking software and the dry matter content results of the first test drive presented in the chapter 8. System boundaries of the energy balance are set so that only the flash drying process is included. Change in energy consumption is analysed based on the results of the first test drive but energy balance is used as an analysis tool also for the results of the second test drive.

When composing energy balances it is assumed that lower heating value of natural gas is 36.4 MJ/m^3 and the emission factor is 55.3 g$_{CO2}$/MJ (Statistics Finland 2020). In calculations it is assumed that there are no material losses in the flash drying process. This means that the pulp flows entering the process and leaving the process are equal. The energy balance components for the flash drying lines are shown in the figure 6 below.

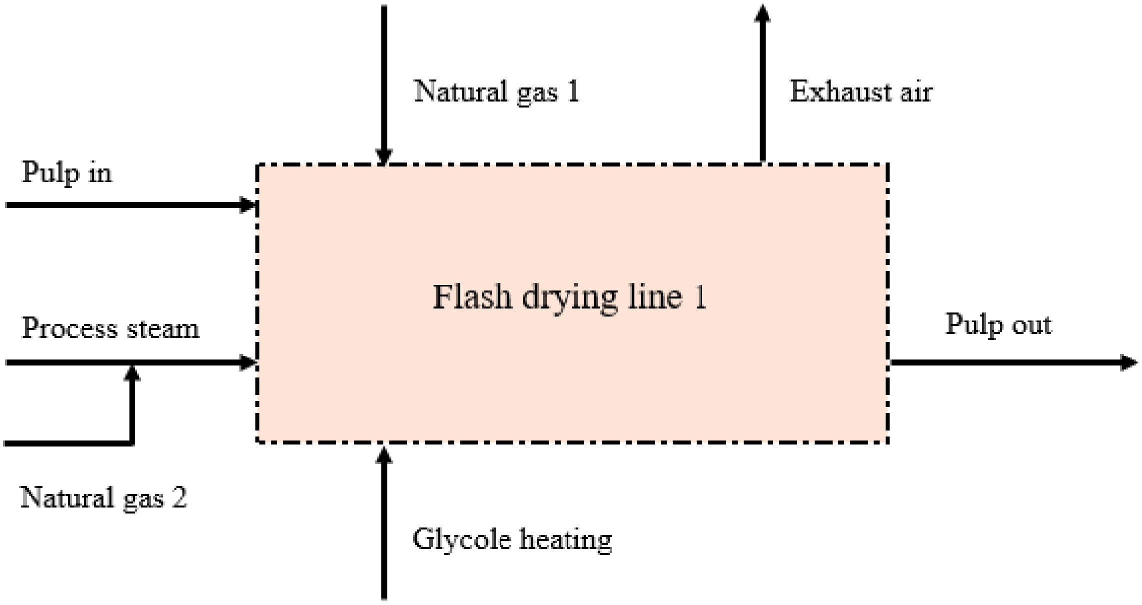


Figure 6. Energy balance components of the flash drying process

The flow chart of the flash drying process consists mainly of pulp, process steam, natural gas and exhaust air flows as shown in the figure 6 above. Both flash drying lines have two drying phases which heat up the drying air, first phase consumes only natural gas (component named “Natural gas 1” in the flow chart) and second phase utilizes either both natural gas and heat gained from process steam (components “Process steam 2” and “Natural gas 2”) or only process steam if that much drying energy is not needed. Additionally the second heating phase utilizes heat obtained from glycol when heating the drying air. During the whole test drives the drying process was set so that in both drying lines natural gas was utilized only in the first drying phase.

In reality the exhaust air is removed from three spots in the flash drying process but in the energy balances this is simplified by combining the flows into one component. Additionally the heat energy leaving the process within exhaust air is so small it can be assumed to be negligible. In terms of components the flow chart of the flash drying line 2 is identical with the drying line 1, but differences in pulp mass flow, natural gas, glycol and process steam consumption occur. This is why the specific energy consumptions differ between the drying lines.

The goal of the installation of the roll press is to reduce the natural gas consumption, in other words make components “Natural gas 1” and “Natural gas 2” smaller. In addition a purpose is to raise the dry matter content before the flash drying process. In the flowchart described in the figure 6 this means that amount of water would be smaller in the incoming pulp flow. Achieving these two goals would lead to decreased specific energy consumption. Analysis about if these goals were achieved and changes in energy balances will be presented in the chapter 9.

7 TEST DRIVES

Two larger test drives and one smaller test drive are organized at Joutseno mill to be able to analyse functioning of the roll press and whole mechanical drying process. In this chapter the test drive plans and practices concerning the sample collection and analysing are gone through. The first test drive is organized during stable production rates to find out what is an impact of the twin-roll press on pulp's dry matter content after the mechanical drying phase. Another test drive is done on different production rates to find out the most optimal production rate in terms of dry matter content and energy consumption of the flash drying. In addition to the two bigger test drives the impact of the torque of the roll press is analysed with few samples. Purpose of these samples is to find out how the torque affects the drying capacity of the roll press. Indented application of the torque sampling is gone through within the second test drive plan in the end of the chapter 7.2.

7.1 Test drive for stable production

The purpose of the first test drive is to find out how large impact the roll press has on pulp's dry matter content after the mechanical drying process. In addition to the dry matter content also steam and natural gas consumptions are examined with the help of energy balances. From each pulp grade two sample series are taken so that each series is taken on different day. This way the impacts of occasional variations in pulp properties can be minimized.

Results of the test drive are compared to the dry matter content statistics before the intensification of the drying process to see how the dry matter content has changed. Two reference days for each test drive days are picked for the comparison. In addition, to be able to estimate the emission reduction, the energy consumption of the flash drying process before and after the roll press installation is estimated. The test drive results and energy balance are utilized when calculating the energy consumption after the installation. To analyse the change in energy consumption the energy consumption statistics of the reference days are gathered from the DNA View software. Energy consumption calculations are gone through in more detail in the chapter 9.

7.1.1 Sampling locations

In the first test drive there are five locations where the samples are taken: after the bleached pulp silo before the mechanical drying process, after the roll-press, after both twin-wire presses and after the flash drying phase from the baling line. This way the initial dry matter content and the dry matter content after each drying equipment can be evaluated. The locations of the sampling points and their notations are visualized in the figure 7 below.

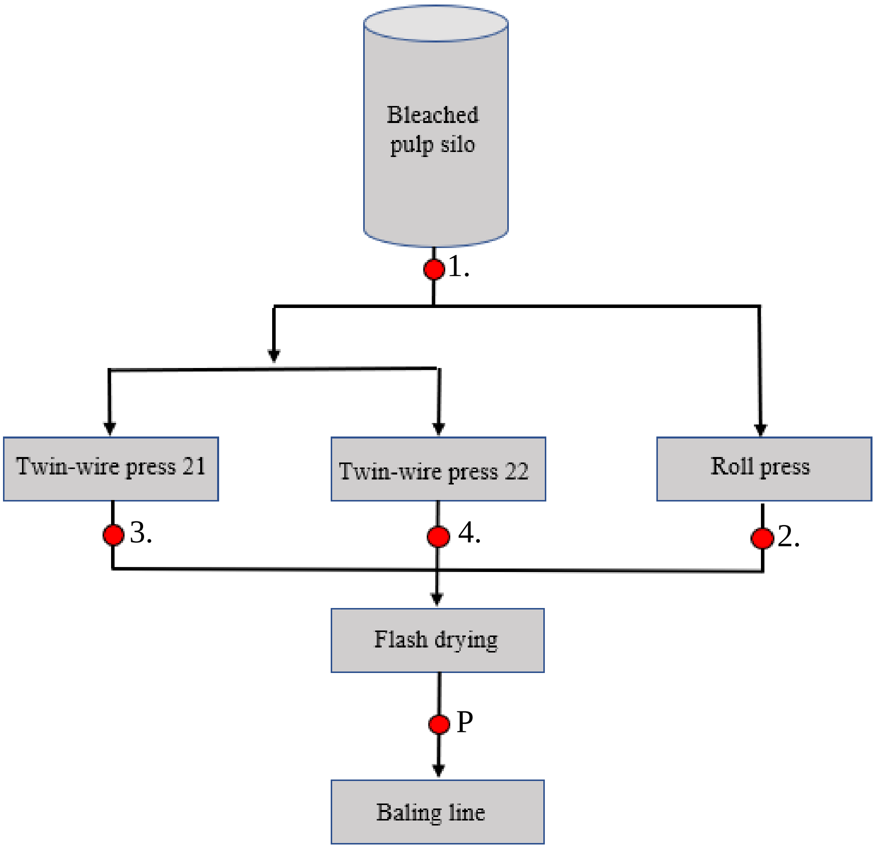


Figure 7. Sampling points of the first test drive and their notations

In the figure 7 the sampling points are marked with red dots. From both of the twin-wire presses three samples are taken in each sample series due to the width of the machines. The dry matter content of the pulp varies depending on if the sample is taken from the middle of the wire or from the edge of it, so by calculating the average of the three samples the overall dry matter content can be estimated. The exact sampling points are difficult to define because the wire moves slightly laterally all the time. This is why approximate sampling points are evaluated and marked so that the outermost samples are not taken too close from the edge and the centremost sample is taken from the middle of the wire. The sampling points of the twin-wire presses are marked to the fences of the machines before the test drive to ensure that samples are taken from the same spots every time. From the baling line two samples are taken in each sample series, one sample from the drying line 1 and one sample from the drying line 2. This way the differences in dry matter content between the two drying lines can be analysed.

7.1.2 Sample names and practises

The pulp samples from the bleached pulp silo and the roll press are taken into the buckets with closable lids, whereas the samples from twin-wire presses and baling line are taken into closable minigrip bags. Closing the sample containers properly is important to prevent the moisture evaporating from the product before analysing. Evaporation of the moisture is also the reason why the dry matter content samples need to be analysed as soon as possible after the sampling.

When a sample is taken, it is named according to the pulp grade, sample series number and sampling point. For example sample name HWE 2.5 means that sample is taken during the EXTRA pulp grade production, from the sampling point 2 and in the sample series 5. As shown in the figure 7, sampling point 2 indicates the roll press sample. The bale samples are marked with the letter P and numbers, for example sample name HWE P-2.1 means that the sample is taken in the second sample series from the drying line number 1. To clarify the naming of the samples, the names for the samples of the series 1 and 2 are presented in the table 4 below.

Table 4. Sample names of the sample series 1 and 2

	Sample series 1	Sample series 2
Bleached pulp silo	HWSW 1.1	HWSW 1.2
Roll press	HWSW 2.1	HWSW 2.2
Twin-wire press 21	HWSW 3.1 OS	HWSW 3.2 OS
	HWSW 3.1 M	HWSW 3.2 M
	HWSW 3.1 MS	HWSW 3.2 MS
Twin-wire press 22	HWSW 4.1 OS	HWSW 4.2 OS
	HWSW 4.1 M	HWSW 4.2 M
	HWSW 4.1 MS	HWSW 4.2 MS
Baling line	HWSW P-1.1	HWSW P-2.1
	HWSW P-1.2	HWSW P-2.2

In the table 4 above the letters OS, M and MS in the sample names refer to the sample locations of the twin-wire presses meaning operating side, middle and maintenance side respectively. As it can be seen from the table 4, one sample series consists of 10 samples in total. Since there are 6 sample series in the first test drive, it results in 60 samples.

In addition to the sample name also the time of the sampling (day and time of the day) is written down. This way process parameters can be reviewed afterwards with the help of DNA View software. For example the torque of the roll press is checked afterwards to analyse if it has an impact on the dry matter content results. For the samples taken from the baling line also the drying line from which the sample is taken is marked. The sample information and results of the laboratory analyses are marked into sampling tables.

7.1.3 Analysing

The centre of the focus in the first test drive is the dry matter content and this is why it is analysed from every sample. For the samples taken from the twin-wire presses standard SFS-EN ISO 638 is applied when determining the dry matter content. The twin-wire press samples are weighed as soon as possible after the sampling because moisture evaporates quickly from the hot pulp samples. Wet weights are written down after which the samples are put into the oven. The minimal drying time of the sample depends on the grammage of the sample, being at least 30 minutes for the grammage below 200 g/m^2 and at least 60 minutes for the grammage over 200 g/m^2. (SFS-EN ISO 638:2008, 2.) Recommended drying time for the pulp samples is at least 4 hours. At Joutseno mill the samples have been dried over a night because the drying oven has no removal valves for the evaporated water so it takes more time to ensure that the samples are completely dry. After drying the samples are reweighed after which the dry matter content can be calculated with the following equation. (SFS-EN ISO 638:2008, 2-3.)

$$w_{dm} = \frac{m_1}{m_0} * 100 \tag{1}$$

w_{dm} = dry matter content [%]
m_1 = mass of the test piece after drying [g]
m_0 = mass of the test piece before drying [g]

The method described in the standard ISO 638 is not applicable for pulps which are still mostly liquids, which means that samples before the drying process need to be analysed with different methods. Determining the consistency of the bleached pulp silo samples is started by weighing approximately 200 – 300 grams of sample to a carafe. The result is written down and marked with the letter A in the consistency equation described below. Next the sample is diluted so that the final weight is between 1 000 – 1 500 grams and this weight is marked with the letter B. Now the sample is mixed well and own sample of 200 – 300 grams is separated from it. The weight of this sample is marked with the letter C. This sample is filtered with a Büchner-funnel through a weighed filtering paper (D). After filtration the sample is dried at least for 5 minutes. Weight of the dry sample is marked with the letter E. After this procedure the consistency can be calculated with a following equation.

$$X = \frac{100*(E-D)*B}{A*C} \tag{2}$$

X = dry matter content [%]
A = thick sample [g]
B = thick sample + dilution water [g]

C = dilution which is to be filtered [g]
D = dry filtering paper [g]
E = filtering paper + filtered pulp [g]

The dry matter content of the roll press and bale samples is determined with quick dryers. Approximately 2 – 3 grams of the sample is dosed into the dryer. Dryer calculates the dry matter content while drying the sample and finishes when the dry matter content does not change anymore. Depending on the moisture content of the sample drying takes time from 3 to 15 minutes. Concerning its consistency the roll press samples could be dried with an oven method, but because the oven utilises circulated air flow the light roll press sample would spread all around the oven. This is why the analysis is easier to conduct with quick dryers even if using two different methods slightly increases the uncertainty of the results. The bale samples are traditionally dried with quick dryers since they are so dry (around 84 %) that margin of error is smaller.

In addition to dry-matter content also freeness and pH are analysed from the samples taken from the bleached pulp silo. This way their possible impact on the roll press' drying efficiency can be evaluated. Shortly explained the freeness is measured so that the diluted and hot-disintegrated pulp sample is filtered through a fibre mat into a funnel, which has two holes: one in the bottom and one on the side of it. The dilution flowing through the side hole is gathered to a dish and measured in millilitres, which is how the freeness of the pulp is achieved in the unit of millilitres.

7.2 Test drive for different production rates and torques

In the second test drive the goal is to find the most optimal production rate in terms of the roll press drying capacity and the energy consumption of the flash drying process. Also the most optimal production rate for the twin-wire presses is determined. Samples of the test drive are taken from the sampling points 1, 2, 3 and 4 described in the figure 7.

The samples are taken with two roll press nip clearances, 5 mm and 4 mm to see if it affects the drying capacity. It is predicted that when the nip clearance is smaller, the drying capacity gets higher since water is removed with larger pressing forces. Right after the roll press installation it was operated with the nip clearance of 7 mm, but with this nip clearance the dry matter content was low, which is why nip clearance was reduced to 5 mm. Purpose of changing the nip clearance to 4 mm in the middle of the test drive is to see if further narrowing can still improve the drying capacity. In addition to the nip clearance also two different feed consistencies are applied, 10 % and 11 % to see how it affects the drying capacity. Most of the samples are taken on the feed consistency of 11 % since it is more commonly applied during normal production.

The range of production rates of the roll press tested in the test drive is from 350 ADt/d to 650 ADt/d and production is increased by 50 ADt/d between the samples. The goal is to maintain total production at the same level all the time. Production rate is normally close to 1 050 ADt/d so this was chosen also for the test drive. This means that the production of the both twin-wire presses varies between 200 ADt/d and 350 ADt/d. As opposite to the first test drive, in this test drive the twin-wire press samples are taken only from the middle of the wire since the change in dry matter content can be assumed to be equal on the edges. In addition the twin-wire press samples are dried with quick dryer instead of the drying oven due to the lack of time and drying capacity. The capacity of the drying oven is 6 samples at a time, and while there are 7 twin-wire press samples per sample series in the second test drive, all of the samples could not be dried in the oven. This is why it was decided to use a quick dryer in the second test drive. However this increases the uncertainty when comparing the twin-wire press results of the two test drives together.

If possible, the regular bale samples are utilized to analyse the changes in the final product's dry matter content, but if needed some additional bale samples are collected during the test drive. An example of the sample numbers of the feed consistency of 11 % and their production rates are described in the table 5 below.

Table 5. Sample numbers and process parameters with the feed consistency of 11 %

		Roll press	Twin-wire presses 21 and 22
Sample number	Feed consistency	Production rate [ADt/d]	Production rate [ADt/d]
1	11 %	350	350
2	11 %	400	325
3	11 %	450	300
4	11 %	500	275
5	11 %	550	250
6	11 %	600	225
7	11 %	650	200

The samples described in the table 5 are taken on both nip clearances of the roll press, 5 mm and 4 mm. The twin-wire press samples are divided so that twin-wire press 21 samples are taken when the nip is 5 mm and twin-wire press 22 samples when the nip is 4 mm. This is done because the nip clearance of the roll press has no impact on the twin-wire presses. This practice also reduces the number of samples during one test drive day. The sampling points of 10 % feed consistency are shown in the table 6 below.

Table 6. Sample numbers and production rates with the feed consistency of 10 %

		Roll press	Twin-wire press 21
Sample number	Feed consistency	Production rate [ADt/d]	Production rate [ADt/d]
1	10 %	450	300
2	10 %	500	275
3	10 %	550	250
4	10 %	600	225

The production rates for the 10 % feed consistency were chosen from the middle of the production rate range because these are the rates which are most commonly applied in normal production of the mill. In addition to the dry matter content also the torque of the roll press is monitored. Additionally pH and freeness are analysed from the feed of the roll press to see if they have an impact on the drying efficiency.

In addition to different production rates also the impact of different torque levels of the roll press is under examination. It is analysed by taking roll press samples on four different torques, 450, 500, 550 and 600 Nm. Production rate of the roll press is maintained on the same level during the sampling so that it doesn't have an impact on the results. During this test drive the feed consistency is around 11 %, as it is during the normal production. From the samples only the dry matter content is analysed according to the table 7 below.

Table 7. Samples for analysing the impact of the roll press' torque on the drying capacity

Production rate [ADt/d]	Torque of the roll press [Nm]	Dry matter content [%]
500	450	
500	500	
500	550	
500	600	

A hypothesis for the torque analysis is that the higher the torque is, the higher is the outlet consistency of the roll press. However the maximum torque is limited since too high torque might cause malfunctions and operational challenges. Too high torque might also cause breakage of the motors of the rolls.

8 TEST DRIVE RESULTS AND ANALYSIS

In this chapter the test drive results of the both test drives are gone through and analysed. Also sources of uncertainty, analysis methods and their possible impact on the results are reviewed. The analysis is started with the test drive of stable production which aimed to find out how large is the impact of the roll press on pulp's dry matter content after the mechanical drying phase and natural gas consumption of the flash drying process. The results concerning the dry matter content are analysed here but the changes in energy consumption are analysed later in the chapter 9.

8.1 Results of the first test drive

The first test drive consisted of 6 sample series so that each sample series was taken on different day. Sampling was scheduled so that the production of the mill was stable and no off-grade was being produced. Production rates during the sample series in the unit of ADt/d are shown in the table 8 below.

Table 8. Production rates during the sample series in the first test drive as [ADt/d]

	HWSW		HYPER		EXTRA	
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Roll press	579	577	553	575	546	530
Twin-wire press 21	240	218	247	263	238	266
Twin-wire press 22	235	212	235	272	253	312
Total	1 054	1 007	1 035	1 110	1 037	1 108

As it can be seen from the table 8 the production rates remained relatively steady between the sample series. Largest deviation is in the production rates of the twin-wire presses during the sample series 6, when the production rates were clearly higher. The production rates are needed later for estimating the drying line-specific production rates.

The most relevant results of the test drive concern the dry matter content after each drying machine. Also freeness and pH of the roll press feed flow were analysed and their possible impact on drying capacity is also reviewed while surveying the dry matter content results. The dry matter content results of the first test drive and the torque of the roll press are shown in the table 9 below.

Table 9. Dry matter content results of the first test drive as [%] and the torque of the roll press as [Nm]

	HWSW		HYPER		EXTRA	
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Drying process feed flow	10.42	10.68	11.28	10.58	9.59	9.71
Roll press outlet	48.71	50.09	48.80	48.79	49.34	48.12
Twin-wire press 21 outlet	48.73	48.73	49.77	48.99	50.25	45.59
Twin-wire press 22 outlet	46.70	45.91	47.40	45.23	48.34	45.99
Drying line 1 outlet	85.71	85.70	86.15	87.38	85.87	85.23
Drying line 2 outlet	85.56	84.92	86.19	86.31	85.43	86.48
Torque of the roll press [Nm]	540	548	500	529	510	537

Based on the results shown in the table 9 it seems that the drying capacity of the roll press is relatively stable within all of the pulp grades. The averages of the HYPER and EXTRA sample series are slightly lower compared to the average of the HWSW sample series (48.80 %, 48.73 % and 49.40 % respectively). During the test drive it was found out that pH and freeness don’t have significant impact on the roll press drying capacity. Their impact most probably is so small that it is covered by the impact of the production rate and the torque of the roll press. However according to the test drive lowering the pH of the pulp might improve the drying efficiency of the roll press but to confirm this more test drives should be conducted. Based on current results it can be concluded that the most important factors affecting the drying capacity are the production rates and the torque of the roll press.

When it comes to the drying capacity of the twin-wire presses, the dry matter content of the twin-wire press 21 remained relatively steady during the whole test drive. Only exception is the sample series 6 where the outlet consistency was lower but this might be caused by a higher production rate as shown in the table 8. Common trend during the test drive was that the outlet consistency of the twin-wire press 22 was lower compared to the twin-wire press

21. It was attempted to adjust the sampling point location and parameters of the twin-wire press but no significant improvement was achieved.

8.1.1 Analysis of the first test drive results

In this chapter the results of the first test drive and functioning of the mechanical drying process are analysed in terms of dry matter content. One goal of the roll press installation is to improve the dry matter content after the mechanical drying phase so this is the process phase where the dry matter content is analysed. Analysis is done by comparing the test drive results with the statistics before the roll press installation.

Differences in the dry matter content before the flash drying phase were analysed by comparing the flash drying feed consistencies after the roll press installation with the feed consistencies before the roll press installation. The feed consistencies before the roll press installation are received as an average of old twin-wire press outlet consistency statistics since then only the twin-wire presses fed the pulp to the flash drying lines as shown in the figure 4. Because twin-wire press samples during normal production are taken relatively seldom, the reference values of specific days could not be used. For each sample series two or three reference values were chosen so that the time of the year and the pulp grade which was being produced were similar with the test drive days. Then the average of the chosen reference values was calculated for each sample series. As described in the figure 5, after the roll press installation the feed consistency depends both on the roll press' and the twin-wire press' outlet consistencies. This means that the feed consistency after the roll press installation needs to be calculated based on the dry matter content results. Next the calculation procedure for the feed consistency of the flash drying after the roll press installation is gone through using the first sample series as an example.

The first step in defining the feed consistency is to define the production rate of mechanical drying machines. According to the table 8 the production rate of the roll press during the sample series 1 was about 579 ADt/d whereas the production rates of the twin-wire presses 21 and 22 were 240 ADt/d and 235 ADt/d respectively. It can be assumed that under normal process conditions all of the pulp from the roll press is taken to the flash drying process, and none is taken pass it to the pulper. In addition it is assumed that the pulp of the roll press divides equally between the two drying lines. This means that during the sample series 1 the roll press fed each drying line about 289.5 ADt/d. Now the total feed flow of each drying line can be calculated with the equation 3 below.

$$m_{tot,x} = m_{rp,x} + m_{tw,xx} \tag{3}$$

$m_{tot,x}$ = pulp feed to the drying line 1 or 2 [ADt/d]
$m_{rp,x}$ = roll press pulp flow going to a drying line [ADt/d]
$m_{tw,xx}$ = production rate of a twin-wire press 21 or 22 [ADt/d]

For example by inserting the roll press' feed flow to drying line 1 and the production rate of the twin-wire press 21 the total production rate of the drying line 1 is achieved as shown below.

$$m_{tot,1} = 289.5\frac{ADt}{d} + 240\frac{ADt}{t} = 529.5\frac{ADt}{d}$$

Similarly for the production rate of the drying line 2 is solved to be 524.5 ADt/d. The rest of the feed flows of the flash drying are calculated in the similar manner and are presented in the table 10 below.

Table 10. Feed flows of the drying lines 1 and 2 during the first test drive

Sample series	Drying line 1 feed flow [ADt/d]	Drying line 2 feed flow [ADt/d]
HWSW 1	529.5	524.5
HWSW 2	506.5	500.5
HYPER 3	523.5	511.5
HYPER 4	550.5	559.5
EXTRA 5	511.0	526.0
EXTRA 6	531.0	577.0

Now that the production rates are known the dry matter content of the feed flows can be estimated with the help of dry matter content results of each drying equipment. Dry matter contents for roll press, twin-wire press 21 and twin-wire press 22 during the first sample series can be received from the table 9 and they were 48.71 %, 48.73 % and 46.70 % respectively. The following equation was used for dry matter content calculation.

$$w_{dm,x} = \frac{(w_{dm,rp} * m_{rp,x}) + (w_{dm,tw} * m_{tw,xx})}{m_{rp,x} + m_{tw,xx}} \tag{4}$$

$w_{dm,x}$ = dry matter content of a drying line's feed flow [%]
$w_{dm,\,rp}$ = roll press outlet consistency [%]
$w_{dm,\,tw}$ = twin-wire press outlet consistency [%]

For example the consistency of the feed flow to flash drying line 1 was calculated in the following manner.

$$w_{dm,1} = \frac{\left(48.71\ \% * 289.5\,\frac{ADt}{d}\right) + \left(48.73\ \% * 240\,\frac{ADt}{d}\right)}{289.5\,\frac{ADt}{d} + 240\,\frac{ADt}{d}} \approx 48.72\ \%$$

Correspondingly the feed consistency of the drying line 2 was solved to be about 47.81 %. The rest of the feed consistency results are calculated in the same manner. The results are shown in the table 11 below with the reference values.

Table 11. Change in flash drying feed consistencies after the roll press installation

	After the roll press installation		Before the roll press installation	
Sample series	Line 1 feed consistency [%]	Line 2 feed consistency [%]	Line 1 feed consistency [%]	Line 2 feed consistency [%]
HWSW 1	48.72	47.81	46.65	46.73
HWSW 2	49.50	48.32	46.70	46.47
HYPER 3	49.26	48.16	46.22	46.72
HYPER 4	48.89	47.06	46.46	46.77
EXTRA 5	49.76	48.86	47.25	47.26
EXTRA 6	46.87	46.98	47.05	46.95

From the table 11 it can be seen that the dry matter content after the mechanical drying phase has improved within the roll press installation. This is mostly because with three mechanical drying machines instead of two, the twin-wire presses are able to operate with lower production rates. This enables more efficient water removal. Based on the comparison presented in the table 11 the dry matter content after the mechanical drying phase has improved averagely 1.60 percentage points. With HWSW and HYPER grades the improvement is averagely 1.95 and 1.80 percentage points respectively. With EXTRA grade there’s some improvement in sample series 5 but not in sample series 6. Based on the dry matter content results presented in the table 9 this is because of clearly lower outlet consistencies of the twin-wire presses. Correspondingly the lower outlet consistency is most probably caused by high production rates, as shown in the table 8. To confirm the change of dry matter content with EXTRA grade more sample series with lower twin-wire press production rates should be taken.

Another conclusion which can be made from the results presented in the table 11 is that during the test drive the feed consistency of the drying line 2 has been lower compared to the drying line 1. The difference varies from 0.9 to 1.9 percentage points. The most likely reason for this is the lower outlet consistency of the twin-wire press 22. However, the production rates of the twin-wire presses remained approximately on same levels. This would indicate that for some reason the drying capacity of the twin-wire press 22 is lower compared to the twin-wire press 21. It is suggested that reason for this is analysed by changing the operating parameters of the twin-wire press 22, for example by lowering the production rate or increasing the nip pressures, to see if it improves the dry matter content.

8.1.2 Sources of uncertainty in the first test drive

During the first test drive probably the largest sources of uncertainty are the analysis methods of the dry matter content. Using two different methods, oven-drying method and quick dryers creates uncertainty since there are differences in the accuracy. The difference between these analysing methods was tested by drying parts of the same sample in both equipment, and it was found out that quick dryer gave averagely 1.9 percentage points higher dry matter content results. The dry matter content result difference varied mainly between 0.8 and 2.1 percentage points but with some samples the difference was even higher. The reason for this might be for example if the oven sample is not weighed quickly enough after sampling, so that it has lost some of the moisture before weighing. This is one big source of uncertainty when analysing pulp samples with the oven method. Similarly if the sample which is to be dried with a quick dryer loses some moisture before it is applied into the dryer the result also changes.

Another source of uncertainty is that there are also small differences in the accuracy between the quick dryers. To make the test drive days and analysing procedures easier two different quick dryers were used for analysing, and depending on the weight of the samples and calibration of the dryers they sometimes gave divergent results for the same samples. The difference varied significantly from 0 percentage points to 2 percentage points which is why it was difficult to estimate which of the dryers was more accurate or how big an average difference was. This source of uncertainty was reduced in the second test drive by analysing the samples of a specific drying machine always with the same quick dryer.

Additionally one source of uncertainty is the way of action while taking the sample. There was always more than one person collecting the samples so that sampling could be conducted faster and because collecting the wire samples demands two persons. Thus there might have been differences in if the sampling dish was closed immediately after taking the sample, if the minigrip bags of the wire samples were closed properly and how big sample was being taken. It was attempted to make these sources of uncertainty more unlike by sending the test drive plans with sampling guidance to the operating personnel in advance before the test drive.

8.2 Results of the second test drive and torque analysis

The purpose of the second test drive was to find the most optimal operation model of the mechanical drying process in terms of dry matter content and energy consumption. The test drive took three days in November and December, two days for 5 mm nip clearance samples and one day for 4 mm nip clearance samples. Nip clearance defines the gap between the rollers of the roll press, and it was changed in the middle of the test drive to see how it affects the drying capacity. Samples were taken on two feed consistencies, 11 % and 10 %. Next the results are gone through starting from 11 % feed consistency and 5 mm nip clearance.

8.2.1 Results on the nip clearance of 5 mm

During the first test drive day there were challenges in the production process which had an impact on sampling procedures. This is why all of the twin-wire press 21 samples could not be collected. The roll press samples could however be collected normally. The results of the first roll press sample series are presented in the table 12 below.

Table 12. Roll press samples and energy consumption on drying line 1. Nip clearance 5 mm and feed consistency 11 %.

Production rate [ADt/d]	Outlet consistency [%]	Torque of the roll press [Nm]	Natural gas SEC [MWh/ADt]	Total SEC [MWh/ADt]
350	53.92	550	0.589	0.706
400	53.04	539	0.480	0.602
450	50.72	544	0.512	0.619
500	49.98	549	0.457	0.561
550	51.67	544	0.422	0.553
600	49.94	561	0.408	0.510
650	49.59	569	0.395	0.514

From the results presented in the table 12 it can be seen that production rate clearly has an impact on the drying capacity of the roll press. With lower production rates even dry matter content of 54 % can be achieved, whereas after the production rate of 500 ADt/d the dry matter content falls to 50 %. The torque of the roll press remained high during the whole test drive which also improved the outlet consistency. The results of the first sample series are mainly very logical and well in line with expectations. Only the result on the production rate of 550 ADt/d clearly differs from the trend in dry matter content results. Exceptionally high dry matter content result most probably is due to the margin of error of the quick dryer or the delay in analysing the sample. Based on earlier experiences and other test drive results it could be assumed that in reality the dry matter content with that production rate has been around 49.96 %, which is an average of the two adjacent samples.

For the twin-wire press 21 the test drive results were not as consistent as for the roll press partly due to the challenges in the production process. It also seemed like the production rate didn’t have as strong impact on the drying capacity as with the roll press. The test drive results for the twin-wire press 21 are presented in the table 13 below.

Table 13. Outlet consistency of the twin-wire press 21. Feed consistency 11 %.

Production rate [ADt/d]	Outlet consistency [%]
350	-
325	-
300	52.78
275	53.11
250	52.92
225	-
200	52.71

Based on the results presented in the table 13, the twin-wire press performed relatively well during the test drive in terms of dry matter content. It should however be noted that the dry matter content is analysed with different method compared to the first test drive. This is why comparing the results of the two test drives is difficult

Due to the lack of samples from the twin-wire press 21 no conclusion can be made about how the production rate affects the drying capacity. Based on earlier perceptions and experiences it could however be assumed that the drying capacity reduces with higher production rates. During the first test drive day also using two different quick dryers created uncertainty of the results. Since the quick dryers are different models, they might give different dry matter content results and thus increase the uncertainty. This was fixed for the other test drive days by using the same quick dryer for the samples of each drying machine. All roll press samples were dried with the same quick dryer and the twin-wire press samples with the another quick dryer.

The energy consumption numbers for the first test drive day presented in the table 12 were calculated with the help of the energy balances utilising the outlet consistencies of the roll press and the twin-wire press 21 presented in the tables 12 and 13 respectively. At this point only the energy consumption of the drying line 1 was analysed because the outlet consistency of the twin-wire press 22 was not analysed so the drying line 2 feed consistency isn't known accurately. Correspondingly when analysing the functioning of the roll press and the twin-wire press 22, the energy consumption of the drying line 2 is calculated. The relation of the outlet consistency of the roll press and energy consumption of the flash drying is described in the figure 8 below.

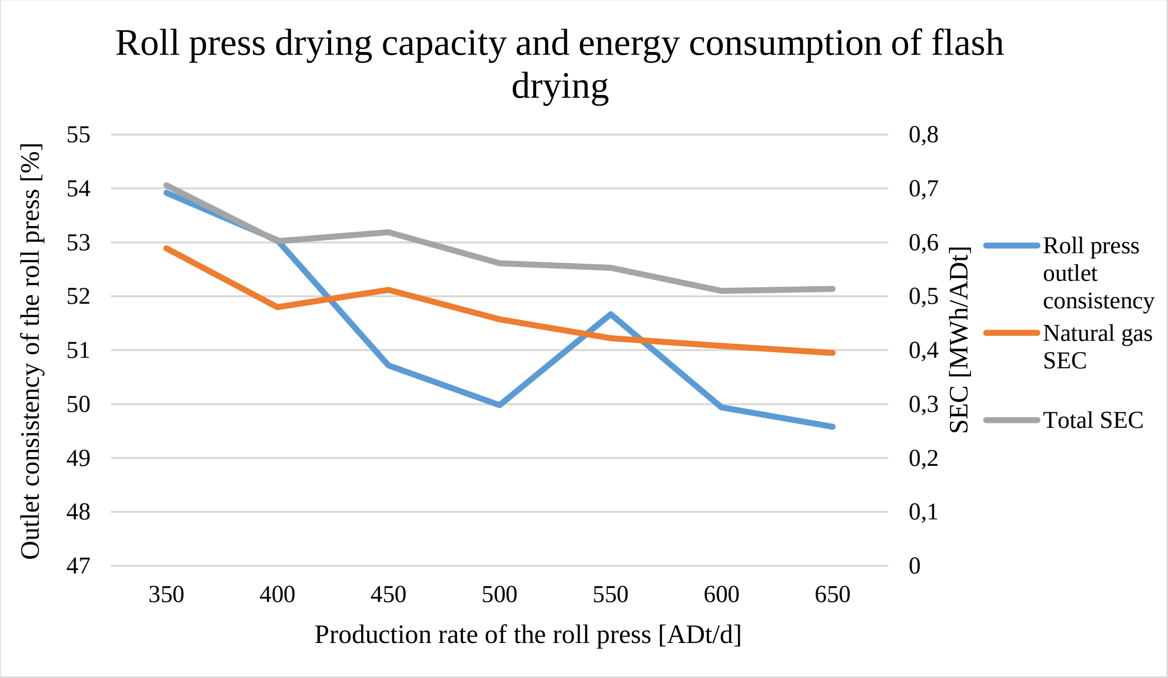


Figure 8. Optimization of the roll press in terms of energy consumption. Nip clearance 5 mm and feed consistency 11 %.

From the figure 8 it can be seen how the outlet consistency of the roll press decreases while the production rate is increased. At the same time also the specific energy consumption decreases. Based on the figure 8 the most optimal production rate of the roll press would be around 500 and 550 ADt/d, since then the outlet consistency is relatively high and energy consumption decent. Even on the production rate of 600 ADt/d the outlet consistency seems to be on relatively good level but to confirm this the production rate should be applied for a longer time span. Based on the figure 8 with production rates below 500 ADt/d higher outlet consistencies would be achieved but then current production of the mill should be reduced. To maintain at least the current levels of the production higher production rates are favoured. As said before, it’s possible that the dry matter content result of the 550 ADt/d is probably a measuring error of the quick dryer, and in reality the outlet consistency can be assumed to be around 49.96 % in that point.

On the second test drive day the same analyses were done but now the feed consistency of the roll press and the twin-wire presses was 10 %. This time less samples were taken only on the most common production rates. The roll press results on 10 % feed consistency are presented in the table 14 below.

Table 14. Roll press samples on 5 mm nip clearance and 10 % feed consistency and the energy consumption on drying line 1

Production rate [ADt/d]	Outlet consistency [%]	Torque of the roll press [Nm]	Natural gas SEC [MWh/ADt]	Total SEC [MWh/ADt]
450	53.23	539	0.416	0.527
500	52.08	553	0.385	0.476
550	49.11	550	0.463	0.582
600	49.09	558	0.370	0.491

As with the results of 11 % feed consistency, also the energy consumption numbers presented in the table 14 are calculated for the drying line 1. Similar graph of the energy consumption and roll press outlet consistency was drawn to more easily find the most optimal production rate. The graph is presented in the figure 9 below.

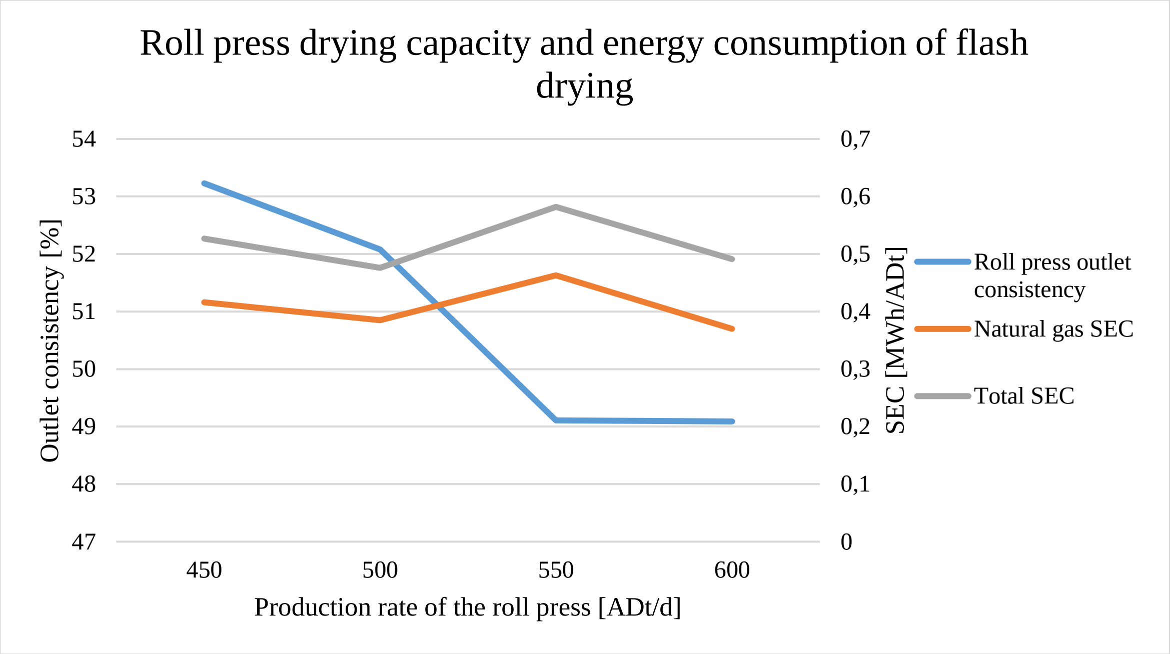


Figure 9. Optimization of the roll press in terms of energy consumption. Nip clearance 5 mm and feed consistency 10 %.

From the figure 9 the same conclusion can be made as from the figure 8, the most optimal production rate for the roll press in terms of energy consumption is around 500 ADt/d. Based on the figures 8 and 9 it is difficult to see if the feed consistency has an impact on the drying capacity of the roll press. To be able to analyse the impact of the feed consistency the dry matter content results were combined into the same graph. Drying capacity of the roll press on the two different feed consistencies is described in the figure 10 below.

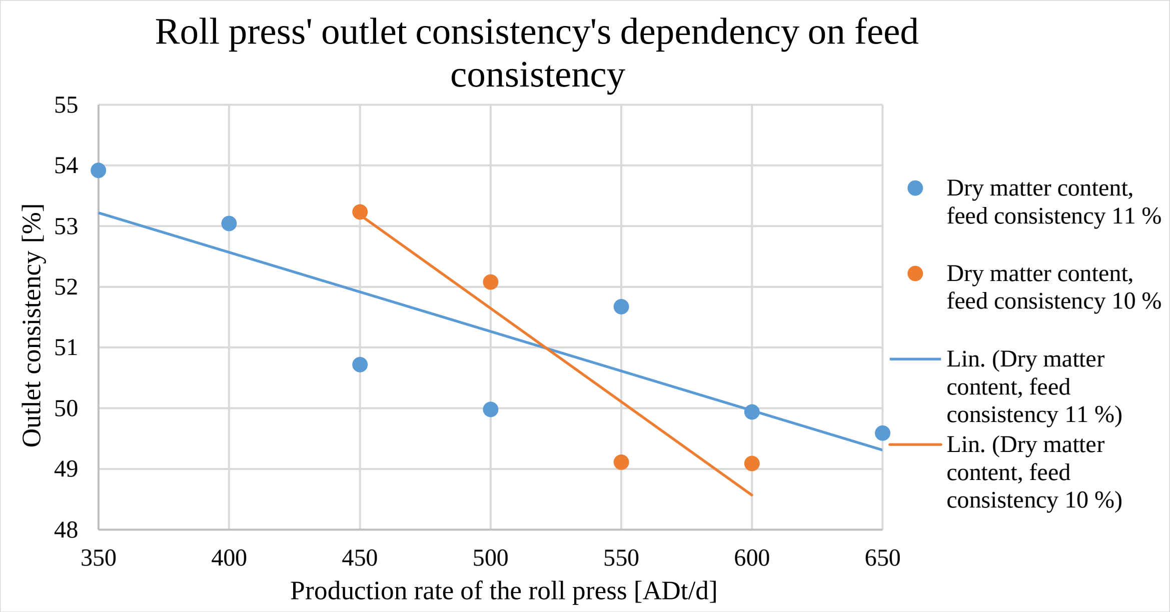


Figure 10. Drying capacity of the roll press on 11 % and 10 % feed consistency

From the figure 10 it can be seen that with a lower feed consistency the drying capacity of the roll press drops faster when the production rate increases. Nevertheless the dry matter content remained on relatively good level on both feed consistencies which might be due to the high torque of the roll press.

8.2.2 Results on the nip clearance of 4 mm

After all samples on 5 mm nip clearance were analysed, the nip clearance was changed to 4 mm. Next the roll press sampling results on the smaller nip clearance are presented. Sampling procedure was similar compared to 5 mm nip clearance. Results of the roll press are presented in table 15 below.

Table 15. Roll press samples on 4 mm nip clearance and 11 % feed consistency

Production rate [ADt/d]	Outlet consistency [%]	Torque of the roll press [Nm]	Natural gas SEC [MWh/ADt]	Total SEC [MWh/ADt]
350	49.24	380	0.429	0.533
400	49.83	470	0.431	0.538
450	49.02	440	0.434	0.546
500	50.31	510	0.427	0.540
550	48.81	510	0.456	0.564
600	50.36	530	0.481	0.597
650	47.93	550	0.444	0.556

When comparing the dry matter content results presented in the tables 12 and 15, it can be seen that during the last test drive day the outlet consistency of the roll press is lower than during the first test drive day. Based on the results it could be concluded that this is because the torque of the roll press is lower during the last test drive day. Similar graph of the energy consumption and the outlet consistency of the roll press was drawn as from the 5 mm results. The graph is presented in the figure 11 below.

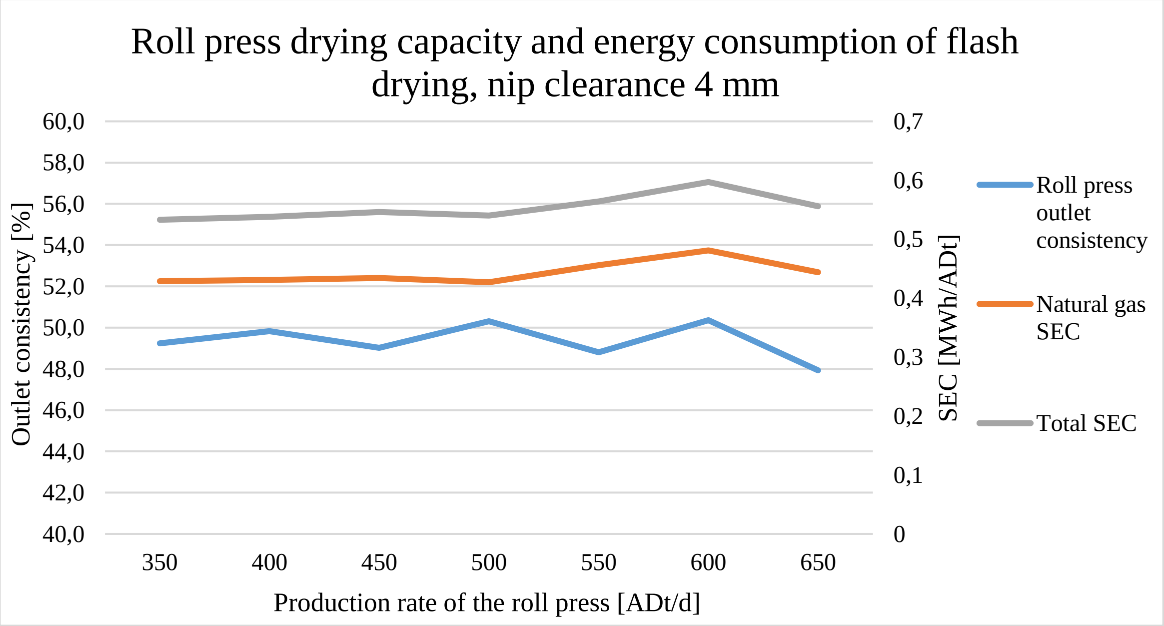


Figure 11. Optimization of the roll press in terms of energy consumption. Nip clearance 4 mm and feed consistency 11 %.

From the figure 11 similar conclusions about the most optimal production rate of the roll press can be drawn as from previous figures. Based on the test drive results it seems that the best outlet consistency with the lowest energy consumption can be achieved with the production rate of 500 or 550 ADt/d. As for the roll press, also for the twin-wire presses the most optimal production rate was estimated. Test drive results for the twin-wire press 22 are presented in the table 16 below.

Table 16. Outlet consistencies of the twin-wire press 22. Feed consistency 11 %.

Production rate [ADt/d]	Outlet consistency [%]
350	53.82
325	52.68
300	51.02
275	52.74
250	53.03
225	54.03
200	55.98

From the results presented in the table 16 it can be seen that the outlet consistency of the twin-wire press 22 remained high during the whole test drive day. However it should be noted that in this test drive the samples were taken only from the middle of the wire instead of three points. In addition analysis was conducted with the quick dryers, not with the oven like in the first test drive. Based on earlier experiences about operating the twin-wire presses the dry matter content should get higher as the production rate decreases. Between the production rates of 200 – 300 ADt/d this applies in the test drive results also, but the dry matter content seems to get higher after the production rate gets over 300 ADt/d. This is most likely because of the margin of error of the quick dryer or delays in analysing the samples. Since the water evaporates from the hot pulp sample relatively quickly it affects the result if the sample can’t be analysed right away.

Even if the results of the twin-wire presses were slightly dispersed and difficult to analyse, based on the table 16 it could be said that the drying capacity increases when the production rate decreases. If the highest production rates presented in the table 16 are excluded due to uncertainty, it could be estimated that the most optimal production rate for the twin-wire presses would be around 250 – 275 ADt/d. However, to ensure the accuracy of the results more sample series should be taken.

As a conclusion from the results of the second test drive the most optimal production rate of the roll press can be concluded to be around 500 – 550 ADt/d, whereas the drying capacity of the twin-wire presses is at its highest at the production rate of 250 or 275 ADt/d. Thus the total production of the mill would be around 1 000 – 1 100 ADt/d. With this production all of the mechanical drying machines can achieve high outlet consistency while the flash drying phase can finish the drying with the least energy. In addition to the production rate also the impact of the roll press' nip clearance and feed consistency were investigated in the test drive. It was found out that with lower feed consistency the drying capacity reduces faster as the production rate increases, as presented in the figure 10. The impact of the nip clearance on the roll press' drying capacity is described in the figure 12 below.

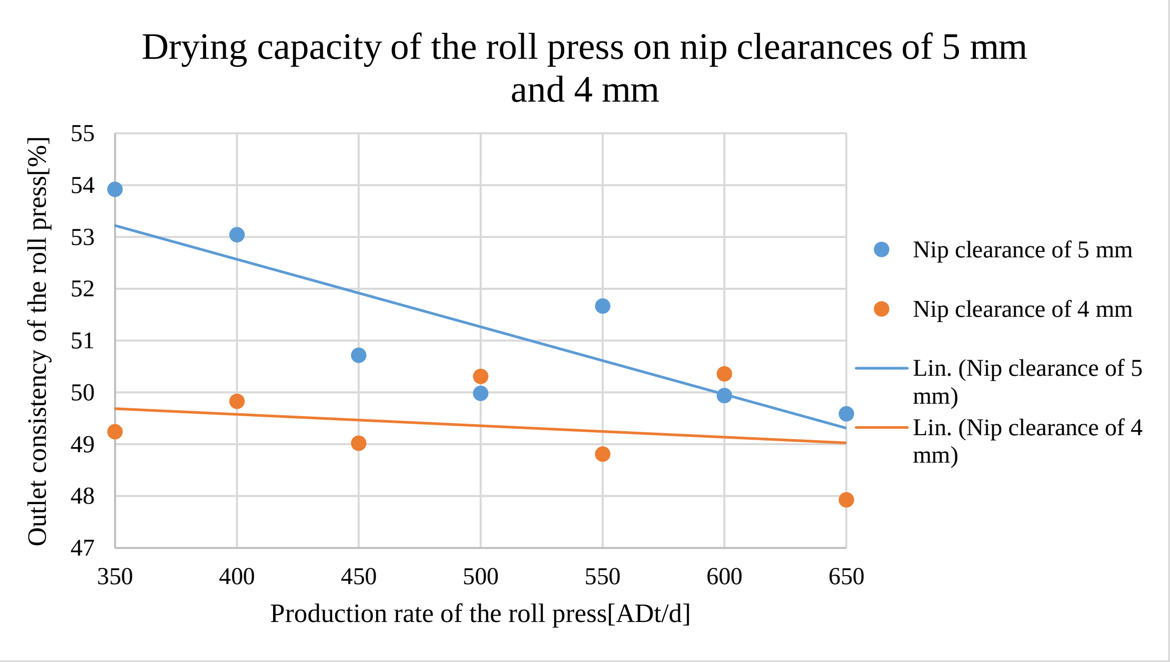


Figure 12. Impact of the nip clearance on the roll press' drying capacity

From the figure 12 it is seen that when the nip clearance is smaller, the increase in production rate has significantly smaller impact on the drying capacity of the roll press. Lower torque of the roll press might be one reason why the outlet consistency is lower on the smaller nip clearance, even if in theory more water should be removed compared to wider nip clearance. If the torque of the roll press would have been higher, the dry matter content results might have been even higher with the nip clearance of 4 mm compared to the nip clearance of 5 mm. In order to define with which nip clearance the roll press operates more efficiently more test drives with similar torques should be conducted.

8.2.3 Results of the torque analysis

In addition to the production rate and nip clearance, also the torque of the roll press is known to have an impact on the drying capacity. In theory, the higher is the torque, the higher is the outlet consistency. The torque however has a limiting value above which it cannot be set safely. To analyse the impact of the torque four samples were taken on constant production rate and four different torques. Of these samples only dry matter content was analysed. The results of the analysis are presented in the table 17 below.

Table 17. Results of the torque samples

Production rate of the roll press [ADt/d]	Torque of the roll press [Nm]	Outlet consistency [%]
500	450	45.32
500	500	48.22
500	550	48.82
500	600	46.72

As it was assumed, according to the table 17 the drying capacity of the roll press increases when the torque is increased. According to the results optimal torque level is on the same level with the production rate or slightly higher, meaning that if the production is 500 ADt/d, the drying capacity is at its highest if also the torque is around 500 – 550 Nm. Results are shown as a graphic in the figure 13 below.

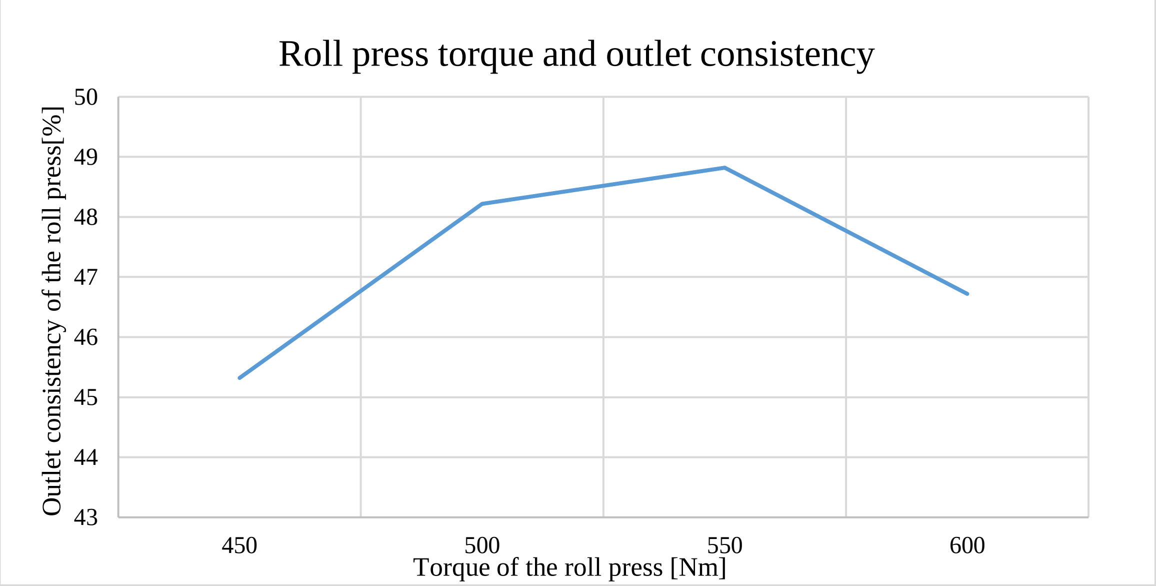


Figure 13. Dependency of the outlet consistency on the torque of the roll press

From the figure 13 it can be seen how steeply the outlet consistency drops after the torque rises above 550 Nm. However, this might be caused by operational problems of the roll press which occurred soon after setting the torque to 600 Nm. This might indicate that too large gap between the production rate and the torque of the roll press might cause operational problems. This supports the conclusion that the most optimal torque level is on the same level with the production rate. To confirm if the upper limit of the torque is so soon after exceeding the production rate more test drives should be conducted in the future.

8.2.4 Sources of uncertainty

Mostly the same sources of uncertainty exist in the two latter test drives as in the first test drive: uncertainties concerning the sample collection, possible delays in analysing the wet samples and margin of error of the analysing equipment. There are however also some new factors which create uncertainty of the results and difficulties when comparing the results of the test drives together.

Perhaps one of the most significant sources of uncertainty was that different analysis method was used for the twin-wire press samples compared to the first test drive. In the first test drive three sample from each wire was taken and they were analysed with the oven-drying method, whereas in the second test drive only one sample from the middle of the wire was taken and it was analysed with a quick dryer. This is because the factor under analysis was the change in dry matter content, and it was assumed to be equal on the edges and in the middle of the wire. In addition the capacity of the drying oven is only 6 samples at a time, whereas in the second test drive 7 twin-wire press samples were taken during one test drive day. The large difference between the results of the quick dryer and oven-dryer method makes it difficult to compare the test drive results together. Additionally the final outlet consistency of the twin-wire presses is slightly lower compared to the dry matter content in the middle of the wire because the pulp is more moist on the edges. This is why it is recommended to repeat the optimization for the twin-wire presses so that three samples of each wire is taken and they are analysed with the oven-drying method. However, for directional analysis the test drive results can be used so that in the upcoming test drives for example the range of production rates to be tested can be narrowed down.

In addition to the above-mentioned factors also the variations of the roll press torque during the second test drives creates uncertainty to the results. Torque has a significant impact on the drying capacity so it made it challenging to analyse the impact of the nip clearance or the feed consistency when the torque was variating in the background. When further analysing the functioning of the twin-wire press this should be taken into consideration by setting a constant target value for the torque.

9 ENERGY BALANCE AND GREENHOUSE GAS EMISSIONS

In this chapter the energy balance and energy consumption calculations for the flash drying process are presented. The purpose is to analyse how the roll press installation has affected the energy consumption of the flash drying process. Based on the energy consumption numbers also the change in greenhouse gas emissions is estimated. This estimation includes only the carbon dioxide equivalent emissions which are formed from natural gas combustion in the flash drying phase.

9.1 Initial values of the energy balances

Before the energy calculations a short introduction to the calculation procedures is presented and the initial values of the energy balance are gone through. In specific energy consumption all energy sources (natural gas, process steam and glycol) are included. First specific energy consumptions are calculated for each sample series, after which sample series of each pulp grade are combined to achieve an estimation of each pulp grade's specific energy consumption. Finally the functioning of the flash drying process as whole is analysed by calculating an average of all sample series' energy consumption results. The energy efficiency and functioning of the drying lines 1 and 2 are analysed both separately and combined. Of the final energy consumption results the amount of greenhouse gas emissions are estimated. One goal of the roll press installation was to reduce the energy consumption of flash drying, so if that is fulfilled, also the greenhouse gas emissions should reduce.

The initial values of the energy balances consist of process parameters which are received from the DNA View software and pulp properties, which are achieved from the test drive results. From the initial values specific energy consumptions are calculated. Components of the energy balances, their units and sources are presented in the table 18 below.

Table 18. Variables of the energy balance

Pulp flows		
Pulp flows in and out	[ADt/d]	DNA View, test drive results
Consistencies	[%]	Test drive results
Heating flows		
Process steam in	[kg/s]	DNA View
Process steam temperature	[°C]	DNA View
Process steam pressure	[kPa]	DNA View
Process steam enthalpy	[kJ/kg]	h,s -diagram of steam
Natural gas feed to burners 1 and 2	[m^3_n/h]	DNA View
Glycol heating	[kW]	DNA View

As it can be seen from the table 18, most of the initial values are received from the process tracking software. Only the pulp consistencies are gotten from the test drive results and enthalpy of the process steam from h,s-diagram of the water vapour. The feed flows and consistencies of the feed flows of the drying lines 1 and 2 were calculated in the chapter 8 based on the production rates of the roll press and the twin-wire presses. These are utilized when calculating the specific energy consumption. The feed flows and their consistencies are presented in the tables 10 and 11 respectively.

9.2 Energy consumption on different pulp grades

In this sub-chapter the energy consumption of the flash drying process on the three different pulp grades, HWSW, HYPER and EXTRA is analysed with the help of the energy balance. For building the energy balance the dry matter content results of the first test drive are utilized. The values calculated from the energy balance are specific energy consumptions of steam, glycol and natural gas, total specific energy consumption and emissions which are caused from burning the natural gas. Calculation procedures are identical for both drying lines. In the calculations the first sample series of the first test drive is used as an example for the flash drying line 1.

For the energy balance calculations the feed flows of the drying lines need to be known. According to the table 10 the feed flow of the drying line 1 is in this case 529.5 ADt/d. The feed flow is converted to the unit of ADt/h by dividing the value with 24 h/d. This way the feed flow of 22.06 ADt/h is achieved. The first step in defining the specific energy consumption is to define the steam consumption at the sampling time with the help of the DNA View software. At the time of the first sample series the steam consumption of the drying line 1 was around 1.21 kg/s. This was converted into a specific steam consumption with the following equation.

$$m_{steam,spec.} = \frac{m_{steam} * 3\ 600 \frac{s}{h}}{m_{pulp}} \tag{5}$$

$m_{steam,spec.}$ = specific steam consumption [kg_{steam}/ADt_{pulp}]
m_{steam} = steam consumption [kg/s]
m_{pulp} = pulp feed to the drying line [ADt/h]

By inserting the values 1.21 kg/s and 22.06 ADt/h into the equation 5 the specific steam consumption is achieved according to the following calculation.

$$m_{steam,spec.} = \frac{1.21 \frac{kg}{s} * 3600 \frac{s}{h}}{22.06\ ADt/h} \approx 197.46\ kg_{steam}/ADt_{pulp}$$

Now to convert the specific steam consumption from mass to energy the steam pressure and temperature were received from DNA View software. After this the enthalpy was estimated from the h,s-diagram of water vapor (Koponen) which is presented in the appendices of the thesis. The temperature of the process steam was about 124 °C and the pressure was 127 kPa. Variations in steam properties were very small varying between 1 – 2 units, so the same enthalpy value was used for each sample series. The enthalpy of the process steam was estimated to be 2 725 kJ/kg_{steam}. This was converted into kWh/ADt with the equation shown below.

$$SEC_{steam} = \frac{h_{steam}}{3\,600\ kJ/kWh} * \ m_{steam,spec.} \tag{6}$$

SEC_{steam} = specific steam consumption [kWh_{steam}/ADt_{pulp}]

h_{steam} = enthalpy of steam [kJ/kg_{steam}]

By inserting the enthalpy of steam and the specific steam consumption as kg_{steam}/ADt_{pulp} the equation forms into the following.

$$SEC_{steam} = \frac{2\,725 \frac{kJ}{kg_{steam}}}{3\,600\ kJ/kWh} * 197.46 \frac{kg_{steam}}{ADt} \approx 149.47\ kWh_{steam}/ADt_{pulp}$$

The next step in defining the energy consumption was to check if glycol was used in heating the drying air or not. In the case of the first sample series glycol heating wasn't in use, but if it would have been, the quantity of glycol heating would have been received from DNA View as kilowatts. This would be converted into kWh/ADt_{pulp} simply by dividing it with pulp feed as ADt/h. The final step in energy consumption calculations was to calculate the natural gas consumption. The natural gas usage was received from DNA View software as m^3_n/h. In the case of the first sample series the consumption was 902 m^3_n/h. During every sample series only the first burner utilized natural gas, which means that in the second heating phase only process steam and glycol were utilized. The natural gas consumption was converted into specific consumption (MJ/ADt) with the help of lower heating value of natural gas and pulp feed flow as shown below.

$$SEC_{ng} = \frac{v_{ng}}{m_{pulp}} * \ Q_{ng} \tag{7}$$

SEC_{ng} = specific natural gas consumption [MJ/ADt_{pulp}]

v_{ng} = natural gas consumption [m^3/h]

Q_{ng} = lower heating value of the natural gas (36.4 MJ/m^3)

When inserting the numbers to the equation 7 the specific natural gas consumption was solved as following.

$$SEC_{ng} = \frac{902 \frac{m_n^3}{h}}{22.06\ ADt_{pulp}/h} * 36.4 \frac{MJ}{m^3} \approx 1\ 488.34\ MJ/ADt_{pulp}$$

To convert this into the same unit with other energy consumption numbers the result of 1 488.34 MJ/ADt was divided with 3 600 MJ/MWh. Thus the specific natural gas consumption of 0.413 MWh_{ng}/ADt_{pulp} was achieved.

Now that specific energy consumptions of process steam, glycol and natural gas are known, the total specific energy consumption can be calculated by summing these three together. This way the specific energy consumption during the first sample series was solved to be around 0.563 MWh/ADt_{pulp}. The calculation procedure described above was done for each sample series. The energy balance with the values of the first sample series of the first test drive is presented in the appendices of the thesis. The results of each sample series for the drying line 1 are presented in the table 19 below.

Table 19. Energy consumption results for the drying line 1

	HWSW		HYPER		EXTRA	
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Feed consistency [%]	48.72	49.50	49.26	48.89	49.76	46.87
Steam SEC [MWh/ADt]	0.1495	0.1459	0.1124	0.1152	0.1088	0.101
Natural gas SEC [MWh/ADt]	0.413	0.413	0.366	0.439	0.339	0.422
Glycol SEC [MWh/ADt]	0	0	0.0145	0.0134	0.0108	0.0136
Total SEC [MWh/ADt]	0.563	0.559	0.493	0.567	0.459	0.537
Outlet consistency [%]	85.71	85.70	86.15	87.38	85.87	85.23

From the results presented in the table 19 it can be concluded that glycol heating has the smallest role in total specific energy consumption. Based on these results it would also seem that HWSW grade demands the largest amounts of drying energy, whereas EXTRA grade demands clearly the smallest amount of energy. Averagely drying the HWSW grades demands about 0.560 MWh/ADt, HYPER demands 0.530 MWh/ADt and EXTRA demands approximately 0.500 MWh/ADt. The differences might be because of differing pulp properties and tree species relations, but also because the test drive was started with HWSW grade and ended with EXTRA. Thus the reduction in energy consumption might also indicate that operating the new roll press has developed during the test drive which leads to higher dry matter content and thus reduced energy consumption. To be sure if there really is that clear difference between the pulp grades' energy consumptions more samples should be taken during a longer time frame. Corresponding energy consumption results for the drying line 2 are presented in the table 20 below.

Table 20. Energy consumption results for the drying line 2

	HWSW		HYPER		EXTRA	
	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6
Feed consistency [%]	47.81	48.32	48.16	47.06	48.86	46.98
Steam SEC [MWh/ADt]	0.1309	0.1372	0.1125	0.0994	0.1007	0.0963
Natural gas SEC [MWh/ADt]	0.397	0.362	0.387	0.393	0.362	0.385
Glycol SEC [MWh/ADt]	0	0	0.0156	0.0136	0.0109	0.0135
Total SEC [MWh/ADt]	0.528	0.499	0.515	0.506	0.474	0.495
Outlet consistency [%]	85.56	84.92	86.19	86.31	85.43	86.48

Based on the tables 19 and 20, results of the two drying lines seem very similar. On the drying line 2 the differences in energy consumption are smaller between the HWSW and HYPER grades (0.514 MWh/ADt and 0.511 MWh/ADt respectively) but EXTRA is still the smallest energy consumer with an average of about 0.485 MWh/ADt. When comparing the average energy consumption numbers from the tables 19 and 20 it can be seen that drying line 2 seems to work more efficiently. The energy consumption of the drying lines is compared in the figure 14 below.

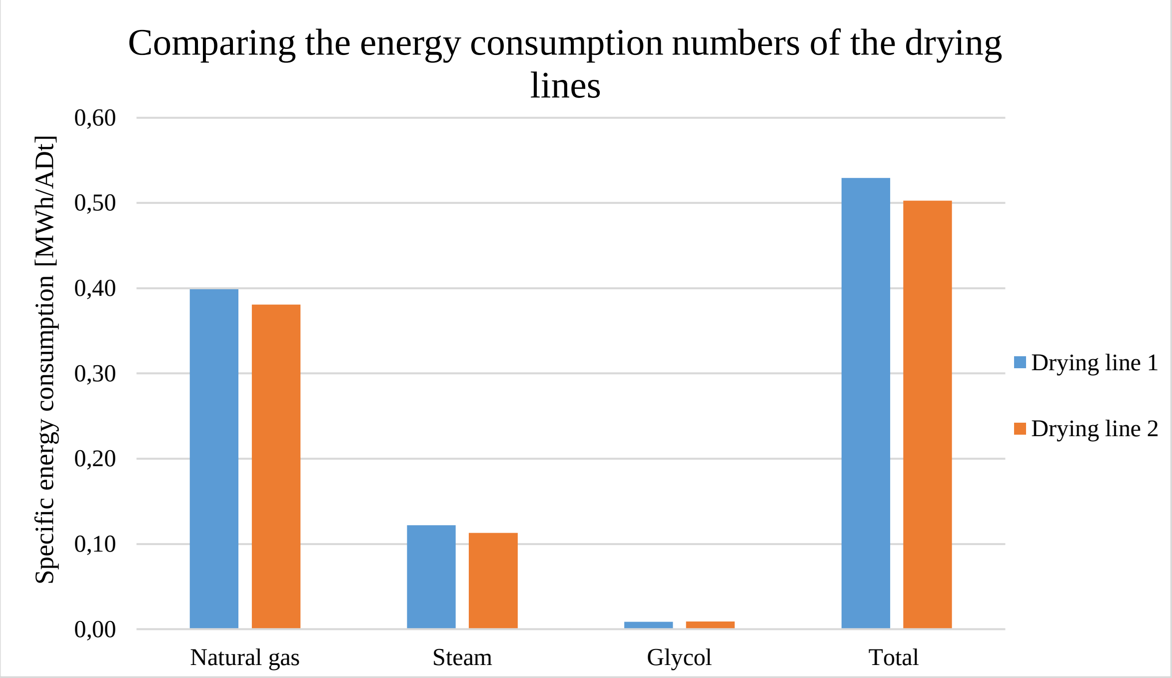


Figure 14. Comparing the energy efficiency of the drying lines 1 and 2

The figure 14 is composed of the averages of the specific energy consumption numbers presented in the tables 19 and 20. From the figure 14 it can be seen that when the different pulp grades are not considered, the drying lines operate quite similarly: the energy consumption numbers differ averagely only 0.02 MWh/ADt. Glycol consumption has been on the same level on both drying lines but otherwise the drying line 2 functions slightly more efficiently compared to the drying line 1. The most clear difference which can be seen from the tables 19 and 20 is that the feed consistency of drying line 2 is lower compared to the drying line 1. This is probably due to the lower dry matter content of the twin-wire press 22, which feeds the pulp to the drying line 2. However, difference in final dry matter content is smaller compared to difference in feed consistency, which also indicates that the drying line 2 works so efficiently that it can narrow down the consistency difference.

9.3 Comparing the energy consumption with the statistics

In this chapter it is analysed how big impact the roll press has on energy consumption by comparing the results with the statistics before the roll press installation. To achieve as accurate comparison as possible two reference days were picked from 2019. Sample series and corresponding reference days are presented in the table 21 below.

Table 21. Sample series of the first test drive and the corresponding reference days

Sample series	Corresponding reference days
HWSW 1	18.3.2019 / 3.11.2019
HWSW 2	16.3.2019 / 27.9.2019
HYPER 3	31.3.2019 / 22.11.2019
HYPER 4	7.4.2019 / 19.11.2019
EXTRA 5	23.3.2019 / 14.10.2019
EXTRA 6	10.10.2019 / 11.10.2019

Reference days presented in the table 21 were picked so that average production rate would be close to the production rates of the test drive days. It was also ensured that no off-grade was produced during the reference days. With the help of the DNA process tracking software it was also made sure that operating conditions of the flash drying process were similar compared to the test drive days. This means that usage of natural gas was similar (only in drying phase 1 as during the test drive days) and that outside temperature was as close to the test drive days as possible. This is because the air for the flash drying process is taken outside so needed heating energy also depends on the outside temperature. This way the comparison of the energy consumption was made as reliable as possible.

The energy consumption values of the reference days were received from the DNA View software. As in dry matter content analysis, the averages of the natural gas SEC, process steam SEC and total SEC of the reference days were calculated and compared to the test drive results. The comparison of the energy consumption values of the drying line 1 is presented in the table 22 below.

Table 22. Comparison of the energy consumption of the drying line 1 before and after the roll press installation as [MWh/ADt]

	After the roll press installation				Before the roll press installation			
Pulp grade	Natural gas SEC	Steam SEC	Glycol SEC	Total SEC	Natural gas SEC	Steam SEC	Glycol SEC	Total SEC
HWSW	0.413	0.150	0	0.563	0.540	0.085	0.0378	0.663
	0.413	0.146	0	0.559	0.565	0.080	0.0336	0.679
HYPER	0.366	0.112	0.0145	0.493	0.530	0.085	0.0162	0.631
	0.439	0.115	0.0134	0.567	0.515	0.080	0.0348	0.630
EXTRA	0.339	0.109	0.0108	0.459	0.515	0.080	0.0225	0.618
	0.422	0.101	0.0136	0.537	0.540	0.080	0.0232	0.643

From the table 22 above it can be seen that the roll press has clearly reduced the energy consumption in terms of natural gas consumption and total specific energy consumption. The process steam consumption has been slightly higher compared to 2019 statistics but nevertheless the total SEC is lower. Also the glycol consumption has been lower after the roll press installation. Grade-specific reductions in natural gas consumption are about 0.140 MWh/ADt on HWSW grade, 0.120 MWh/ADt on HYPER and 0.147 MWh/ADt on EXTRA. If different grades are not taken into account, averagely the SEC of natural gas has reduced 0.136 MWh/ADt whereas the total SEC has reduced by 0.114 MWh/ADt. When multiplying the natural gas consumption reduction with an average daily production of one drying line, which is assumed to be 500 ADt/d, daily natural gas consumption reduction of 68 MWh/d is achieved. Annually this accounts for a reduction of 23 800 MWh/a, if it is assumed that the mill operates about 350 days in a year. Similar comparison is done also for the drying line 2. As in the table 22, test drive and reference values for the drying line 2 are presented in the table 23 below.

Table 23. Comparison of the energy consumption of the drying line 2 before and after the roll press installation as [MWh/ADt]

	After the roll press installation				Before the roll press installation			
Pulp grade	Natural gas SEC	Steam SEC	Glycol SEC	Total SEC	Natural gas SEC	Steam SEC	Glycol SEC	Total SEC
HWSW	0.397	0.131	0	0.528	0.425	0.080	0.0337	0.539
	0.362	0.137	0	0.499	0.420	0.070	0.0277	0.518
HYPER	0.387	0.113	0.0156	0.515	0.415	0.075	0.0349	0.525
	0.393	0.099	0.0136	0.506	0.420	0.085	0.0327	0.538
EXTRA	0.362	0.101	0.0109	0.474	0.425	0.085	0.0208	0.531
	0.385	0.096	0.0135	0.495	0.505	0.070	0.0233	0.598

When comparing the values of the tables 22 and 23 it can be seen that changes in energy consumption are much smaller on drying line 2 than on drying line 1. The grade-specific natural gas consumption reductions are 0.043 MWh/ADt for HWSW, 0.028 MWh/ADt for HYPER and 0.092 MWh/ADt for EXTRA. Based on the energy consumption values presented in the table 23 the natural gas consumption of the drying line 2 has reduced averagely 0.054 MWh/ADt whereas the total specific energy consumption has reduced by 0.039 MWh/ADt. This is however logical when taking into account that drying line 2 has worked much more efficiently in 2019 compared to drying line 1 so there is less room for improvements in the first place. As on drying line 1, also on drying line 2 the specific glycol consumption has reduced and some of the reduced natural gas consumption is substituted with process steam.

To better describe the reduction in energy consumption on the two drying lines, the energy consumption numbers for drying lines 1 and 2 are presented in the figures 15 and 16 respectively. Diagrams are composed from the average consumptions presented in the tables 22 and 23. Different pulp grades are not taken into consideration in the figures.

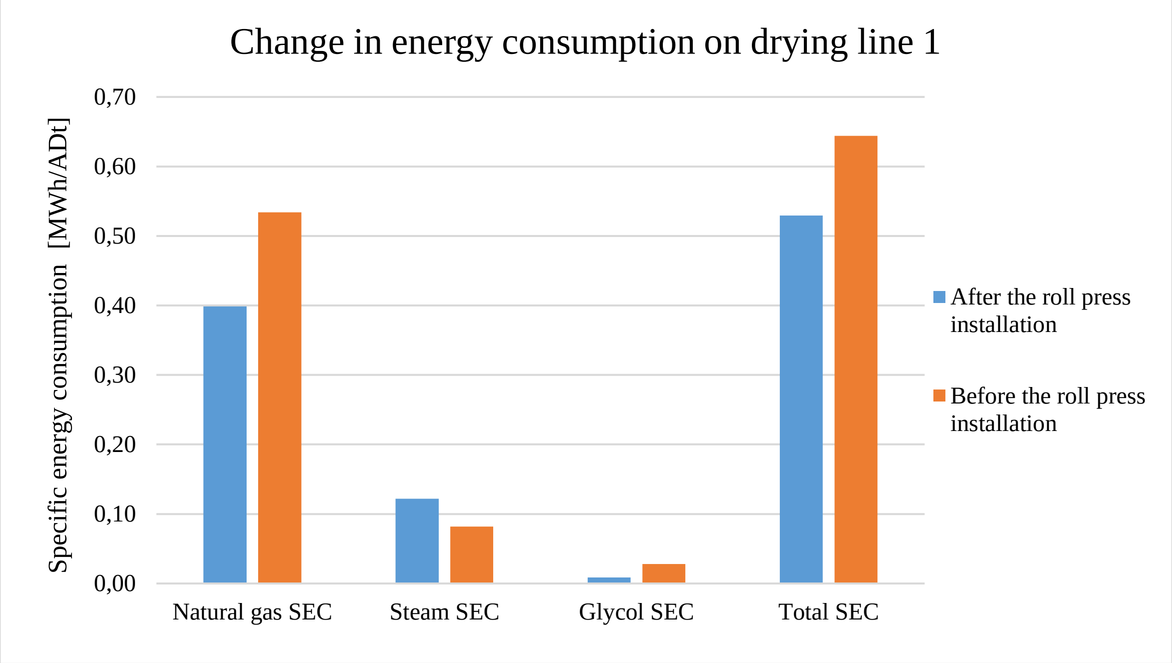


Figure 15. Change in energy consumption on drying line 1

The figure 15 above shows the average specific energy consumptions of natural gas, steam and glycol and total specific energy consumption for the drying line 1. Based on the figure 15 the natural gas consumption has reduced about 25.4 % on drying line 1 while the total specific energy consumption has reduced about 17.8 %. As it was shown also in the table 22, some of the natural gas consumption has been substituted with steam. In the figure 16 below a similar diagram is presented also for the drying line 2.

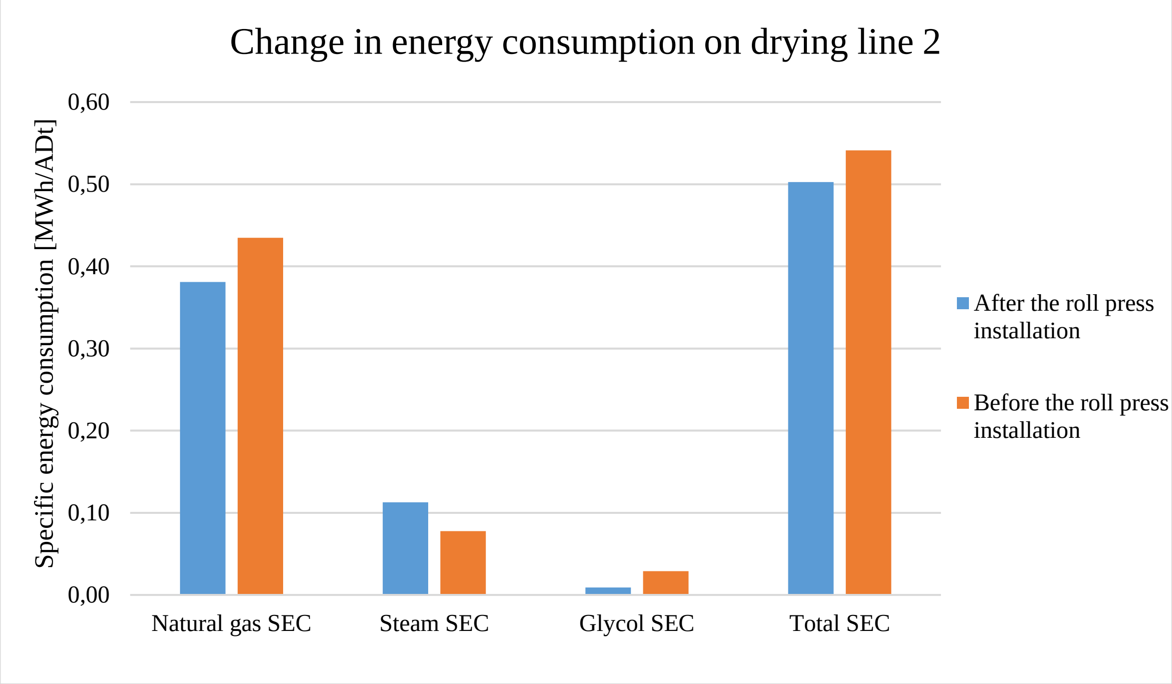


Figure 16. Change in energy consumption on drying line 2

As it can be seen when comparing the figures 15 and 16, the trends in energy consumption between the drying lines differ from each other substantially. As on drying line 1, also on drying line 2 the natural gas consumption has reduced, even if the change is clearly smaller being around 12.4 %. As on drying line 1, also on drying line 2 some of the natural gas consumption has been substituted with process steam, which makes the reduction in total specific energy consumption smaller. On drying line 2 the total specific energy consumption has reduced about 7.1 %. Even if the energy consumption reductions are smaller on the drying line 2, it still functions slightly more efficiently compared to the drying line 1. However, difference in energy efficiency is now smaller than before the roll press installation.

While interpreting the energy consumption results it should be remembered that they represent only single days both before and after the roll press installation. More accurate energy consumption reduction numbers are received after the roll press has been in usage for a longer time so that longer time spans can be compared together. This is why it is recommended to repeat the energy consumption calculations later with a longer time span. It could be beneficial to for example compare different months or seasons of different years together to analyse the impact of the roll press more accurately.

9.4 Emissions of the flash drying

In this sub-chapter the reduction in natural gas consumption is converted into carbon dioxide equivalent emissions and the size of the emission reduction is being analysed. The energy consumption numbers presented in the previous chapters are used when estimating the carbon dioxide emissions on a year-level. Combined natural gas consumption numbers of the drying lines 1 and 2 after the roll press installation are described in the table 24 below. In emission calculations only the emissions from burning the natural gas are taken into account.

Table 24. Natural gas consumption of the flash drying process after the roll press installation

Sample series	[MWh/ADt]	[MJ/ADt]	[m^3/ADt]
HWSW 1	0.405	1 458	40.05
HWSW 2	0.388	1 395	38.32
HYPER 3	0.377	1 355	37.24
HYPER 4	0.416	1 498	41.14
EXTRA 5	0.351	1 262	34.66
EXTRA 6	0.404	1 453	39.91

For emission calculations the energy consumption numbers were converted from the unit of MWh/ADt into m^3/ADt. Different steps of the conversion are shown in the table 24 above. Next the conversion process is described using the sample series 1 as an example. First the SEC value of 0.405 MWh/ADt is multiplied with 3 600 to convert it into megajoules. As shown in the table 24, as megajoules the natural gas consumption is 1 458 MJ/ADt. With the help of lower heating value of natural gas this can be converted into volume in following manner.

$$V_{NG} = \frac{SEC_{ng}}{Q_{ng}} \tag{8}$$

V_{NG} = volume of natural gas [m^3]

By inserting the values into the equation 8 the volumetric consumption of 40.05 m^3/ADt is achieved. For the emission calculations the average of the volumetric consumptions is used.

Based on the values presented in the table 24 the average natural gas consumption of 38.55 m^3/ADt is achieved. To calculate the reduction of the natural gas consumption also the energy consumption values of the reference days need to be summed. Average energy consumption numbers of the flash drying process on reference days are presented in the table 25 below.

Table 25. Natural gas consumption of the flash drying process before the roll press installation

Sample series	[MWh/ADt]	[MJ/ADt]	[m^3/ADt]
HWSW 1	0.483	1 737	47.42
HWSW 2	0.493	1 773	48.71
HYPER 3	0.473	1 701	46.73
HYPER 4	0.468	1 683	46.24
EXTRA 5	0.470	1 692	46.48
EXTRA 6	0.523	1 881	51.68

The unit conversion from MWh/ADt to m3/ADt was done similarly as for the values presented in the table 24. The average volumetric natural gas consumption of the reference days is about 47.93 m^3/ADt. This indicates that the average natural gas consumption has reduced about 9.38 m^3/ADt.

The emission calculation starts with calculating the natural gas consumption on a year level. This is done simply by multiplying the average consumption first with production rate during one day, which is assumed to be 1 000 ADt/d and then with operating time of the mill, which is assumed to be 350 days in a year. This way the annual natural gas consumption before the roll press installation is solved to be about 16 775 500 m^3/a whereas after the roll press installation the natural gas consumption is 13 492 500 m^3/a. Thus the reduction in natural gas consumption is around 3 283 000 m^3/a.

To calculate the emission reduction the volumetric reduction in natural gas consumption needs to be multiplied with the carbon dioxide emission factor of the natural gas. The CO_2 emission factor of the carbon dioxide is 55.3 g_{CO2}/MJ (Statistics Finland 2020). When this is multiplied with lower heating value of natural gas, 36.4 MJ/m^3, the emission factor can be converted into the unit of g_{CO2}/m^3. This way the emission factor is 2 012.92 g_{CO2}/m^3, which means that in kilograms it is 2.013 kg_{CO2}/m^3. Now the natural gas reduction can be multiplied with the emission factor so that the mass of reduced CO_2 emissions is achieved. This reduction is solved to be approximately 6 608 t_{CO2}/a. If described as percentages the reduction is about 19.57 %.

10 CONCLUSIONS

The purpose of this thesis was to analyse the impacts of the new twin-roll press installed at the Metsä Board mill in Joutseno. The factors under analysis were the pulp's dry matter content and specific energy consumption in the flash drying process. Additionally the changes in natural gas consumption and greenhouse gas emissions were analysed. Finally the most optimal operating model for the renewed mechanical drying phase was built.

As the result of the test drives it was found out that the dry matter content after the mechanical drying phase has increased after the roll press installation. Averagely the dry matter content after the mechanical drying improved by 1.60 percentage points, raising from about 46.70 % to 48 – 49 %. This indicates that now the final dry matter content can be achieved with smaller energy consumption in the flash drying phase since now there is less water to be removed. When analysing the change in energy consumption on the two drying lines it was found out that energy consumption has reduced more on drying line 1 than on drying line 2. Specific natural gas consumption has reduced by 25.4 % on the drying line 1, whereas on the drying line 2 the reduction is around 12.4 %. The total specific energy consumption has reduced about 17.8 % on the drying line 1 and 7.1 % on the drying line 2.

When the energy consumption reduction was estimated on a year-level for the whole flash drying process, it was found out that in total the consumption of the natural gas reduced about 3.28 million m^3/a, which accounts for 19.57 % reduction compared to the statistics before the roll press installation. When estimating the emissions of the flash drying only the emissions caused from burning the natural gas were included. On a year level the total emission reduction was solved to be about 6 608 $t_{CO2eq.}$/a.

As the result of the second test drive it was found out that the most optimal production rate for the roll press is around 500 – 550 ADt/d, while for the twin-wire presses the most optimal production rate would be between 250 – 275 ADt/d. With these production rates the drying capacities of the mechanical drying machines are on the highest levels and the specific energy consumption of the flash drying process is low. This way also the emissions of the flash drying process remain as low as possible. Thus the most optimal total production of the mill would be around 1 000 – 1 100 ADt/d. When testing different torque levels on the roll press with a constant production rate of 500 ADt/d it was found out that the drying capacity is at its highest when the torque is on the same level with the production or slightly above. This means that for example when the production rate of the roll press is 500 ADt/d, the torque should be around 500 – 550 Nm.

From the results it could be concluded that they are well in line with the theory presented in the thesis. Operating principles of the drying machines were gone through in theory chapters which also supported the planning of the test drives so that some hypotheses of possible results could be done. Assumed impacts of the freeness and pH on the drying capacity did not come completely true in the test drives, but this is probably because the torque and the operating rate of the roll press had more major impact. With the help of the test drives it was found out that increasing the feed consistency of the roll press and tightening the nip clearance most probably has a positive impact on the drying capacity, as it was stated in the theory part of the thesis.

As always also the results of these test drives include sources of uncertainty. Uncertainties of the test drives mostly originate from using two different methods for analysing the twin-wire press samples and from using two quick dryers of different models. In addition to these also the sampling procedure and how quickly a hot pulp sample had been analysed might have affected the dry matter content results. To minimize these uncertainties the test drive plans with sampling guidance were shared to the operating personnel in advance and the sampling spots of the twin-wire presses were marked. In addition to the sampling procedures also the analysing process had some sources of uncertainty in it. When the results were analysed the roll press had been in use only for some months. This means that there isn’t long-term knowledge about operating it or about how it affects the final product and other production processes. If dry matter content or energy consumption could have been compared from a time span of a month or a year the results would have been more accurate.

The sources of uncertainty mentioned above can be reduced in the future with further research. As further analysis more test drives could be conducted. For example the torque of the roll press, its upper limits and its impact on the drying capacity could be investigated more deeply. This way the most optimal operation model could be further developed. Also the differences between the pulp grades could be investigated more since differences in tree species relations or freeness levels might have an impact on the drying efficiency of the roll press. This way the operation model could be modified for each pulp grade separately for example in terms of the torque of the roll press. Also the change in energy consumption could be analysed more accurately with a longer time span for example during different seasons or months. Also impact of the nip clearance and feed consistency is recommended to analyse more accurately with different production rates and stable torque levels of the roll press. This way a decision could be made if it is more efficient to utilize smaller nip clearance or a bit higher feed consistency to achieve higher drying efficiency. After the test drive the roll press has been operated with a nip clearance of 4 mm instead of 5 mm which was applied before the test drives. Impact of this on the drying efficiency would be good to be defined with test drives.

The estimation of the most optimal operation model of the mechanical drying process can be utilized at the mill in the future when operating the roll press. In addition the estimations about how the nip clearance, torque and feed consistency affects the outlet consistency can be utilized if there is a drop in the drying capacity of the roll press. When applying the most optimal operation model even larger increase than 1.60 percentage points in the flash drying process’ feed consistency can be achieved. More accurate increase can be defined when applying the operation model and implementing test drives. Additionally the results of energy consumption and dry matter content reductions can be utilized as a reference material for the upcoming improvements and investments.

As a conclusion of the test drives and the thesis it could be said that, as intended, the new roll press manages to reduce the energy consumption of the flash drying process and improve the dry matter content of the pulp. With the energy consumption reduction also the greenhouse gas emissions of the mill reduce, which is more and more important while the customers keep demanding as environmental friendly products as possible. In addition to greenhouse gas emission reduction the roll press installation can be thought to have also other positive environmental and economical impacts. The maintenance breaks of the twin-wire presses reduce when they can be operated with lower production rates without losing total production. Additionally raw material efficiency improves while the transportation costs decrease since the final product contains less water. When the pulp is produced in more environmental friendly manners, also the paperboard produced from the pulp has smaller negative environmental impacts in the future. This is important in improving the environmental friendliness of the forest industry sector especially in Finland where it is the largest industrial sector.

11 SUMMARY

This master's thesis was ordered by Metsä Board's BCTMP mill in Joutseno, where a new roll press was installed in autumn 2020 for drying the pulp. The purpose was to find out how much the new roll press could increase the pulp's dry matter content and reduce the energy consumption of the flash drying phase, and to calculate how much the reduction in natural gas consumption reduces the CO_2 emissions. In addition one goal was to find the most optimal production rates for both the roll press and old twin-wire presses in terms of dry matter content and energy consumption of flash drying.

The thesis consisted of two parts, theory part and empirical part. In the theory part the production process of bleached chemi-thermo mechanical pulp, its phases and most relevant drying process equipment were gone through on general level. In addition some important wood properties and pulp characteristics were reviewed since they have an impact also on the drying of the pulp. Finally some energy and environmental aspects of mechanical pulp were presented before moving to empirical part, which started with case mill presentation. The rest of the empirical part consisted of test drive plans, their implementation and analysis of the results.

The methods utilized during the empirical part of the thesis were test drives, laboratory analyses and statistical analyses. In total two larger test drives were arranged at the case mill, one for analysing the roll press' impact on the dry matter content and one to find the most optimal production rate for the mechanical drying machines. In addition one single sample series was conducted to analyse the impact of the roll press' torque on the drying capacity. The first test drive was conducted on all three pulp grades, HWSW, HYPER and EXTRA, whereas the second test drive was conducted only on HYPER grade. The energy balances for the flash drying lines 1 and 2 were built in order to calculate the steam and natural gas consumptions and the CO_2 emissions. In emission calculations only the emissions from burning the natural gas in the flash drying phase were included. In addition the material balances were simplified so that it was assumed that all of the pulp from the roll press goes to the flash drying process and none is bypassed to the pulper.

As the result of the test drives it was found out that installation of the roll press significantly reduced the natural gas consumption of the flash drying phase, 25.4 % on the drying line 1 and 12.4 % on the drying line 2. On a year level the natural gas consumption of the flash drying process reduced about 19.57 %, which accounts for about 3.28 million m^3 of natural gas each year. As emissions this reduction accounts for about 6 608 tons of CO_2 equivalents per year. In addition to the reduction in energy consumption the dry matter content after the mechanical drying process increased about 1.60 percentage points. Finally one goal of the thesis was to find the most optimal operation model for the mechanical drying phase, in other words for the roll press and the two twin-wire presses. For the roll press the most optimal production rate was found to be 500 – 550 ADt/d and correspondingly for the twin-wire presses about 250 – 275 ADt/d. In addition it is recommended to maintain the torque of the roll press at least at the same level with the production to achieve as high dry matter content as possible. The emission reduction numbers are estimated based on the results of the first test drives, which means that when applying the recommended operation model for the mechanical drying process the energy consumption might decrease even more since the dry matter content should be higher.

As a conclusion it is clear that the roll press installation has reached the goals which were set for it. It significantly reduces the natural gas consumption of the flash drying and thus the carbon dioxide emissions which is important for reaching the carbon neutrality targets and to mitigate the climate change. For the future research it is recommended to analyse the differences between the pulp grades and more accurate impact of the nip clearance and the feed consistency of the roll press. This way the most optimal operation model could be further developed. Additionally the upper limits of the torque of the roll press should be defined more accurately to see if applying higher torques is possible and if it would further increase the drying efficiency.

REFERENCES

Ali-Yrkkö J. et al. 2016. Suurten yritysten ja niiden arvoketjujen rooli taloudessa. The Research Institute of the Finnish Economy. Updated May 18, 2016. [Retrieved September 1, 2020]. From: https://www.etla.fi/wp-content/uploads/ETLA-Raportit-Reports-53.pdf

Andritz. Dewatering of fiber pulps. [Retrieved September 14, 2020]. From: https://www.andritz.com/products-en/group/pulp-and-paper/pulp-production/kraft-pulp/pulp-drying-finishing/dewatering-machines-fiber

Biotalous. 2020. Korona koettelee myös metsäteollisuutta, silti pehmopapereiden ja pakkaustuotteiden kysyntä pysynyt vahvana. Updated April 28, 2020. [Retrieved September 2, 2020]. From: https://www.biotalous.fi/korona-koettelee-myos-metsateollisuutta-silti-pehmopapereiden-ja-pakkaustuotteiden-kysynta-pysynyt-vahvana/

Cai J. & Meng W. 2010. Intelligent operation parameters optimization for screw conveyor based on PSO. [e-article]. [Retrieved September 21, 2020]. From: https://ieeexplore-ieee-org.ezproxy.cc.lut.fi/stamp/stamp.jsp?tp=&arnumber=5636805&tag=1

CNBM International. Twin Roll Press. [Retrieved September 14, 2020]. From: http://www.paperpulpingmachine.com/twin-roll-press/

Ek M. et al. (ed.). 2009. Pulping and Paper Chemistry and Technology Volume 2 – Pulping Chemistry and Technology. 484 p. ISBN 978-3-11-021341-6.

Elahimehr A. 2014. Low consistency refining of mechanical pulp: the relationship between plate pattern, operational variables and pulp properties. [Dissertation]. The University of British Columbia (Vancouver). 120 p. [Retrieved October 6, 2020]. From: https://www.semanticscholar.org/paper/Low-consistency-refining-of-mechanical-pulp-%3A-the-Elahimehr/6870678184011f118770e699554fbfa7e4147585

Deutsche Welle. 2020. EU agrees on tougher climate goals for 2030. Updated December 11, 2020. [Retrieved December 16, 2020]. From: https://www.dw.com/en/eu-agrees-on-tougher-climate-goals-for-2030/a-55901612

El idrissi B. et al. 2019. Dewatering parameters in a screw press and their influence on the screw press outputs. [e-article]. Elsevier. [Retrieved September 25, 2020]. From: https://www-sciencedirect-com.ezproxy.cc.lut.fi/science/article/pii/S0263876219304630?via%3Dihub

European Commission. 2019. National energy and climate plans (NEPCs). Updated October 14, 2020. [Retrieved December 16, 2020]. From: https://ec.europa.eu/energy/topics/energy-strategy/national-energy-climate-plans_en

European Commission. 2030 Climate Target plan. [Retrieved December 16, 2020]. From: https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en

European Parliament. 2019. What is carbon neutrality and how can it be achieved by 2050? Updated September 23, 2020. [Retrieved September 28, 2020]. From: https://www.europarl.europa.eu/news/en/headlines/society/20190926STO62270/what-is-carbon-neutrality-and-how-can-it-be-achieved-by-2050

Finnish Forest Association. Biologinen hapenkulutus (biological oxygen demand). [Retrieved September 29, 2020]. From: https://smy.fi/sanasto/biologinen-hapenkulutus-biological-oxygen-demand/

Finnish Government. Hiilineutraali ja luonnon monimuotoisuuden turvaava Suomi. [Retrieved August 17, 2020]. From: https://valtioneuvosto.fi/marinin-hallitus/hallitusohjelma/hiilineutraali-ja-luonnon-monimuotoisuuden-turvaava-suomi
Finnish Forest Industries. 2017. Metsäteollisuus ja energia. [e-document]. [Retrieved September 9, 2020]. From: https://www.metsateollisuus.fi/uploads/2017/03/30041711/880.pdf

Finnish Forest Industries. 2018a. Sähkönkulutus sektoreittain 2017. Updated October 11, 2018. [Retrieved September 3, 2020]. From: https://www.metsateollisuus.fi/tilastot/energia-ja-logistiikka/

Finnish Forest Industries. 2018b. Metsäteollisuuden tehdaspolttoaineet 2017. Updated October 11, 2018. [Retrieved September 3, 2020]. From: https://www.metsateollisuus.fi/tilastot/energia-ja-logistiikka/

Finnish Forest Industries. 2019. Metsäteollisuuden osuus tavaraviennistä 20,7 prosenttia vuonna 2019. Updated June 6, 2019. [Retrieved September 1, 2020]. From: https://www.metsateollisuus.fi/edunvalvonta/talous-ja-suhdanteet/metsateollisuuden-osuus-tavaraviennista/

Finnish Forest Industries. 2020. Massan tuotanto Suomessa. Updated March 15, 2020. [Retrieved September 8, 2020].

Finnish Forest Industries. 2020. Korona painoi metsäteollisuuden tuotantoa – vain kartongin ja sellun tuotanto kasvoi huhti-kesäkuussa. Updated July 7, 2020. [Retrieved August 17, 2020]. From: https://www.metsateollisuus.fi/tiedotteet/korona-painoi-metsateollisuuden-tuotantoa/

Gao J. 2014. Modelling latency removal in mechanical pulping processes. [Dissertation]. The University of British Columbia (Vancouver). 140 p. [Retrieved October 7, 2020]. From: https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0167251

Hartler N. 1986. Wood quality requirements in mechanical pulping. [e-article]. Sweden, Stockholm: Royal Institute of Technology. [Retrieved September 25, 2020]. From: http://npprj.spci.se/spcihtml/storage/1986-01-01-p004-010-Hartler.pdf

Hietanen M. 2007. Hiokkeen laatuvaihteluja aiheuttavat tekijät ja vaihteluiden vaimentamismahdollisuudet. [Master's thesis]. Lappeenranta: LUT University. 92 p. [Retrieved September 25, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/30186/TMP.objres.645.pdf?sequence=1

Houtman C. & Tapas K. 2004. Evaluating chemical-, mechanical-, and bio-pulping processes and their sustainability characterization using life-cycle assessment. [Retrieved September 8, 2020]. From: https://onlinelibrary-wiley-com.ezproxy.cc.lut.fi/doi/epdf/10.1002/ep.10054

Ikonen U. 2012. Suomen kemiallisen metsäteollisuuden päästökehitys vuoteen 2020. [Master's thesis]. Lappeenranta: LUT University. 137 p. [Retrieved September 30, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/78918/Diplomityo_Ikonen_Ulla_2012.pdf?sequence=1&isAllowed=y

Illikainen M. 2008. Mechanisms of thermomechanical pulp refining. [Dissertation]. Oulu: University of Oulu. 78 p. [Retrieved October 7, 2020]. ISBN 978-951-42-8906-4. From: http://jultika.oulu.fi/files/isbn9789514289064.pdf

Kallioinen A. et al. 2003. Biotechnical methods for improvement of energy economy in mechanical pulping. VTT. [Retrieved September 29, 2020]. From: https://www.vttresearch.com/sites/default/files/pdf/tiedotteet/2003/T2183.pdf

Kilpeläinen J. 2000. Sellun kuivauskoneen ajettavuusongelman monimuuttujainen tarkastelu. [Master's Thesis]. Lappeenranta: LUT University. 118 p. [Retrieved September 14, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/34703/nbnfi-fe20021182.pdf?sequence=1

Kivistö A. & Vakkilainen E. 2014. Forest industry energy consumption – trends and effect of modern mills. Lappeenranta: LUT University. 166 p. ISBN 978-952-265-649-0.

Koponen. Termodynamiikan taulukot. Lappeenranta: LUT University. 42 p.

Kähkönen S. 2019. Energy efficiency of Finnish forest industry. [Master's thesis]. Lappeenranta: LUT University. 121 p. [Retrieved September 9, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/159263/diplomity%c3%b6_k%c3%a4hk%c3%b6nen_satu.pdf?sequence=1&isAllowed=y

Laitinen T. 2011. Reduction of specific energy consumption of thermo-mechanical pulping plant. [Master's thesis]. Lappeenranta: LUT University. 84 p. [Retrieved September 28, 2020].

Lakanen L. 2011. Luonnon kasvihuonekaasulähteiden ja -nielujen laskenta maakunnallisella tasolla. [Master's thesis]. Lappeenranta: LUT University. 87 p. [Retrieved September 28, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/69662/nbnfife201105051508.pdf?sequence=3&isAllowed=y

Lamminen M. 2020. Understanding the fines in BCTMP process. [Master's thesis]. Lappeenranta: LUT University. 90 p. [Retrieved September 25, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/160829/Diplomityo_Lamminen_Mikko.pdf?sequence=1&isAllowed=y

Leino V. 2018. Ruuvikuljettimen jäähdytystehon määrittäminen. [Master's Thesis]. Lappeenranta: LUT University. 56 p. [Retrieved September 14, 2020]. From: https://lutpub.lut.fi/bitstream/handle/10024/152961/Diplomity%c3%b6_Ville_Leino.pdf?sequence=1&isAllowed=y

Metsä Board. Joutseno BCTMP pulp mill. [Retrieved September 1, 2020]. From: https://www.metsaboard.com/About-Us/Joutseno-pulp-mill/Pages/default.aspx#

Metsä Group. a. Kestävän kehityksen tavoitteet ja toteumat. [Retrieved August 17, 2020]. From: https://www.metsagroup.com/fi/kestava-kehitys/kestavan-kehityksen-johtaminen/kestava-kehitys-tavoitteet-toteumat/Pages/default.aspx#

Metsä Group. b. Towards fossil free mills. [Retrieved September 1, 2020]. From: https://www.metsagroup.com/en/media/Pages/Case-Towards-fossil-free-mills.aspx#

Mingxing S. et al. 2018. Uncovering energy use, carbon emissions and environmental burdens of pulp and paper industry: a systematic review and meta-analysis. [e-article]. ScienceDirect. [Retrieved September 8, 2020]. From: https://www-sciencedirect-com.ezproxy.cc.lut.fi/science/article/pii/S1364032118302636?via%3Dihub

Ministry of Agriculture and Forestry of Finland. Suomen metsävarat. [Retrieved September 1, 2020]. From: https://mmm.fi/metsat/suomen-metsavarat

Ministry of Economic Affairs and Employment of Finland. 2019. Finland's Integrated Energy and Climate Plan. Helsinki. 183 p. ISBN 978-952-327-478-5.

Mujumdar A. (ed.) 2015. Handbook of industrial drying. [e-book]. 1318 p. ISBN 978-1-4665-9665-8.

Natural Resources Institute Finland. 2019. Suomen metsät 2019. [Retrieved September 1, 2020]. From: https://www.luke.fi/wp-content/uploads/2019/09/finlands-forests-facts-2019-fi.pdf

Ocean & Climate Platform. The Ocean, a carbon sink. [Retrieved September 28, 2020]. From: https://ocean-climate.org/?page_id=3896&lang=en
Official Statistics of Finland. 2018. Teollisuuden energiankäyttö. Updated November 19, 2018. [Retrieved September 3, 2020]. From: https://www.stat.fi/til/tene/2017/tene_2017_2018-11-19_tie_001_fi.html

Paterson D. 2020. Understanding the dynamics of pulp fibre suspension dewatering. The University of British Columbia (Vancouver). [Dissertation]. [Retrieved September 21, 2020]. From: https://open.library.ubc.ca/cIRcle/collections/ubctheses/24/items/1.0392476

Regional State Administrative Agency of Southern Finland. 2017. Päätös 229/2017/1. Joutsenon tehtaan ympäristöluvan lupamääräysten tarkistaminen, Lappeenranta. [Environmental permit decision]. Updated November 30, 2017. [Retrieved: September 7, 2020].

Reme P. 2000. Some effects of wood characteristics and the pulping process on mechanical pulp fibres. [Doctoral thesis]. [Retrieved September 29, 2020]. From: https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/248066/123085_FULLTEXT01.pdf?sequence=1&isAllowed=y

Roberts A. 2015. Bulk Solids: Optimizing screw conveyors. The University of Newcastle (Australia). [e-article]. [Retrieved September 21, 2020]. From: https://search-proquest-com.ezproxy.cc.lut.fi/docview/1653394012/fulltextPDF/F6B7E64A58B8425BPQ/1?accountid=27292

Sandberg C. et al. 2019. On the development of the refiner mechanical pulping process – a review. [e-article]. [Retrieved September 10, 2020]. From: https://www.researchgate.net/publication/339180607_On_the_development_of_the_refiner_mechanical_pulping_process_-_a_review

Sandberg C. et al. 2017. Process intensification in mechanical pulping. [e-document]. [Retrieved September 10, 2020]. From: https://www.diva-portal.org/smash/get/diva2:1168778/FULLTEXT01.pdf

Sappi North America. 2017. Understanding paper brightness. [e-document]. [Retrieved September 28, 2020]. From: https://cdn-s3.sappi.com/s3fs-public/sappietc/Understanding%20Paper%20Brightness.pdf

Seppälä M. et al. 2004. Kemiallinen metsäteollisuus 1 - Paperimassan valmistus. Saarijärvi: Opetushallitus. 2-2nd edition. 196 p. ISBN 952-13-1142-8.

SFS 2470. 2003. Paper, board and pulps. Measurement of diffuse blue reflectance factor (ISO brightness). Helsinki: Finnish Standards Association SFS. 19 p. [Retrieved October 6, 2020].

SFS 638. 2008. Paper, board and pulps. Determination of dry matter content. Oven-drying method. Helsinki: Finnish Standards Association SFS. 18 p. [Retrieved October 13, 2020].

Statistics Finland. 2020. Fuel classification. [Retrieved December 2, 2020]. From: https://www.stat.fi/tup/khkinv/khkaasut_polttoaineluokitus.html

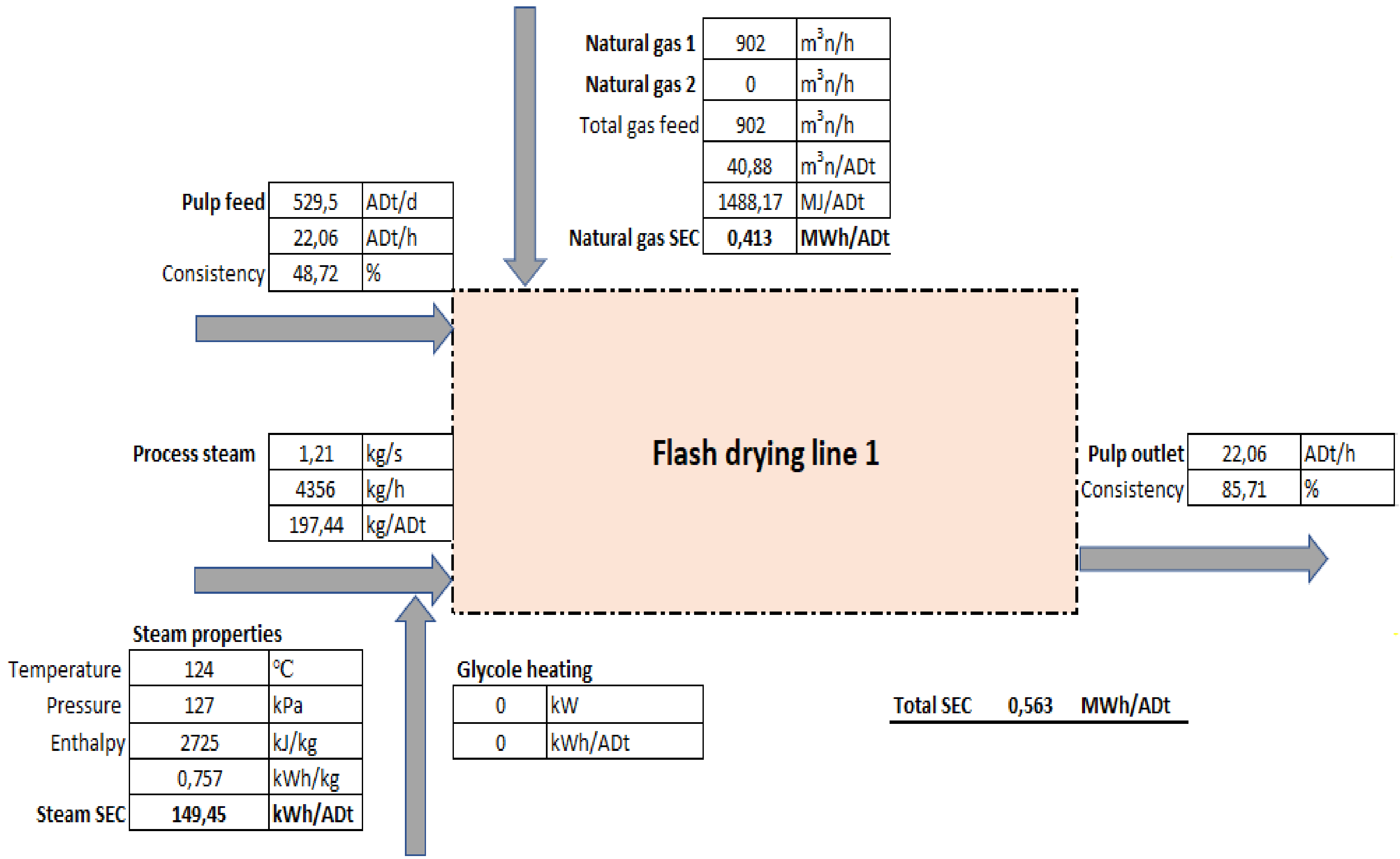
Ukkonen M. 2005. Metsäteollisuuden jätevesien häiriöpäästöt ja niihin varautuminen CASE: Kaakkois-Suomi. Kaakkois-Suomen Ympäristökeskus. ISBN 952-11-1999-3 (PDF).

Valmet. Conical disc refiner. [Retrieved September 10, 2020]. From: https://www.valmet.com/pulp/mechanical-pulping/refining-and-grinding/high-consistency-refiner/conical-disc-refiner/

Vanninen Markus. 2009. Tyypillisten biomassamateriaalien kemiallinen koostumus. University of Jyväskylä. [Master's thesis]. Updated May 12, 2009. [Retrieved September 7, 2020]. From: https://jyx.jyu.fi/bitstream/handle/123456789/21265/1/URN_NBN_fi_jyu-200906261753.pdf

Zhang J. et al. 2017. Fatigue and fracture failure analysis of a twin-roll press. [e-article]. Updated October 4, 2017. [Retrieved September 14, 2020]. From: https://www-sciencedirect-com.ezproxy.cc.lut.fi/science/article/pii/S1350630717310592?via%3Dihub

Energy balance of the flash drying process



Natural gas

Natural gas 1	902	m^3n/h
Natural gas 2	0	m^3n/h
Total gas feed	902	m^3n/h
	40,88	m^3n/ADt
	1488,17	MJ/ADt
Natural gas SEC	**0,413**	**MWh/ADt**

Pulp feed	529,5	ADt/d
	22,06	ADt/h
Consistency	48,72	%

Process steam	1,21	kg/s
	4356	kg/h
	197,44	kg/ADt

Pulp outlet	22,06	ADt/h
Consistency	85,71	%

Steam properties

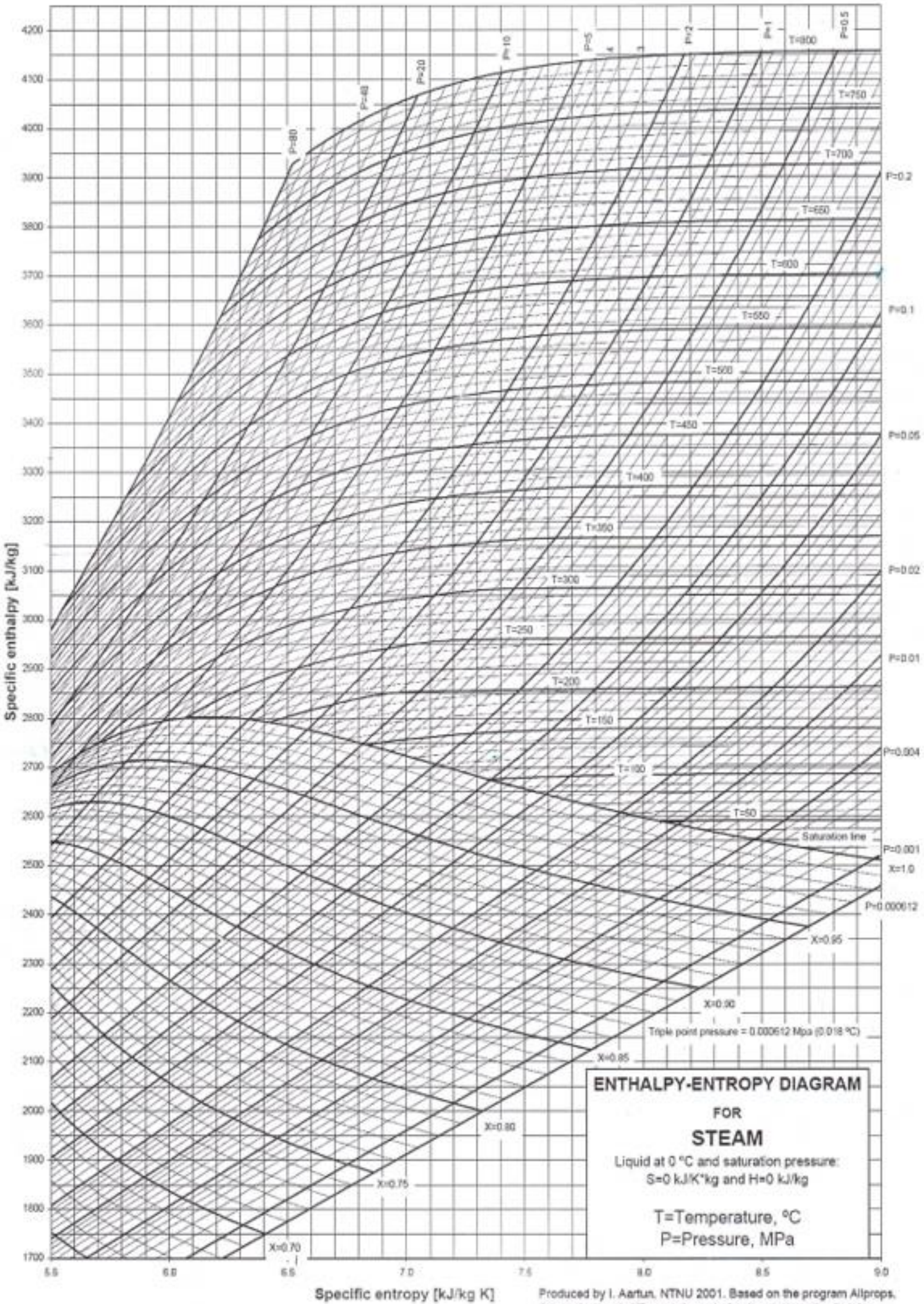
Temperature	124	°C
Pressure	127	kPa
Enthalpy	2725	kJ/kg
	0,757	kWh/kg
Steam SEC	**149,45**	**kWh/ADt**

Glycole heating

0	kW
0	kWh/ADt

Total SEC	**0,563**	**MWh/ADt**

Enthalpy-entropy diagram for steam



Produced by I. Aartun, NTNU 2001. Based on the program Allprops, Center for Applied Thermodynamic Studies, University of Idaho.