Lappeenranta University of Technology

School of Energy Systems

Energy Technology

Jaakko Leino

Technological aspects of implementing Industrial Symbiosis in forest industry

Examiner: Professor Esa Vakkilainen

Supervisor: Professor Eeva Jernström

ABSTRACT

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Master's thesis

2016

68 pages, 21 figures, 11 tables and 1 appendix

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Keywords: Industrial Symbiosis, Paper industry, Lignin, Hemicellulose, Waste heat, Sludge, Teollinen symbioosi, Paperiteollisuus, Ligniini, Hemicelluloosa, Jätelämpö, lietteet Energia / Energy; Tekniikka / Technology

Object of this thesis is to discover possibilities how preselected side streams found in UPM Kaukas can be utilized as a part of industrial symbiosis and what are the main points when implementing new technologies to existing pulp mill. Secondary objective is to find out how UPM Kaukas compares to other eco-industrial parks and industrial symbioses.

Current state of UPM Kaukas industrial symbiosis and comparison to other similar eco-industrial parks and the impacts of the pre-selected side stream utilization technologies to existing pulp mill were studied with literature review. Following side stream utilization technologies were selected for technoeconomic analysis: Lignin extraction, hemicellulose extraction and organic rankine process. Technoeconomic analysis was conducted by calculating internal return rate with 10-year payback duration.

On the basis of side stream utilization technologies impacts to existing pulp mill and their economic profitability instruction to develop industrial symbiosis was made.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
School of Energy Systems
Energiatekniikan koulutusohjelma

Jaakko Leino

Teollisen symbioosin teknologinen toteutus metsäteollisuudessa

Diplomityö

2016

Tarkastaja: Professori, TkT Esa Vakkilainen
Ohjaajat: Professori TkT Eeva Jernström

68 sivua, 21 kuvaa, 11 taulukkoa ja 2 liitettä

Hakusanat: Industrial Symbiosis, Forest industry, Lignin, Hemicellulose, Waste heat, Sludge, Teollinen symbioosi, metsäteollisuus, Ligniini, Hemiselluloosa, Jätelämpö, lietteet Energia / Energy; Tekniikka / Technology

Tässä työssä perehdytään teollisen symbioosin teknologiseen toteutukseen paperiteollisuudessa. Työn tavoitteena on selvittää miten ennalta valittuja sivuvirtoja voidaan hyödyntää osana teollista symbioosia ja mitkä ovat tärkeimmät toimenpiteet uusien teknologioiden käyttöönotossa. Työn toisena tavoitteena on selvittää UPM Kaukaan teollisen symbioosin nykytila ja sen suhde muihin samankaltaisiin toimijoihin.

UPM Kaukaan teollisen symbioosin nykytila ja sen suhde muihin toimijoihin selvitettiin kirjallisuuskatsauksen avulla. Tarkasteluun valittujen sivuvirtojen hyödyntämistekniikoiden vaikutukset sellutehtaan toimintaan käytiin läpi kirjallisuuskatsauksen kautta. Taloudelliseen tarkasteluun valittiin ligniinin ja hemiselluloosan erotus sekä jätelämmön hyödyntämiseen orgaaninen rankine prosessi. Taloudellisessa tarkastellussa valituille tekniikoille laskettiin 10-vuoden efektiivinen korko. Tarkasteluun valittujen hyödyntämistekniikoiden vaikutukset nykyisen sellutehtaan toimintaan ja niiden taloudellisten kustannuksien perusteella muodostettiin toimintaohjeet teollisen symbioosin kehittämiseen.

TABLE OF CONTECTS

ACKNOWLEDGEMENTS

I wish to thank my supervisors Professors Esa Vakkilainen and Eeva Jernström for great assistance for this work and for giving me this opportunity. This thesis was done for UPM Kaukas and it was very challenging and rewarding.

Five years ago I did not expect this work to be done so quickly. I'm forever grateful to be allowed to do all the great things in the past years. Being a member of Armatuuri and LTKY has taught me a lot about life and how to face people how they are. I want to thank all my friends for helping me with school and life in general. I hope that everyone I had to pleasure to meet remembers all the good things we did.

I thank my family for always having my back even when I was feeling down. Especially my sister Maija who gave me a lot of guidance for doing this Thesis.

Lastly I want to thank my girlfriend Inari who has stood with me all these years and gave her unconditional love.

Lappeenranta, September 18th, 2016

Jaakko Leino

LIST OF SYMBOLS

a	present value factor that gives net present value zero	
C_e	Shared side stream flow utilization examined	
C_t	Total side stream utilization connections examined	
C_product	annual revenue from selling end product	
$C_\mathrm{O\&M}$	annual operating and maintenance cost	
C_inv	total investment cost	
L_e	By-product flows	
L_p	Product flows	
S	Companies in a eco-industrial park	
MW_e	power of electricity production	[J/s]

Abbreviations

NPV	Net present value
ORC	Organic Rankine cycle

1 INTRODUCTION

Global population growth and continuously rising consumption of natural resources has led to growing pressure on ecosystem and to sustainability crisis. Actions to resolve this crisis must be taken quickly. If these challenges are not taken seriously global markets and wellbeing of humankind could be threatened. Scarcity of natural resources will increase the prices of important resources and higher utilization rates or materials are needed. Forerunning countries and companies can harvest the greatest economic benefits in this situation as they have prepared to the new conditions and can help others to survive. (Sitra 2014, 3) Industrial symbiosis studies the exchange of resources between companies. Such resources are materials, energy and water in regional and local economies. Availability of these resources in contrast to price is usually under interest but sharing and co-operation to share these resources are often overlooked. (Chertow 2000, 313)

This master's thesis is a part of UPM Corporate decision to build a model of industrial symbiosis to UPM Kaukas Eco-Industrial park. This master's thesis is focused on the technological aspects of how industrial symbiosis could be implemented in UPM Kaukas and master's thesis by Tuomas Lankinen discusses business models around industrial symbiosis to UPM Kaukas. These two master thesis were also supervised by steering group which had representatives from UPM, Lappeenranta University of Technology, and Green Campus Innovations.

Object of this thesis is to discover possibilities how preselected side streams found in UPM Kaukas can be utilized as a part of industrial symbiosis and what are the main points when implementing new technologies to existing pulp mill. Other objective is to find out how UPM Kaukas compares to other eco-industrial parks and industrial symbioses. Kalundborg industrial symbiosis was selected as an comparison site due to its well documented development and the availability of literature discussing the realization of the symbiosis. Other eco-industrial parks were also studied due to their similarity and location that match UPM Kaukas operation environment.

The side streams of UPM Kaukas to be focused on this thesis were decided by the steering group. Possible solutions for each side stream were selected with the help of expert advice. After the technical presentation of each solution for each side stream three side streams were selected for economic analysis. Criteria for economic analysis selection were their relevancy to UPM Kaukas.

First this thesis will go through relevant industrial symbiosis theory and how Finnish paper industry has developed in regards to industrial symbiosis. Then the current side stream utilization state of UPM Kaukas is discussed and it is compared to other similar eco-industrial parks. Identified technological solutions are analyzed through their impacts on current pulp mill operation. Technoeconomic analysis is conducted with costs assumptions acquired from other similar studies. The object of the calculation is to find out internal return rate for each technological solution.

2 INDUSTRIAL SYMBIOSIS

Industrial symbiosis is usually seen as subfield of industrial ecology. Traditionally, industrial symbiosis gives separate companies an advantage through exchange of materials, by-products, energy and water. (Chertow 2007, 12) The term symbiosis comes from biological symbiosis in nature where two species exchange needed goods in a way that benefits both. Collaboration and exchanging goods between companies benefits both parties compared to stand alone case. (Chertow 2000, 315)

The most used definition of industrial symbiosis is: “Engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and synergistic possibilities offered by geographic proximity” (Chertow 2000, 313). It has however been proposed to be changed to the following: “Industrial symbiosis engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes.”(Lombardi et al. 2012, 31-32)

The aim of industrial ecology is to move towards re-cycling material and energy flows and minimizing losses of materials and energy. It is usually considered that the more connections a symbiosis has the more stable it is. Number of connections compared to the number of companies in a symbiosis is a way of comparing the state of symbiosis. More companies usually means that it is more environmentally friendly. (Pakarinen et al 2009, 1394)

Industrial symbioses have set of requirements that they have to meet to be in a good enough state to be further developed. Trust and co-operation are important for successful industrial symbiosis and innovative solutions increase improvements in material usage.

It has been shown that industrial symbioses that evolve naturally are more durable and more profitable for both parties of the deal. (Pakarinen et al 2009, 1394)

Elements like geographic proximity of partners, symbiosis organizers, diversity of industries, resource sharing and recognition of added profit from material flows are important for the symbiotic relationship. Connections between companies can be physical by products and utilities or logistics or other shared services. (Chertow 2004, 10)

The classical example of industrial symbiosis is the symbiosis of the Kalundborg municipality in Denmark. The studies done in Kalundborg have helped spreading the term industrial ecology and industrial symbiosis both intentionally and by showcasing the benefits of mutualism. All of the connections of the Kalundborg symbiosis have been negotiated independently at it has evolved on economical benefits of using side streams and waste products. Economical benefits have been the sole reason for expansion of the symbiosis. (Chertow 2012, 4)

2.1 Driving forces of industrial symbiosis

The greatest driving forces behind industrial symbiosis are the mutual economic benefits. The highest economical benefits are usually reached through lower raw material costs and decreased waste handling costs. These benefits are acquired by using waste or by-product streams of other companies as a raw material in company’s own production processes. As mentioned earlier, this was also an important part of the development of Kalundborg symbiosis. (Zhang 2015, 92)

Second driving force of the development of the industrial symbiosis is legislation. Legislation can tighten the emission levels or waste discharge amounts that factories can produce and regulates the needs for sustainable production. Legislation has been the main factor of designed industrial symbioses as opposed to naturally evolved symbioses. (Zhang 2015, 92)

Third driving force of industrial symbiosis are the improvements in different technologies. These improvements include new innovations and improved methods of producing new products from waste materials. These reuse applications can allow better material utilization and better waste management. (Zhang 2015, 93)

All these driving forces together influence the development and beginning of industrial symbioses. Which of the driving forces influence the most differs greatly between cases. Figure 1 presents the formation conditions of industrial symbiosis. When co-operation between symbiosis partners is organized and well planned formation conditions are beneficial for symbiosis. Economic benefits must be good enough for both of the new symbiosis parties and exchange of goods have to be possible to enable good formation conditions for industrial symbiosis.

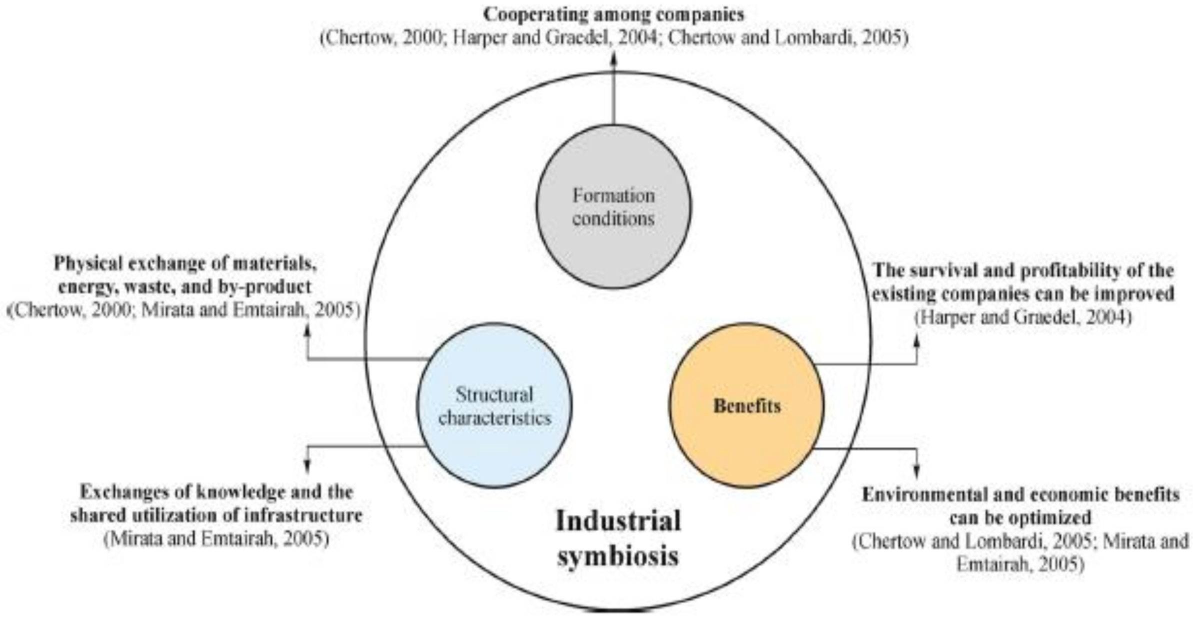


Figure 1: The formation conditions of the industrial symbiosis. Source: Zhang 2015

2.2 Types of industrial symbioses

Industrial symbioses types are usually categorized in the literature in regards to following factors: proximity and how the formation was influenced. Proximity based specification is usually dived in to virtual eco industrial parks and co-located eco industrial parks. Co-located eco industrial parks are formed in immediate proximity or in a very small location. Virtual eco-industrial parks can be more spread out as the distance is not a factor. Benefits of virtual eco industrial parks are mainly in the low costs of the infrastructure as no new plants or equipment is needed to be constructed or purchased. (Zhang 2015,94)

Co-located parks however have multiple advantages compared with virtual eco industrial parks. Costs of transportation are minimized and the risks that include to it are minimized e.g. risks of leakage or possible contamination of the product during the transportation. As mentioned earlier the problem of using waste and by-products is usually low refining potential. If the transportation costs are too high the material costs might rise too high to be profitable.

Classification types on the basis of how the formation was influenced are planned eco industrial parks and self-organized eco industrial parks. For the self-organized parks the connections and the processes have been independently negotiated and the economic benefits are the main driver. The economic benefits include, as listed before, lower costs of raw material, lower waste treatment costs and lower emissions for both parties of the symbiosis. The most used example for self-organized parks is the Kalundborg symbiosis. Planned eco industrial parks are as the name implies planned before hand and usually due the government regulations of waste and emissions. (Zhang 2015, 94)

2.3 Stages of implementing industrial symbiosis

This section will discuss the stages of industrial symbiosis and they are described based on the work of Chertow & Ehrenfeld (2012). As these stages are being presented the latter can’t exist without the former stages. The stages of industrial symbiosis are 1) Sprouting, 2) Uncovering, and 3) Embeddedness and institutionalization. In the sprouting stage only couple side stream exchange connections are formed and waste is not seen as a resource. Existing or not even started exchange connections are formed due to legislation, economic efficiency, material security and waste treatment costs. Connections are seen as one sided affairs one being the payer and other the user or the one that processes the wastes. This stage can’t be seen as industrial symbiosis. (Chertow & Ehrenfeld 2012, 13)

Companies share the mutual goal of seeking new revenue and cutting costs of current business. For material or resource exchanging connections to be successful they have to be beneficial for both. If not done with cation finding new business partners and side streams to utilize can produce more costs. (Chertow & Ehrenfeld 2012, 15)

In uncovering stage previously established connections are important. Companies that form connections benefit from new material exchange connections so greatly that alsonew companies want to join in. When enough connections are formed they produce enough benefits to keep people working together and differences in production processes have lesser impacts. If these benefits are not publicly presented symbiosis can have difficulties to grow and formed connections will work only as long as they produce net benefits for the participants. (Chertow & Ehrenfeld 2012, 18)

Institutions that do continuous work towards developing symbioses can be formed from the existing companies or can be totally new actors. But it is very important that it is agreed on by the symbiosis partners to be equal in the decision making. These institutions can have members from government organizations or academic world in addition to the company representatives. Institutional examples are Kwinana Industry Council in Australia, Kawasaki Liaison Center for Creation of Industry and Environment in Japan, National Industrial Symbiosis Programme in United Kingdom and Symbiosis Institute in Denmark. (Chertow & Ehrenfeld 2012, 20)

This phase relies greatly in champion companies that take the next step towards formation of symbiosis.

In the first stage, sprouting, new connections are formed and in second stage, uncovering, system is under a closer look so it can be more evolved and utilize all the possibilities. In the third stage, embeddedness and institutionalization, institution helps in involving companies to quantify the indirect benefits into more easily understandable form that can be added to company’s favor such as social capital. Measuring social capital is not always easy and it can be difficult to define. Social capital includes ways to share mutual benefit like norms, networks and trust. (Chertow & Ehrenfeld 2012, 27)

2.4 Industrial Symbiosis in Finnish paper industry

Pulp and paper industry in Finland has been an important part of Finnish industry for a long time. The development of paper industry is a good example of symbiotic relationship. All the production facilities are part of bigger complex that has one key process in mind the development throughout the history of paper industry is remarkable way of getting most out of the raw material. Chemical manufacturing plant, power plant activities, waste water treatment and chemical regeneration all link to the pulp mill. Usually the power plant is connected to municipality to provide heat, electricity and employment. (Pakarinen et al 2010)

Pakarinen et al. researched UPM Kymi’s evolution as an Eco-industial park. From the first two plants that were built in 1872 they used wastes as raw material as the material used for paper making was old rags and used cotton. In the figures 2 and 3 evolution of so called internal industrial symbiosis can be seen as other processes use energy or side streams. Usage of the term internal symbiosis was proposed by Chertow in 2000 but as stated earlier industrial symbiosis is usually defined as multiple companies working together.

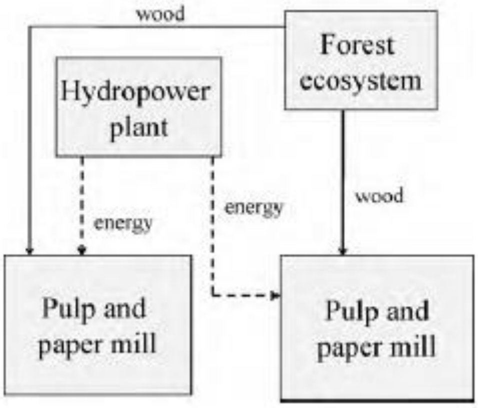
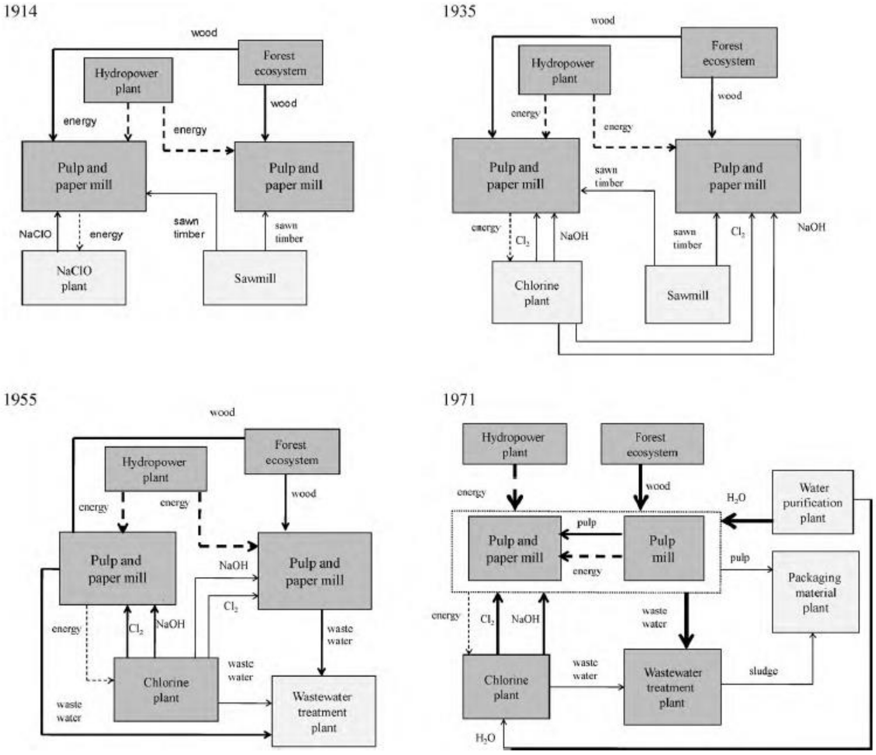


Figure 2: First paper mill in Kymi (Pakarinen et al 2010)



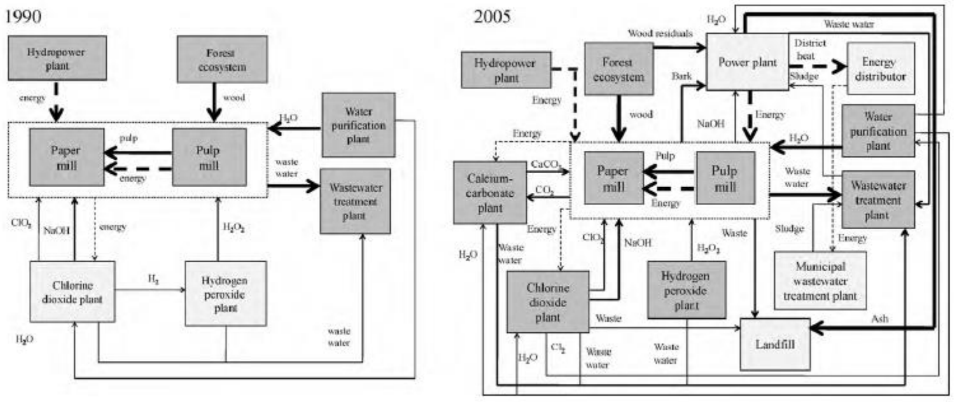


Figure 3: Process evolution of UPM Kymi paper mill. Light grey boxes are new processes. (Pakarinen et al. 2010)

2.5 Sustainable development and industrial symbiosis

When considering industrial symbiosis in pulp and paper industry Sokka et al. (2008) have proposed set of system conditions to help analyze if industrial symbioisis is beneficial in the context of sustainable development. System conditions and indicators used are presented in table 1.

Table 1: Industrial symbiosis system conditions in the context of sustainable development. After: Sokka et al. 2008.

Condition 1	Condition 2	Condition 3	Condition 4
Does the IS systematically contribute to:			
Reducing the throughput of minerals that are scarce in nature?	Substitution of substances that are persistent and non-degradable in nature?	Phasing out destructive patterns of interference with the ecosystems?	Reducing risks to human health caused by the pollution of the environment?

More eco-efficient use of extracted materials?	More eco-efficient use of materials/products?	Extracting resources from well-managed ecosystems only?	Preserving resources for future generations (through systematic dematerialization and substitution)?
Reducing the dependence on fossil fuels?		Favouring less area-consuming activities?	Not undermining the living conditions of the world's poor people?
Indicators used			
Recycling of metals	Recovery of process chemicals	Extraction of wood and other resources	Health risks of the pollution
Waste and by-product utilization	Hazardous emissions to water	Other area consuming activities	Local social sustainability
Fuel use	Other emissions to water		
	Emissions to air		
	Recycling and waste treatment		

In the first system condition indicators used to evaluate this case eco-industrial park improved continuously during the time span that was under inspection in this article. Use of renewable raw materials and energy sources increased significantly and waste reuse was present from the start. Times of recession and war produced the biggest leaps of development in the Finnish forest industry. Finnish legislation also promoted better waste management. (Pakarinen et al. 2010, 1401) Latest addition to organic waste handling that need to be taken into consideration is Finnish government regulation (Finnish government decree on land fields 331/2013) which restricts dumping of the organic material in to landfill. (Pakarinen et al. 2010, 1401)

System condition 2 indicators were substantially improved when Finnish legislation started to oversight emission values. Emissions per ton of pulp were lowered by changing fuels used but total SO_x and NO_x emission amounts were significantly rising until legislation was restricted and technology improved. (Pakarinen et al. 2010, 1401)

System condition 3 indicators were focused on land use change. Total area of land needed increased throughout the development of the case symbiosis due to increased pulp production which needs more wood, development of paper quality caused by mineral fillers and most significantly the drying of the marshlands which has decreased biodiversity. Total land are needed for ton of pulp is lower but total land usage is not considered to be beneficial to sustainable development. (Pakarinen et al 2010, 1401)

System condition 4 focused on social and health effects on humans. Biggest effects in this category this case eco-industrial park has had to water pollution. Studied toxicology studies imply that emissions released to nature have ill effects for decades after release. Worker safety and interaction with local municipality has improved throughout the history of case eco-industrial park. Worker safety has been improved by the actions of the government and labor union and necessary improvements have been made. Interaction with local municipality has changed towards more collaboration than education. (Pakarinen et al. 2010,1401)

Improvements that has been made in UPM Kymi can be seen in grand scheme of Finnish paper industry. In some cases one of the biggest driving forces of improvement has been Finnish legislation.

3 UPM KAUKAS

UPM Kaukas mill is located in Lappeenranta on the shore of Lake Saimaa. Mill produces 740 000 tonnes of pulp annually. Other products include paper, biochemicals, electricity and heat, and crude tall oil. The industrial site includes Pulp mill, Kaukaan Voima biomass power plant and UPM Biodiesel refinery. Figure 4 is the map of the Kaukas eco-industrial park. Current actors in the Kaukas eco-industrial park site are UPM, Kaukaan Voima which is owned by Pohjolan Voima Oy and Lappeenrannan Energia Oy and shared utility provider Caverion.

Figure 4: UPM Kaukas

UPM Kaukas consist of saw mill, kraft pulp mill, mechanical pulp mill, saw mill, biorefinery and bio-power plant Kaukaan Voima. Current process flow is presented in figure 5.

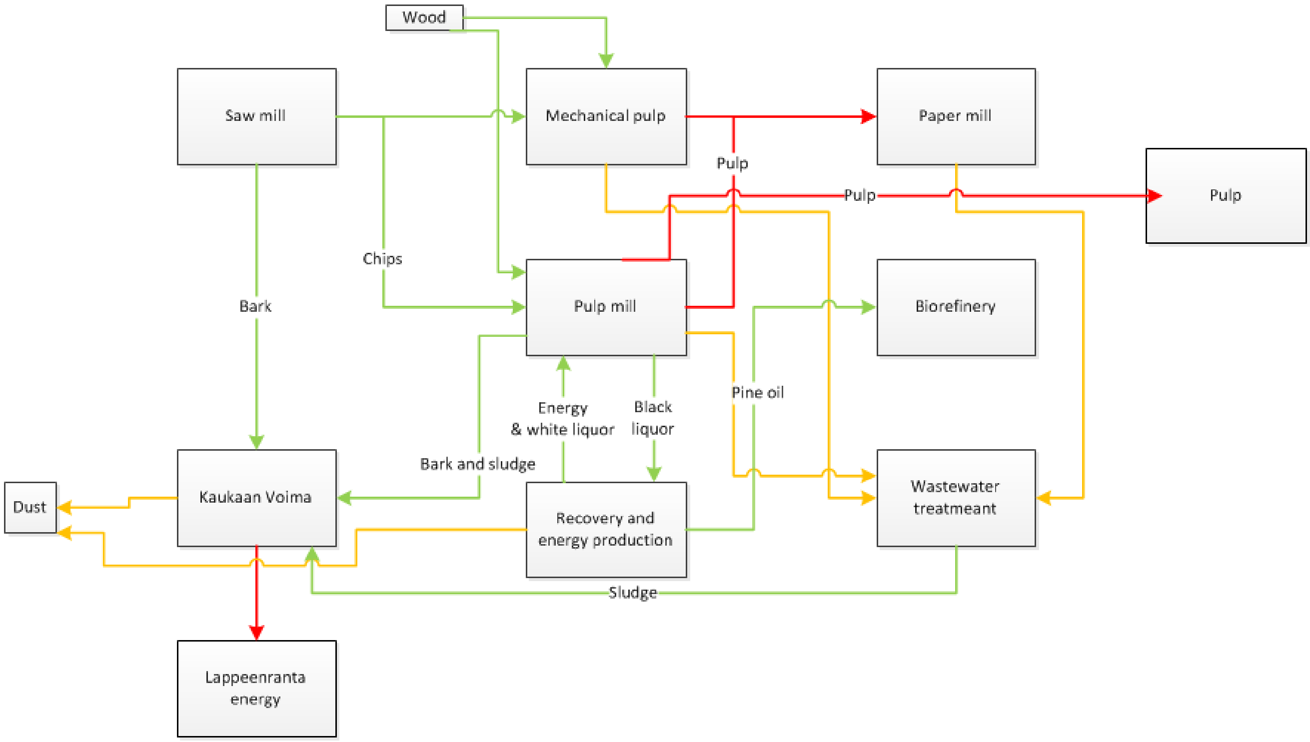


Figure 5: Current state of material flows. Green arrows are raw material, orange arrows are waste flows and red arrows are core business flows.

3.1 Current situation of waste usage

In 2015 total waste amount was 42 000 tons of solid wastes. From this amount 6 745 was deposited to Tuosa landfill. Biggest single waste stream was green liquor dregs. Same year 29 800 tons of waste were reused or stored. Table 2 presents all the waste streams that are currently utilized.

Table 2: Current waste handling situation. Source 2015 UPM Kaukas EMAS

Waste to landfill	**Amount [t/a]**
Green liquor dregs	5582
Mixed Waste	276
Effluent drainage	1175
Reused waste	
Cleaned wood waste	4938
Green liquor dregs and lime	1333
Coating colour sludge	9059
Fibre sludge	6752
Sludge from effluent treatment plant	302
Lime kiln ash	663
Fly ash and bottom ash	200
Recyclable carbon and paper	8632
Metals	3
Other	496
Storaged waste	
Fibre sludge	3734
Lime kiln ash	3734
Sludge from effluent treatment plant	
Coating colour sludge	
Ash	
Total waste	**46879**
Waste re-usage percentage	**0,85**

3.2 Possible evaluation methods for UPM Kaukas eco-industrial park

As mentioned earlier eco-industrial parks and industrial symbiosis systems are complex and usually have multiple companies as partners and they exploit multiple side streams from each other processes. This chapter will discuss the way of comparing how the industrial symbiosis is evolving and how they can be compared with other similar eco-industrial parks. The need for evaluation methods are more thoroughly discussed in the master thesis of Tuomas Lankinen, that was made under the same project as this thesis. In this master thesis the technical aspects of evaluation will be discussed.

3.2.1 Quantitative methods to analyze UPM Kaukas

Tienjun (2010,442) proposed indicators for eco-connectance and waste and by-product utilization rates. Connections with companies can be divided to product flows (L_p) and by-product flows (L_e) and these material flows make up the total flows (L_t) by the equation 1.

$$L_\mathrm{t} = L_\mathrm{e} + L_\mathrm{p} \qquad (1)$$

Eco-connectance can be calculated with equation 2.

$$C_\mathrm{t} = \frac{L_\mathrm{e}}{S(S-1)/2} \qquad (2)$$

where,

S Number of factories or enterprises in a eco-industrial park

Total connectance in eco-industrial park can be calculated using equation 3.

$$C_\mathrm{t} = \frac{L_\mathrm{e} + L_\mathrm{p}}{S(S-1)/2} \qquad (3)$$

At the moment only truly symbiotic relationships in Kaukas eco-industrial park is between UPM, Kaukaan Voima Oy and Lappeenrannan Energia Oy. In calculating the eco-connectance waste stream used is sludge and product flows are heat, electricity and bark. Figure 6 presents how different eco-industrial parks compare with each others using this evaluation method.

Figure 6: Eco-connectance applied to UPM Kaukas and reference. After Tiejun 2010.

Country	**Park**	**S**	**L_e**	**C_e**	**L_t**	**C_t**
Denmark	**Kalundborg eco-industrial park 1975**	6	1	0,067	6	0,400
	Kalundborg eco-industrial park 1985	9	7	0,194	11	0,305
	Kalundborg eco-industrial park 1995	10	12	0,266	16	0,356
China	**Guigang eco-industrial park in Guigang city of Guangxi province**	15	20	0,190	22	0,210
	Nanhai eco-industrial park in Nanhai city of Guangdong province	21	25	0,119	35	0,167
	Lubei eco-industrial park in Wudi country of Shandong province	12	20	0,303	31	0,470
	Shihezi eco-industrial park in Shihezi city of Xinjiang municipality	6	6	0,400	7	0,476
	Tuopai Alcohol eco-industrial park in Shehong county of Sichuan province	7	9	0,429	10	0,476
	Shenyang Tiexi eco-industrial park in Shenyang city of Liaoning province	25	25	0,083	34	0,113
	Fushun Mining eco-industrial park in Fushun city of Liaoning province	14	12	0,132	19	0,209
	Tonghua Zhangjia eco-industrial park in Tonghua city of Jilin province	13	22	0,282	24	0,308
Finland	**UPM Kaukas**	4	1	0,17	4	0,83

The differences between Kalundborg, Chinese eco-industrial parks and UPM is that the first one is naturally developed, Chinese are designed and UPM Kaukas is not yet truly symbiotic eco-industrial park by nature. In the case of Kaukas this model is flawed due the companies number of involved is not high and existing symbiotic connections are low in numbers (Tiejun 2010,447). What this model however tells when Kaukas symbiosis is developed how it can be compared to other eco-industrial parks.

3.3 State of UPM Kaukas

We conducted interviews with Tuomas Lankinen of the current state and future aspects of the industrial symbiosis. Current status in regards of moving towards industrial symbiosis is hopeful. Company has understood the need of seeking new markets in the upper management level. At the moment almost all of the waste and side stream utilization connections are one sided and they only cut some costs instead of bringing new revenue. Main exceptions are feedstock for Kaukaan Voima and tall oil for biorefinery. In table 3 all the current connections are listed.

Table 3:

Waste or side stream	**Other company's end use**
Sand from chip screening	Soil improvement
Lime kiln ash	Soil improvement
Bark and sludge	Burned in Kaukaan Voima boiler
Ash from Kaukaan Voima	Fertilizer
Tree branches	Material for making art
Coating sludge	Landfill closing material

Main reason to consider new side stream connections are to cut costs. Indirect economic benefits are seen as supplementary but they are not alone good enough to start new connections. They however have been in some cases but not in the case of UPM. Indirect economic benefits can be bigger incentives if general opinion turns against some circumstances as seen with the quality of lakes.

The greatest obstacles to starting new industrial symbiosis connections based on the interviews are:

- Uncertainty of new technology
- Legislation is too strict
- Payback times for investments are too long

3.3.1 Differences with Kalundborg symbiosis

As noted before Kalundborg symbiosis has developed in the time scale of decades. It has evolved rather slowly but has had continuous development over time. Table 4 has all the connections that are utilized in Kalundborg but are not used in UPM Kaukas.

Kalundborg symbiosis began to form in the 1960's and 1970's. First three companies were Statoil(Esso), Gyproc, and Dong Energy(Asnæs) sharing water and gas. (Symbiosis.dk 2016a) Biggest actors in the current symbiosis are the DONG Coal powered power plant with 1 500 MW_e, Statoil oil refinery, Novo Nordisk pharmaceuticals and enzymes and Gyproc plasterboard factory. In Table 4 is shown current list of companies involved in the symbiosis and their main business's. Figure 7 show the current flow diagram of the Kalundborg symbiosis.

Table 4: Companies in Kalundborg Symbiosis and their main business's

Company	**Main business**
DONG Energy	Electricity and heat
Novo Nordisk & Novonzymes	Pharmaceuticals
Statoil	Oil refining
Gyproc	Plasterboard
Inbicon	Biorefinery
Kara/Noveren	Waste treatment
Kalundborg Utility	City water supply and waste water treatment
Kalundborg municipality algae plant	Waste water treatment
Novozymes wastewater and biogas	Biomethane production

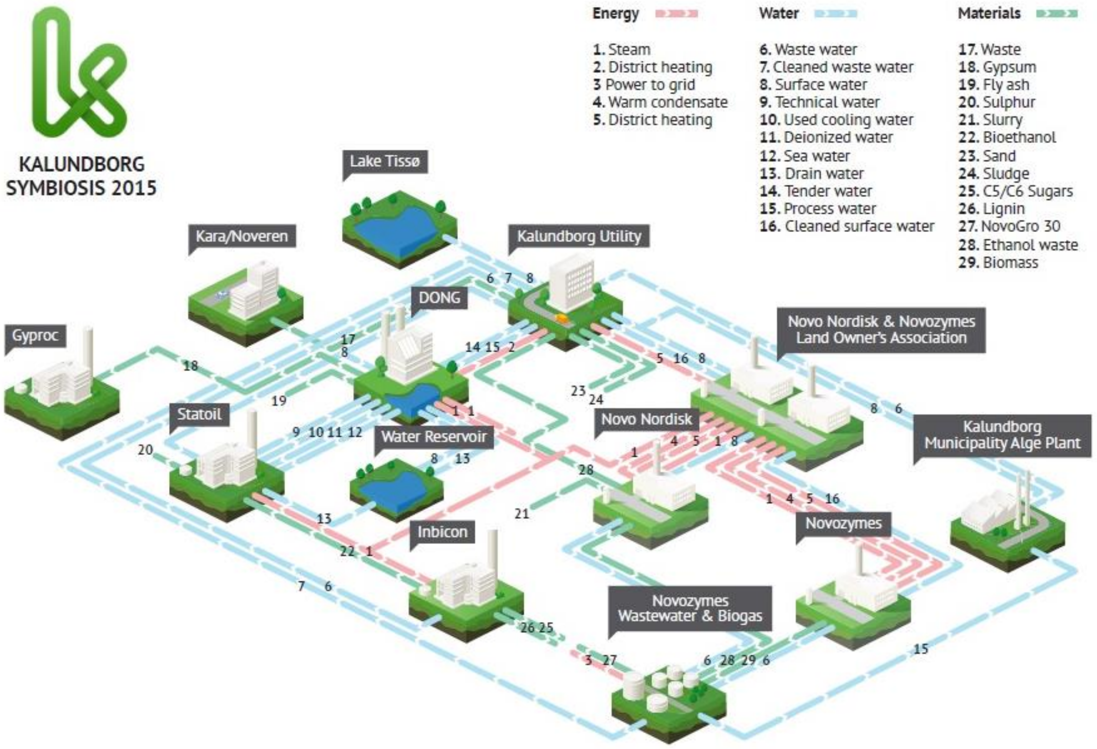


Figure 7: Current Kalundborg symbiosis (Symbiosis.dk 2016b)

Formed side stream connections are listed in the Figure 8 by their year of first exchange. The newest exchange connection of used process water to algae plant is not included in the picture.

Figure 8: Development of Kalundborg symbiosis. (Symbiosis.dk 2016a)

Kalundborg symbiosis and UPM Kaukas have similar possible side streams to be utilized. All the side streams are listed in table 5.

Table 5: Kalundborg flows compared with Kaukas flows. Source: Symbiosis.dk 2016

	Side stream in Kalundborg	**Side streams currently utilized in UPM Kaukas**	**Possibility to be utilized in kaukas**	**Remarks**
Energy flows	Steam	YES	YES	
	District heating	YES	YES	
	Power to grid	YES	YES	
Water flows	Warm condensate	NO	YES	
	Waste water	NO	YES	
	Cleaned waste water	NO	YES	
	Surface water	NO	YES	
	Technical water	NO	YES	
	Used cooling water	NO	YES	
	Deionized water	NO	YES	
	Sea water	NO	YES	
	Drain water	NO	YES	
	Process water	NO	YES	
	Cleaned surface water	NO	YES	
	Waste water	NO	YES	
Material flows	Gypsum	NO	NO	boiler fuels have low Sulphur content
	Fly ash	YES	YES	
	Sulphur	NO	NO	
	Slurry	NO	NO	
	Bioethanol	NO	YES	
	Sand	YES	YES	
	Sludge	NO	YES	
	C5/C6 Sugars	NO	YES	
	Lignin	NO	YES	
	NovoGro 30	NO	NO	
	Ethanol waste	NO	NO	
	Biomass	YES	YES	

Side streams which are found in UPM Kaukas but not in Kalundborg are presented in table 6. Only green liquor dregs are disposed to land fill. Some of these side streams could have potentially better end use than currently utilized. Examples for better utilization are presented in chapter 4.

Table 6: Side streams unique to UPM Kaukas

Side streams found in Kaukas	**Possibility to be utilized in kaukas**	**Remarks**
Cleaned wood waste	YES	Could be potentially used in hemicellulose extraction
Green liquor dregs and lime	NO	High cadmium content
Coating colour sludge	YES	Already highly utilized
Fiber sludge	YES	
Sludge from effluent treatment plant	YES	
Lime kiln ash	YES	
Recyclable carbon and paper	YES	Already highly utilized
Sand from screening	YES	In use

3.4 Similar eco-industrial sites with Kaukas

This chapter discusses comparable kraft pulp mills that are in construction or are waiting for environmental permission. It has to be noted that first two of these projects are green field projects, which means they are designed from the start in a way that allows side stream utilization.

3.4.1 Finnpulp

This new pulp mill would produce annually 1 200 000 ADt/a. Production of 60 000t/a crude tall oil, turpentine 6 000t/a. Recovery boiler would have capacity of 1 TWh of electricity produced in a year. Which would be about 1,5 % of total electricity produced yearly in Finland. Planned lignin extraction would yield 150 000 t/a. If this lignin process is implemented it will lower the amount of electricity produced. Electricity production is also done partly with gasification of the bark. (Finnpulp environmental permit application 2015)

Future pulp mill will have traditional kraft pulp mill process with addition of following technologies:

- Lignin extraction
- Bark gasification plant
- Bio-coal plant
- Biomethane digester

The side streams with highest refining potential and the largest waste streams in Finnpulp are the following: Crude tall oil, lignin, sludge, bark, green liquor dregs and ashes.

Plans for extracted lignin are dry it and sell or use it as bio-fuel. They are going to keep the possibility to sell it with higher water content to be used in chemistry industry. Half of the produced bark is gasificated and used to replace fossil fuels in the lime kiln. The other half of the bark has possibility to be burned in a separate bark boiler or to be processed to bio-coal. Bio-coal is supposed to be sold to Finnish heating markets. (Finnpulp environmental permit application)

3.4.2 Metsä Fibre Äänekoski

New expansion and replacement of old kraft mill in Äänekoski. It will have annual pulp production of 1 300 000 adt/a, 45 000 t/a crude tall oil, 2000 t/a turpentine. Products include pulp, crude tall oil, turpentine, bio electricity, district heating, bio gas and lignin products. Bio-oil will be produced in a separate process using pyrolyzed biomass. (Metsä Fibre Environmental permit application 2014)

Metsä Fibre calls the project bio-product factory and the construction is well on the way. They have received permission to build following production facilities besides traditional Kraft pulp process:

- bio-oil refinery
- bio-ethanol refinery
- biomethane reactor
- biomass gasification facility
- bio coal facility.

(Metsä Fibre Environmental permit application 2014)

Bio-product factory is designed in a way that allows high utilization of side streams. Most significant side streams are saw dust, lignin, sludge, bark, green liquor dregs and ashes.

Saw dust will be refined in to bio-ethanol using hydrolysis. Annual production capacity is designed to be 18 000 – 20 000m^3/a. Lignin will be sold or used to replace fossil fuels in the lime kiln or in chemical recovery. Sludge is processed in bio-methane reactor. Bark and some of the saw dust is gasificated and used in the lime kiln. Gasification process is designed to produce 150 MW of gas but can be used to provide only lime kiln need that is 105 MW of gas. Bio-coal is manufactured by torrefication.

It has to be noted that most of these projects are symbiotic in nature.

3.4.3 Stora Enso Sunila

Stora Enso Sunila is quite significantly smaller eco-industrial park than Kaukas. This is however interesting due the added LignoBoost process. Sunila mill produces 370 000 t/a of softwood pulp and 45 000 t/a lignin. (Stora Enso 2016)

Lignin is extracted from black liquor when the percentage of dry solids is 40% and after lignin is extracted the black liquor is returned to evaporation. Precipitation of lignin starts with sulfuric acid that is acquired from the process. The final precipitation is done using CO_2-gas and pH of the lignin mixture is raised to 10. Required CO_2 is 300 kg/t of lignin.

When this extraction process was implemented it had impacts on the mills Na/S – balance. Extra Sulphur is removed by soaking with Sodium sulfate that acquired from flue gas of the recovery boiler. When producing lignin with full capacity removal rate of sodium is 9 kg/ADT pulp and increases required NaOH needed for 4,3 kg/ADT pulp. (AVI 232/2014/1)

3.4.4 Comparison to similar eco-industrial parks

Currently one pulp mill in under construction and one has environmental permit application under inspection. Under construction is Metsä Fibre Äänekoski and under environmental permit inspection is Finnpulp in Kuopio. Both of these new pulp mill have side stream utilization techniques planned and implemented which are presented in this thesis. Metsä Fibre has designed side stream usage in a symbiotic way and they have other companies using and refining these side streams. (Yle.fi 2016)

Table 7 presents side stream utilization techniques that are being built or designed in the compared eco-industrial parks. Finnpulp and Metsä Fibre Äänekoski are greenfield projects so they can be designed to be economic from the start but it has to be noted that these techniques could also be implemented in to UPM Kaukas.

Table 7: Sidestream utilization techniques used in similar eco-industrial parks

Eco-industrial site	UPM Kaukas	Finnpulp	Metsä Fibre Äänekoski	Stora Enso Sunila
Lignin extraction		X	X	X
Hemicellulose extraction				
Biomethane digester		X	X	
Gasification		X	X	
Torrefication		X	X	
Ethanol production			X	
Biodiesel production	X		X	

4 IDENTIFIED POSSIBLE TECHNOLOGICAL SOLUTIONS FOR UPM KAUKAS

This chapter will discuss the predetermined side streams that are in interest of UPM Kaukas. These side streams are the following and in no order of importance: Waste heat, heat of Kaukaan Voima, saw dust residues, sludges, lignin, hemicellulose. Possible treatment techniques and extraction methods are presented. Figure 9 shows majority of the possible processes that can be utilized in kraft pulp mills. Technical solutions chosen for examination are based in expert interview (Vakkilainen 2016).

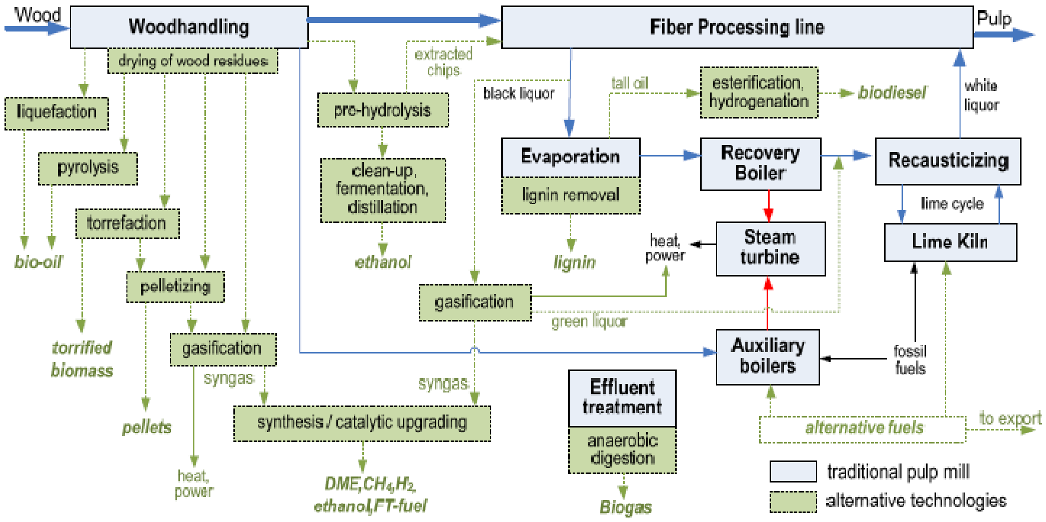


Figure 9: Possible biorefining processes in kraft pulp mill. (Hamaguchi, 2012)

4.1 Lignin extraction

Components of wood are 40-50 % cellulose, lignin 15-30 % and hemicellulose 23-32%. Roughly a half of the wood is made in to kraft pulp and the other half of the organic parts of the wood goes to evaporation plant and after that to energy production. Extraction of lignin lowers the load of recovery boiler and it is possible to increase pulp production.

Extracted lignin can be used to replace fuels or to be used to manufacture chemicals. (Vakkilainen & Kivistö 2008, 5)

4.1.1 Lignin extraction methods

Two main extraction methods for lignin extraction are acidic precipitation and ultrafiltration. The extraction process in precipitation is based on decreased solubility of lignin due to increasing acidity. This can be done using mineral acid (e.g. H_2SO_4 and HCl). Carbon dioxide can also be used as in LignoBoost method. When using sulphuric acid it will bring a lot of sulphur to the recovery cycle and the balance between sulphur and sodium can result in higher costs. Using CO_2 helps to avoid balance problems but then mixing phase of the CO_2 must be designed more carefully.

Figure 10 shows the phases of lignin extraction by precipitation. Main phases are precipitation with CO_2, dewatering and washing.

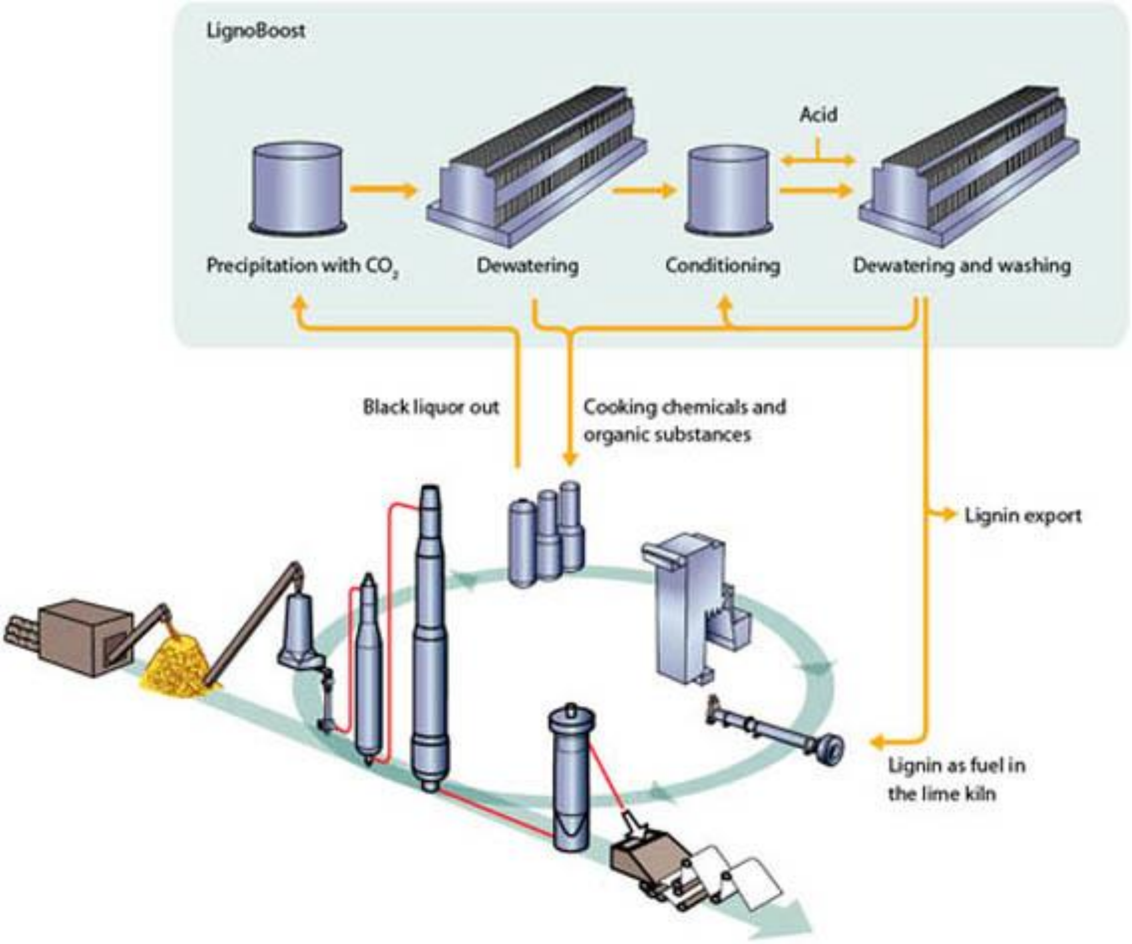


Figure 10: LignoBoost process. Source: Valmet 2016

By using ultrafiltration it's possible to filtrate molecules that have molecular weight between 1000 to 1 000 000. Lignin has varying molecular weight and it is possible to extract it using ultrafiltration and this can be done without added chemicals. Ultrafiltration process is presented in figure 11. (Toledano et al. 2010)

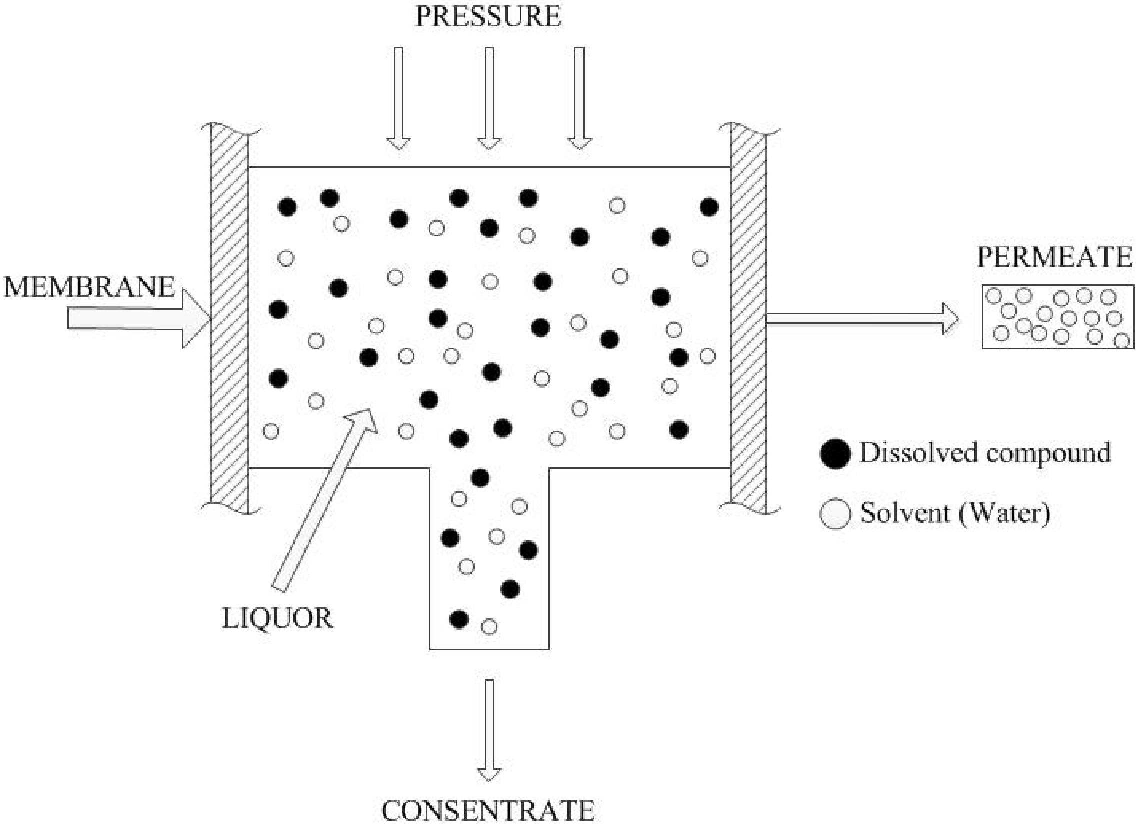


Figure 11: Ultrafiltration principle. Partanen 2015.

4.1.2 Effects on the chemical recovery

Lignin extraction lower organics in black liquor and increases inorganics. As mentioned earlier heating value of black liquor decreases and this can lead to more char formation in the recovery boiler. Load does not increase in lime kiln. (Vakkilainen & Kivistö 2008, 19)

Biggest concern in lignin extraction is the Na/S-balance. Black liquor pH must be decreased to precipitate lignin and to prevent other issues in evaporation black liquor must be alkalized. Calculations for UPM Kaukas has been done in earlier studies. Higher the extraction rates more alkali and more Sulphur is needed. (Vakkilainen & Kivistö 2012, 36)

4.1.3 Possible uses for lignin

The United States Department of Energy has produced reports that categorizes the ends uses of lignin in to three categories. They are thought from the technological and economic views to be short-, medium- and long-term categories. The first category is renewable fuels produced from lignin. Solid, liquid and gaseous fuels by combustion, pyrolysis, hydroliquefaction and gasification. (Stuart et al. 2013, 504)

Second category for lignin end use are polymer modifiers, carbon fibers, binders and adhesives. Production methods for these are close to be commercially viable. Great deal of R&D must be done before these have commercial avaibility. This due to different processing methods and the type of biomass from the lignin is extracted. (Stuart et al. 2013, 504)

The third category uses lignin’s specific molecular structure. Aromatic chemicals by depolymerization can produce benzene, xylene and toluene. These chemicals can be used to produce plastics. Although this category needs a lot of R&D lignin can be used in the future for these usages. (Stuart et al. 2013, 505)

4.2 Hemicellulose extraction

Hemicellulose is possible to extract before pulping. The downside for hemicellulose extraction is that it usually means lower paper quality pulp. In normal conditions when hemicellulose is not extracted it will go to recovery process. Extracting hemicellulose can lower the quantity of total flow to recovery process. It has lower heating value than lignin and by removing it from black liquor it can increase the pulp production if the recovery boiler is restrictive part of the pulping process. (Stuart et al., 500) Other benefits of the extraction of hemicellulose is that it can provide feedstock of fermentable sugars for other products. (Hamaguchi et al. 2013)

In hemicellulose extraction process part of the lignocellulosic portion is recovered by hydrolyzing before pulping. Figure 12 Presents at which stage hemicellulose could be extracted. Current method of making dissolving pulp has steam pre-hydrolysis phase to extract hemicelluloses before cooking. This method however is problematic because the hydrolysis components are hard to recover. (Hamaguchi et al 2013)

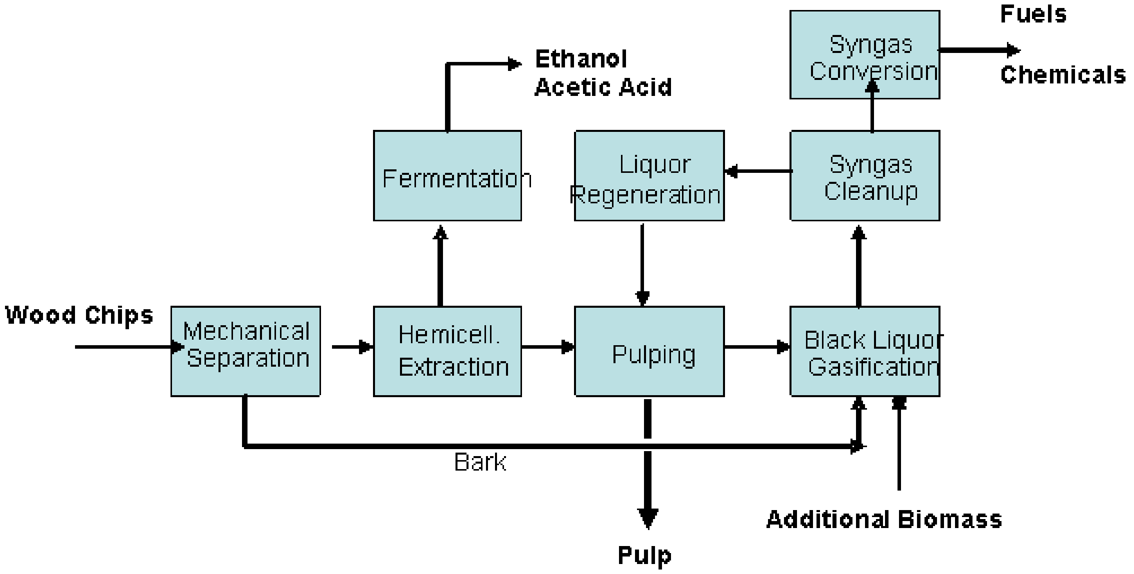


Figure 12: Integrated hemicellulose extraction to kraft pulp mill with added black liquor gasification. (Lohi T, 2008)

4.2.1 Hemicellulose extraction methods

Hemicellulose can be extracted by different methods like acidic pre-hydrolysis or by auto-hydrolysis. Current results of using different methods to extract hemicellulose has produced mixed results and because the quality of pulp is the most important factor for the mill it is very important to be sure of the used method.

In the extraction of hemicellulose a small part of the lignocellulosic material is hydrolyzed and taken before the wood chips are going to pulping. There is two main methods to use before kraft cooking. Acidic pre-hydrolysis process the hemicellulose is hydrolyzed to monomeric and oligomeric sugars. They are dissolved into hydrolysate with a mineral acid. Mineral acid (e.g. H_2SO_4) is also a catalyst for the hydrolysis. The other method is auto hydrolysis (AH). The right conditions are produced with enough acetic acid with hot water at temperatures of 130-175°C. In both methods hydrolysis catalyst is hydronium ions(H_3O^+). If the hemicellulose is wanted to be extracted in alkaline conditions it can be extracted from green liquor. Extraction from green liquor is possible with white liquor or alkaline solution. Temperature affects greatly to the time hydrolysis process takes. (Hamaguchi et al 2013)

4.2.2 Effects on the fiberline

Extraction of hemicellulose can significantly reduce pulp cooking time. In auto-hydrolyzed pulp reduced cooking time is considered to be achieved by increased volumes of pores, cell wall permeability and hydrolytic cleavage of lignin. Also the alkaline method has reports of decreased cooking times.

Water pre-hydrolysis and dilute acid process can lead to lower yield in overall pulping mass. Extraction in alkaline phase have produced normal or little lower yields. It is assumed that the part of the reduced yield is due the xylan extraction. (Hamaguchi 2013)

4.2.3 Effects to pulp properties

Greatest effects from hemicellulose extraction are found in strength and beating properties of pulp. When the portion of hemicellulose is lower in pulp the fibers will not swell as much. During the beating process fiber contacts is decreased due the lower swelling. When hemicellulose is extracted the needed PFI-mill revolutions can be five times higher compared to normal unhydrolyzed pulp. From strength perspective the hemicellulose extraction increases tear indexes and lower the tensile indexes. Some studies suggest that this is also due the reduced interfiber connections. (Hamaguchi 2013)

4.2.4 Effects on the chemical recovery

Hemicellulose extraction will lower the amount of dissolved organics in the black liquor. This is due integrated dilute acid and water hydrolysis decreases pulp cooking yield if the amount of wood is constant. This also works the other way if the pulp production must stay constant the amount of used wood must be increased. (Hamaguchi 2013

4.2.5 Possible uses for hemicellulose

From softwood hemicellulose can be hydrolyzed to five carbon and six carbon sugars. Five carbon sugars can be converted to xylan or xylose to be used in furfural or xylitol. Six carbon sugars can be fermented to hydroxymethylfurfurals. (Stuart et al. 2013, 505)

4.3 Sludge

Producing pulp generates large amounts of sludge which contains organic materials but has low heat value due it's high water content. Current solution for sludge handling is to dewater and burn it in Kaukaan Voima boiler. Different methods could be applied for increasing heating value of sludge or converse it to different form to make it more accessible to use. (Stuart et al. 2013, 509)

4.3.1 Biomethane from Sludge

Producing biomethane from organic materials by anaerobic digestion is widely utilized process. There are multiple applications in municipal sludge usage worldwide but in forest industry it is still a not well utilized technique. Biggest reason for this is the digestion reactor needs long process times and the requires a large scale reactor. Investments are high and the yield is not seen satisfactory. (Stuart et al., 509)

Conversion of sludge to biomethane is process that has multiple steps. It is usually limited to specific rates that are determined for each sludge type. New pretreatment methods can however increase the rate of the conversion. Benefits of the biomethane production is that left over sludge is less odorous and has still applications for land improvements. (Stuart et al. 2013, 510)

Figure 13 presents basic flowchart of biomethane process. Largest and most time consuming stage is anaerobic digester. Retention times range from 60 days with cold fermentation done with temperatures of 15-30°C to lowest of under 15 days with temperatures over 50°C. Majority of digesters have temperature range of 30-50°C and have retention times of 17-45 days. (Deublein et al. 2008, 250)

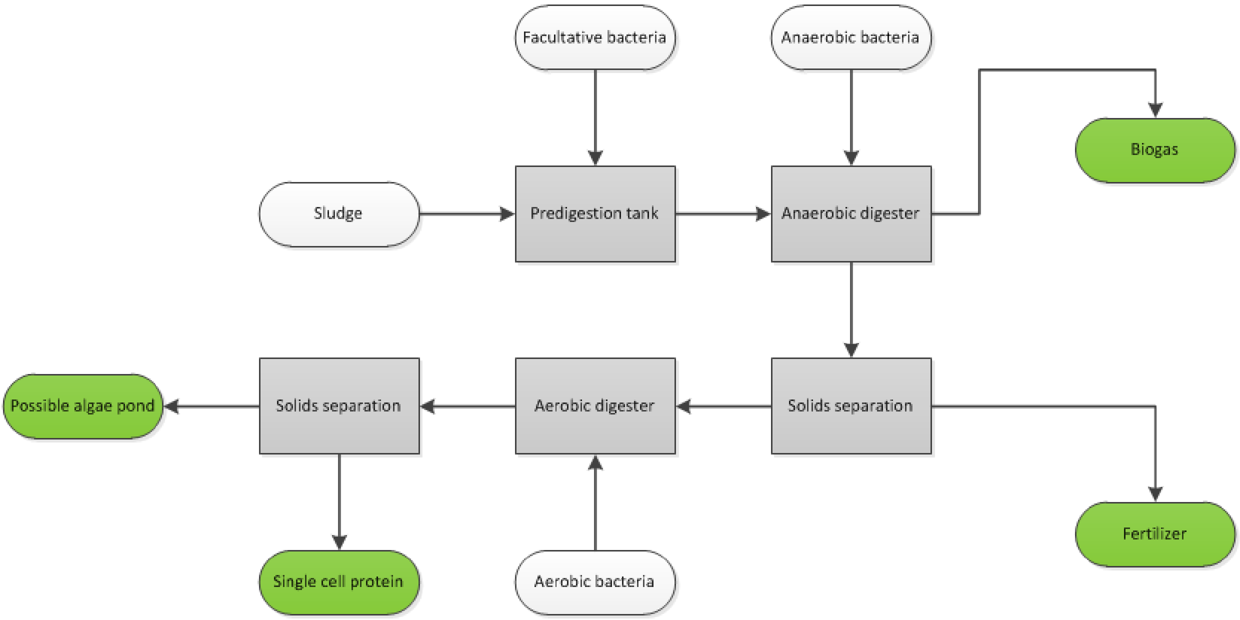


Figure 13: Biomethane process. After: Hart & Evers 2011

4.3.2 Sludge used as fertilizer

Restrictions for sludge as a fertilizer come from Finnish legislation. Law 2006/539 defines the boundary values for pollutants. Fertilizer manufacturer has to file a application from Finnish food safety authority (1784/14/2011). Usually different fertilizer are allocated by their properties and end usage. Fertilizer can’t contain salmonella in 25 g of fertilizer or Escherichia coli more than 100 pmy/g. Sludge must be heat treated for at least an hour at 70°C to remove all disease inflicting bacteria. This heat treatment has to be taken into consideration when thinking about investments. Waste water sludge can't be used in agricultural land that is used directly for growing crops for humans or animals (1034/14/2012). This law however allows sludge to be used as fertilizer for energy crops when the boundary properties are not too high and the levels of heavy metals are within boundaries and the pH of the soil is higher than 5,8. Boundary values are shown in the Table 7. . (Metli 2012, 58)

Table 8: Heavy metal concentration limit (mg/kg dry)

	Forest fertilizer	**Agricultural crops fertilizer**
As	30	25
Cd	1,5	0,5
Cr	300	200
Cu	600	100
Hg	1	0,2
Ni	150	60
Pb	100	60
Zn	1500	150

4.4 Solutions for excess heat

The amount of excess heat is large and because of the cycle of the plant it is not possible to sell it year round. Waste heat could however be recovered used to produce electricity by Organic Rankine Cycle(ORC) and excess heat from Kaukaan Voima could be used to dry biofuel. It has to be noted that both of these solutions would not be symbiotic in nature.

4.4.1 Organic Rankine Cycle

ORC process is similar to normal steam generator process but instead of water circulation it has organic fluid with high molecular mass. Using organic circulating fluid bring benefits that are not feasible using water in low temperatures. Organic fluids lower enthalpy of vaporization and therefore due to lower specific enthalpy decreases less in turbine than water. This enables higher efficiency in one stage high speed turbines. Most widely used organic circulation fluids superheat when expanding and for that reason process usually has recuperator which preheats circulating fluid. Figure 14 shows ORC-turbine process that is attached to flue gas line. (Heinimö & Jäppinen 2005, 12)

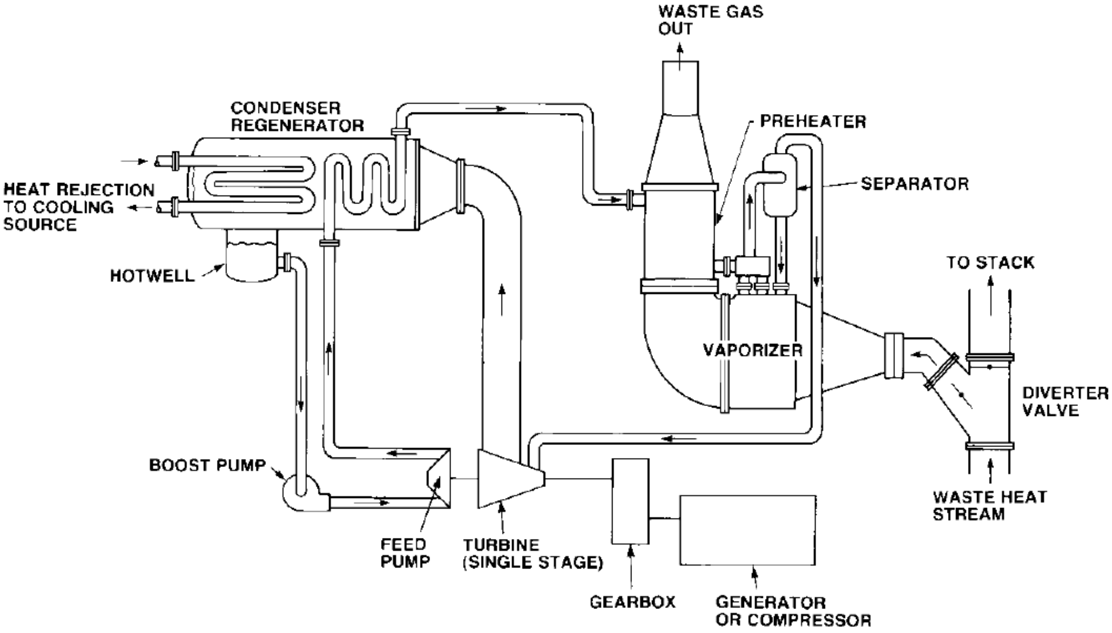


Figure 14: Basic layout of ORC-process. Larjola et al. 2013.

ORC process follows following pattern in T, s diaphragm which is shown in Figure 15.

1-2 Expansion of steam in turbine

2-3 Removal of superheating

3-4 Condensing

4-5 Pressure of the circulation fluid increased in feed pump

5-6 Circulation fluid preheating

6-7 Evaporation of circulation fluid

7-1 Superheating of circulation fluid

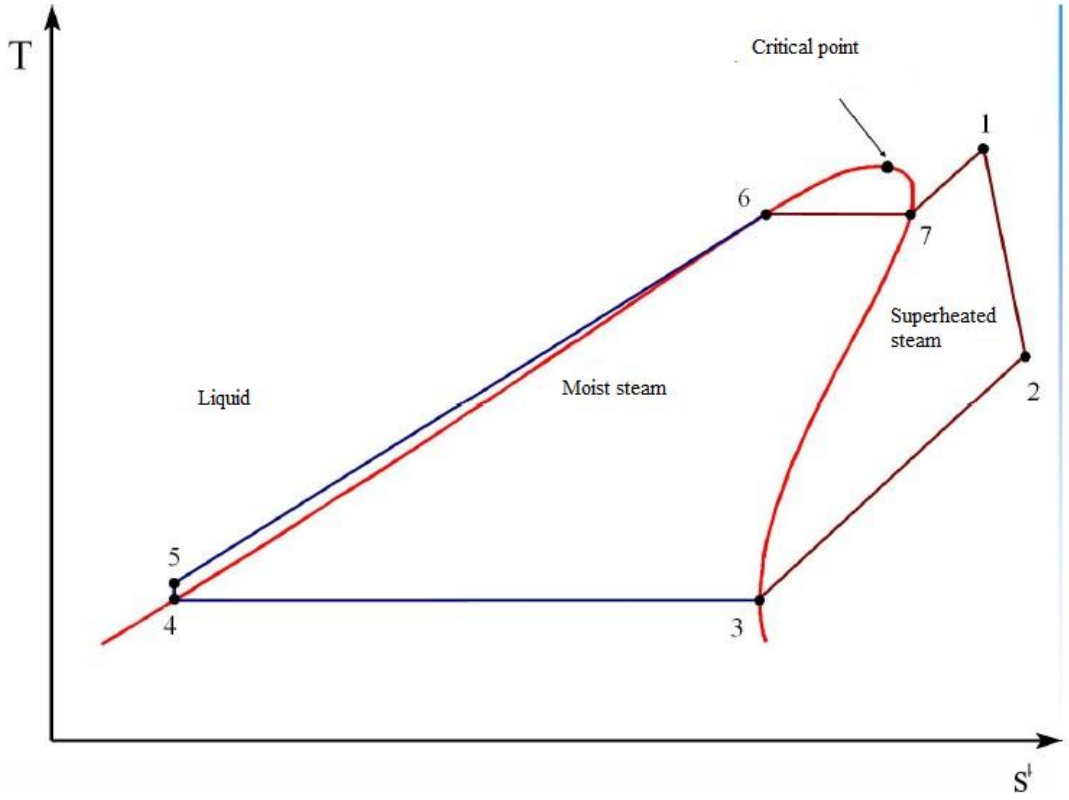


Figure 15: ORC Process flow. After Larjola et al 1991.

Circulation fluid is essential part of ORC process and selection of right fluid increases efficiency in low temperatures. Properties of working fluids differ from water and the most important of them to ensure proper functioning of the process are:

- Molecular weight
- Boiling point
- Correlation between temperature and enthalpy
- Thermic and chemical endurance
- Toxicity
- Fire safety
- Availability and price

(Heinimö & Jäppinen 2005, 17)

Thermodynamic properties of the circulation fluid such as boiling point at the process pressure dictate operation parameters as circulation fluid has to reach both gas and fluid phases. Organic fluids tend to break down chemically in high temperatures and that’s why good thermic endurance is required. Different substances that get mixed with circulation fluid like turbine lubricant oil speed up the chemical breakdown of the circulation fluid and weaken the heat transfer properties. Oxygen leakage to process can lead to formation of uncondensing gases that weaken the heat transfer properties. (Heinimö & Jäppinen 2005, 17)

Toxicity and fire safety of the working fluids are very important part of the safety of the ORC process as organic fluids have high carbon content they are flammable fluids. If the process operates in higher temperature than the ignition temperature there is a risk of fire if leakage occurs. Health risks and environmental risks have to be considered when selecting right fluids. (Heinimö & Jäppinen 2005, 18)

Most widely used circulation fluids are pentane and silicone fluids. Pentane is used when the operation temperatures are lower than 200°C. These conditions apply typically to geothermal and industrial waste heat applications. Silicone fluids have operation temperature of 280°C and toluene can work in 350°C.

ORC has applications in paper industry. Munskjö Aspa Bruk produces 200 000 t/a pulp and Opcon energy systems has installed ORC system to recover heat from evaporation plant and bleach plant. This ORC process lower the waste heat load in to nearby lake and preheats lake water that is going to be process water. ORC system could be implemented to Kaukas as amount of waste heat to Lake Saimaa is considered too high. Layout of Aspa Bruk ORC-process is shown in figure 16. (Opcon 2016)

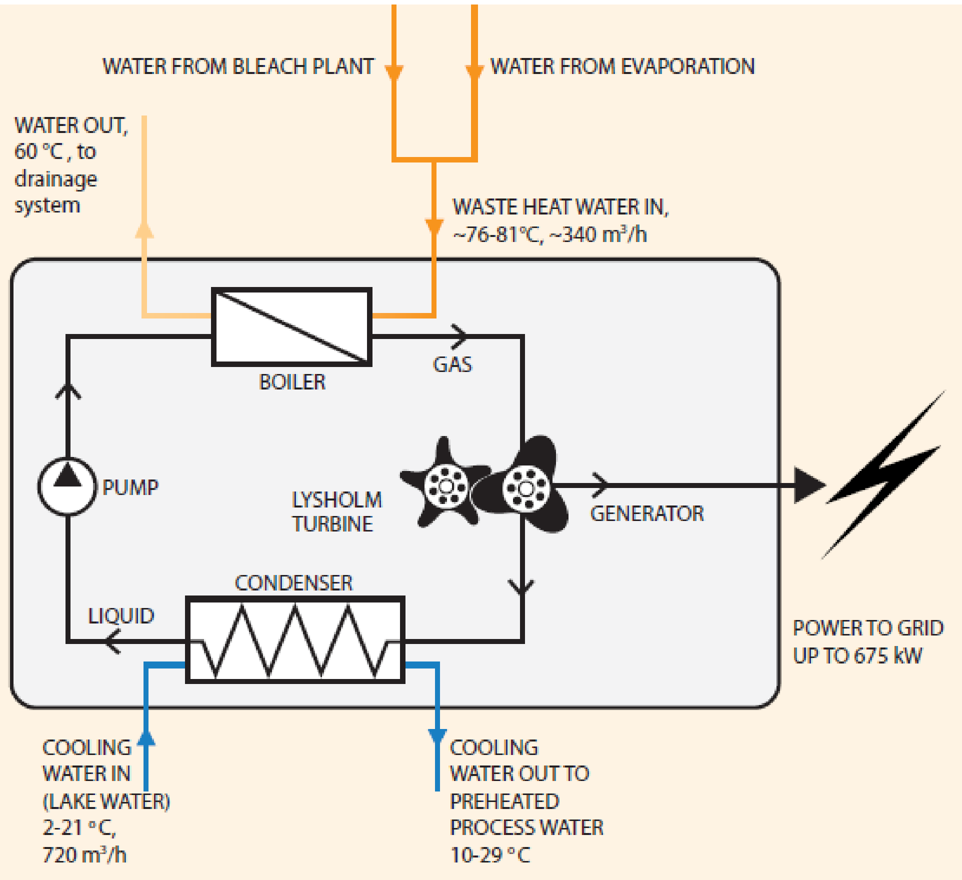


Figure 16: Working principle of ORC. Source: OPCON 2016.

4.4.2 Biofuel drying with excess heat

Biofuels have high moisture content and this brings multiple undesired effects to energy efficiency of the Kaukaan Voima biomass boiler. Part of the heat load of the boiler is spent on evaporating the water from the fuel which lowers the heating value of the fuel. Evaporated water vapor also increases the volume of the flue gas flow and increases the load of the flue gas blower. (Motiva 2014, 13)

Main benefits for the drying of the biofuels are:

- Increased heat value
- Increase in boiler efficiency
- Decreased need for burning air
- Lower volume of flue gas flow
- Better usability of the biofuel
- Enables boiler and accessory equipment to be used with lower power (Motiva 2014,13)

Selected drying method should be decided on the basis of used fuel and the desired moisture content after drying. Table 8 presents the main operating values of presented drying techniques.(Motiva 2014, 20)

Table 9: Typical parameters for different drying methods. After: Motiva 2014,20

Drying technology	**Drum dryer**	**Flow dryer**	**Screen dryer**
Medium substance	Flue gas/ Steam	Flue gas/ Steam	Air
Retention time [min]	1-30	0,1-3	30-90
Drying temperature[°C]	200-600	150-200	30-120
Particle size [mm]	20-100	0,5-50	5-50
End moisture content [%]	2-10	15-20	>5
Drying capacity [t/h H_2O]	5-75	10-30	5-40

Heat source	Steam/ Flue gas	Steam/ Flue gas	low pressure steam, flue gas, hot water

In drum dryer fuel and drying gas enters to slowly rotating drum. Drum wall is fitted with fins that enable better heat transfer and mix fuel particles. Figure 17 presents the basic side view of the drum dryer. Parallel flow of the drying gas is used when biomass is dried. Drying gas is typically flue gas but hot air can also be used. Parallel flow is used to ensure highest temperature when the moisture content of the biomass is the highest and to ensure temperatures are not too high when the biomass is dried. Drying has to happen in over 100°C to avoid condensing of organic compounds. (Motiva 2014, 20)

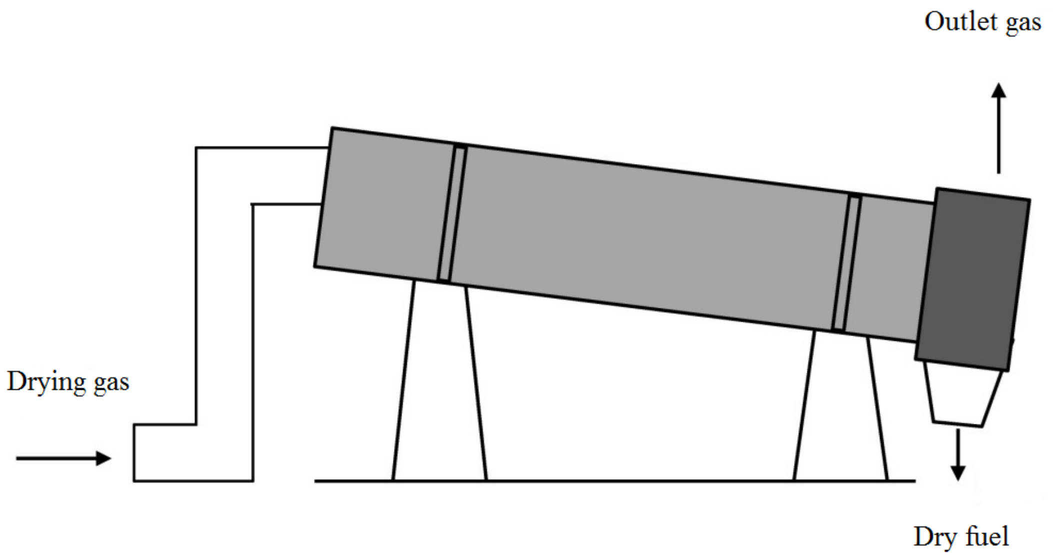


Figure 17: Drum dryer basic layout. Source: Motiva 2014, 21

In flow drying bio fuel is fed in to high velocity hot drying gas. Drying gas can be flue gas, air or superheated steam. Main differences between flow drying methods are used drying gas and how flow channels are designed. Typical methods for flow drying are flash-drying, cascade drying, fluidized-bed drying and steam drying. Figure 18 presents basic layout of Flash drier. Retention times with these methods are typically low. Drawback of flow drying methods is their high internal electricity consumption, need of pretreatment to ensure consistent quality and particle size. Needed temperatures are also relatively high and flow drying is not preferred method to increase energy efficiency. Flow drying is applicable if the aim of the drying is to produce higher quality end products for gasification or pyrolysis processes. (Motiva 2014,22)

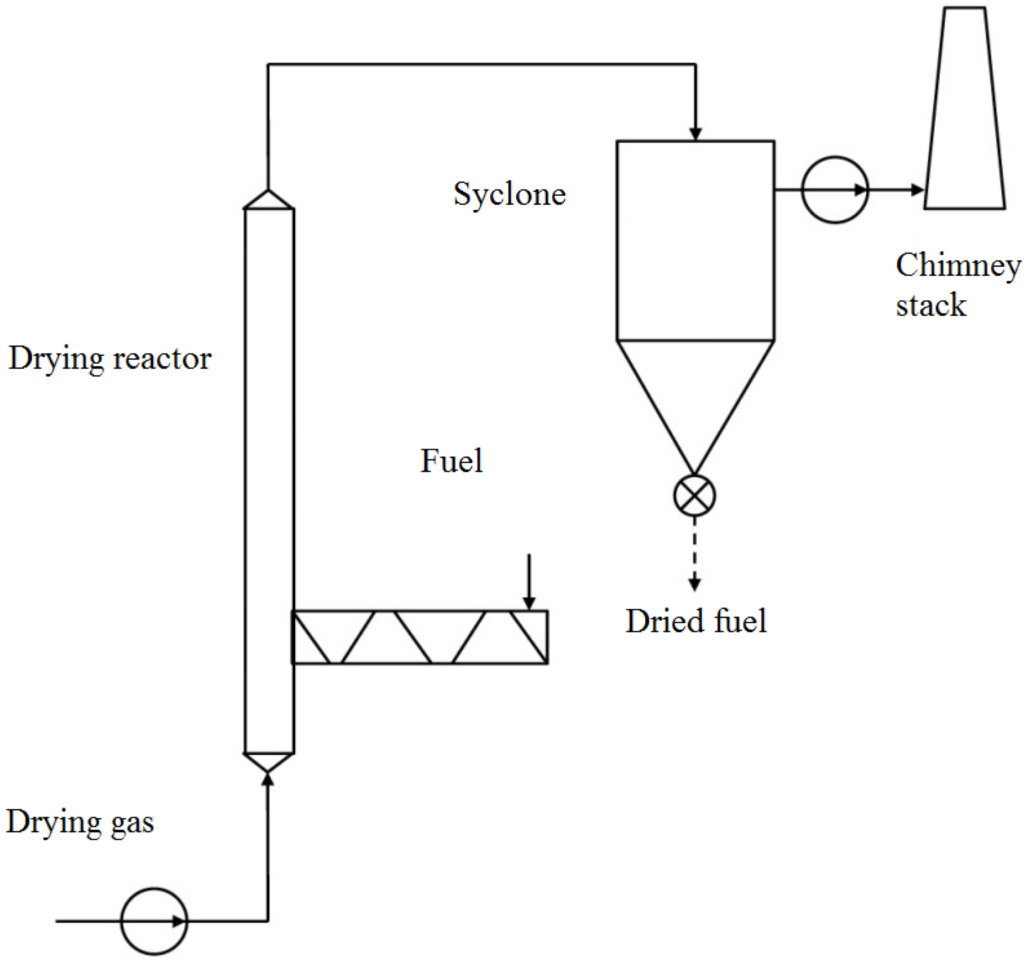


Figure 18: Flash drier. Source: Motiva 2014, 22

Screen drying is preferred method when heat source with lower temperatures is available. It’s used for large variety of biofuels such as saw dust, wood chips, bark, bagasse and sludge. Fuel is spread to screen with typical thickness of 0,1-0,2 m depending which fuel is used. Screen drier can have multiple layers to achieve desired dryness of the fuel. Figure 19 presents basic layout of the screen drier. Outside air is usually used as drying gas and it is heated in heat exchanger. Air flow is either directed from above or under of the screen. Pressure drop in fuel layer is higher when air is directed from above of the layer but it produce less dust compared to under fuel layer flow. (Motiva 2014, 23)

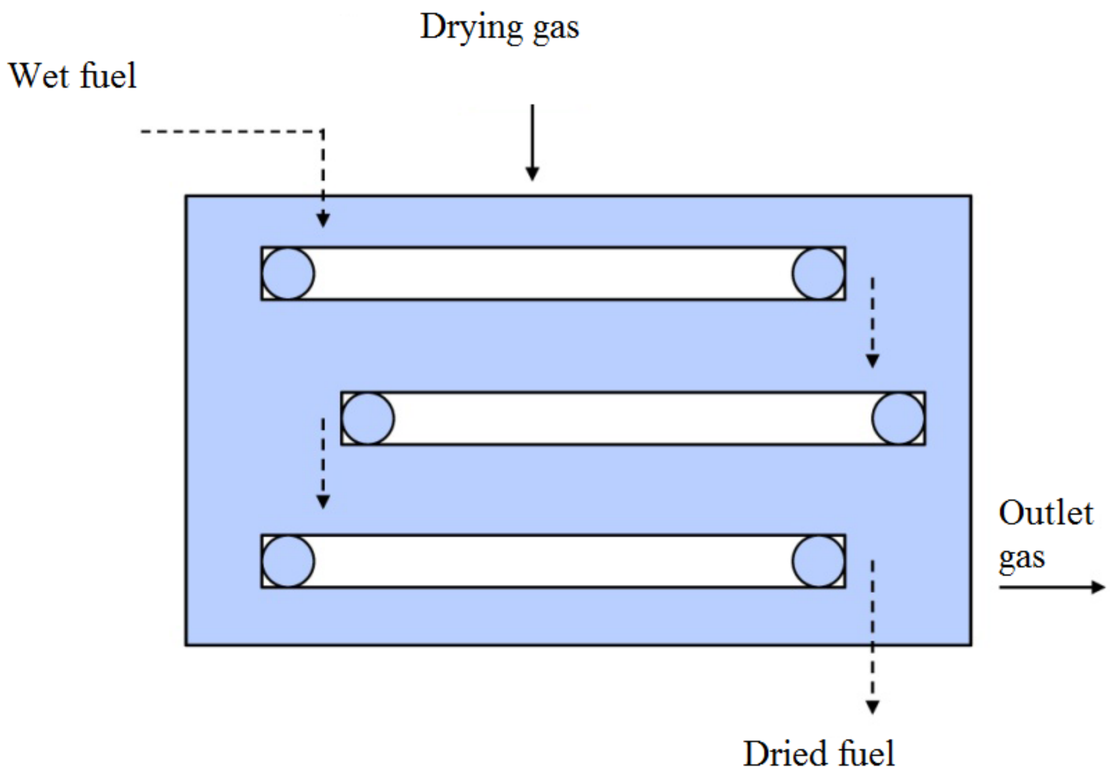


Figure 19: Screen drier. Source: Motiva 2014, 23

Main benefits for screen drier is its applicability for multiple different biofuels, high usability, durable and simple structure and lower emissions than drum driers. Drawbacks for screen drying are higher investment costs, higher internal electricity consumption, bigger land are needed and higher maintenance costs. (Motiva 2014,24)

Drying biofuels is only applicable if excess heat is possible to utilize. Otherwise, with current state of UPM Kaukas process it would not be beneficial. Table 9 presents previously mentioned benefits and drawbacks for different drying methods.

Table 10: Benefits and drawbacks for different drying methods. After: Motiva 2014, 31

Drying method	**Benefits**	**Drawbacks**
Drum drying	Multiple equipment suppliers Quality can differ in feedstock Energy efficiency High capacity for drying	Emissions: VOC, smell and small particles Risk of fire High temperatures required
Flow drying	Multiple equipment suppliers Quick drying process and compact structure	High temperatures required Emissions: VOC, smell and small particles Corrosion and errosion problems
Screen drying	Multiple equipment suppliers Quality can differ in feedstock Lower temperatures required Ease of adjustability	Large land area needed High internal electricity consumption Investment and maintenance costs are high

4.5 Summary of the techniques

Lignin removal lowers the heating value of black liquor and lowers the load of recovery boiler enabling mill to produce more pulp. Negative effects of lignin removal appear in chemical recovery and especially in Na/S-balance control. Hemicellulose extraction prior pulping process has multitude effects on kraft process. Biggest drawback for hemicellulose extraction is its effect on pulp quality. Currently sludge is not utilized anyway but rather seen only as an expense. It could be used to produce biomethane and to be used as a fertilizer.

Waste heat could be utilized with Organic Rankine Cycle which would lower heat load that is dumped in to Lake Saimaa. Size of the removed heat load will differ on the size of the electricity power of the process. Surplus heat from Kaukaan Voima bio boiler can be used to dry biofuel that is used in the boiler. This option is beneficial only if heat is not used in anything else.

5 TECHNOECONOMIC ANALYSIS OF SIDE STREAMS

Side streams chosen for economic analysis are hemicellulose, lignin and ORC. Cost estimates are hard to find due to unique to each case. Prediction of future product prices can differ from estimates since product markets are still developing. (Hamaguchi 2013, 3406) Analysis is done using internal rate of return (IRR) using 10 years payback period. It is based on finding the net present value at zero after the payback period with chosen interest rates. Operating and maintenance costs were considered to be 5% of the investment costs. (Hamaguchi 2013, 3406)

$$NPV = a\left(C_{\mathrm{e}} + C_{\mathrm{product}} - C_{\mathrm{O\&M}}\right) - C_{\mathrm{inv}} = 0 \tag{4}$$

where,

a	present value factor that gives NPV zero
C_{product}	annual revenue from selling end product
$C_{\mathrm{O\&M}}$	annual operating and maintenance cost
C_{inv}	total investment cost

As mentioned earlier lignin can be used in lime kiln to replace fossil fuels and this would but lignin base price to match it to natural gas price at same heat power in June 2016 of 177€/t. (Finnish Energy authority, 2016)

Hemicellulose is more complicated as the produced product portfolio can differ greatly but if used in ethanol production can be 158 liters per one ton of wood. This would require all the hemicellulose and is not realistic. More accurate rates are 50% of that which is 79 liters per ton of wood. When compared to current ethanol price of €/l (tradingeconomics.com) this would give price of 1422€ per ton of hemicellulose. However ethanol could not be seen as the feasible final product as the price is very low.(Stuart et al. 2013,501)

Investment values were acquired from Mao 2007 for hemicellulose, Laaksometsä et al. 2007 for lignin and Heinimö and Jäppinen 2005 for Organic Rankine cycle. Reference price for electricity price is chosen to be 30 €/MWh. This a bit high considering electricity price futures for years 2018, 2019 and 2020 which are around 20€ - 22€ (Nasdaqomx.com 2016), but lower prices are considered in the calculation.

Chosen production under consideration are 20 000 t/a lignin extraction, 20 000 hemicellulose extraction and Organic Rankine cycle producing electricity with 1,3 MW_e of power. Base end-product prices are low because they are based on lowest refining ratio products which are currently in use. With higher refining ratio products product prices are higher and more profitable.

Table 11: Basic information for economic assessment

		Hemicellulose 20 000[t/a]	Lignin 20 000	ORC 1,3 MW_e
Construction	k €	1 000	-	320
Equipment	k €	11 200	-	3 000
Piping, electrification and automation	k €	1 000	-	500
E&PM	k €	6 000	-	300
Reference price of product	€/t	240	177	30
O&M		-960	-700	-206
Yearly production		20 000	20 000	10920
Yearly Revenue		3843,2	2840	121,6
Total investment cost	k€	-19 200	-14 000	-4 120

Figure 20 presents the internal return rate with different end product values. At reference end product prices both lignin and hemicellulose have positive internal return rate. Organic Rankine process does not however reach positive until the electricity prices reaches 30% over reference price. ORC process achieves 9% IRR when the electricity market price is 80€/MWh which is significantly higher than electricity prices in markets are going to be and because there is no need for more produced electricity this is not economically beneficial.

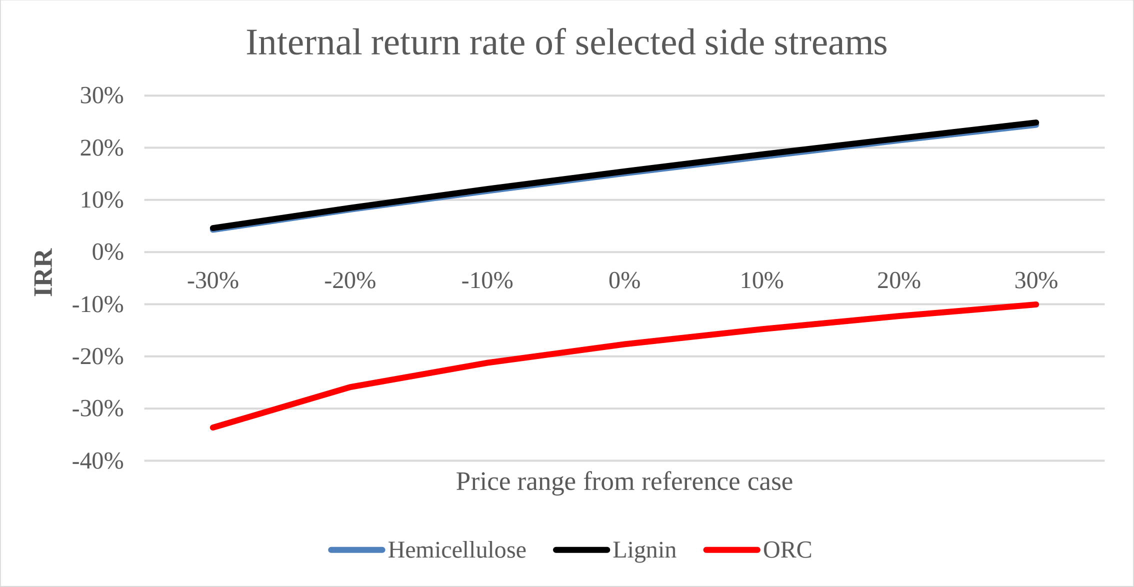


Figure 20: Internal return rate of side stream utilization solutions with end product price variability

Figure 21 presents the IRR with investment cost being the variable. Lignin and hemicellulose extraction have the best tolerance against fluctuations in investment cost. And Organic Rankine Cycle will not reach positive IRR in the chosen boundaries.

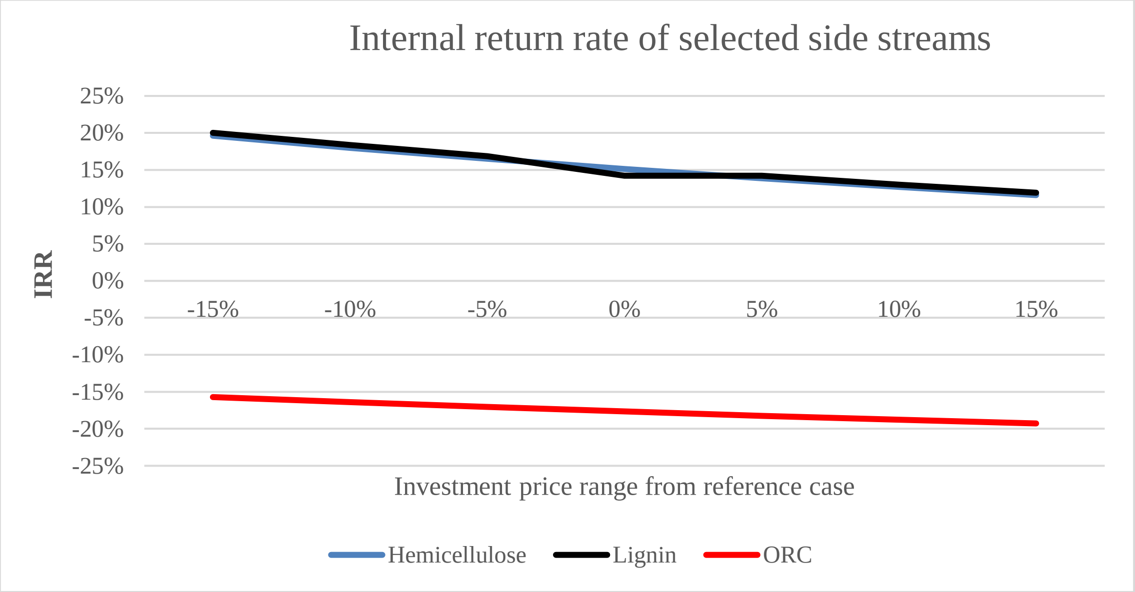


Figure 21: Internal return rate of side stream utilization solutions with investment variability

In these internal return rate calculations, lignin extraction and hemicellulose extraction investments seem more viable option than Organic Rankine cycle producing electricity. Lignin extraction could potentially bring more economic benefits than hemicellulose extraction when pulp production is taken in consideration. Hemicellulose extraction has great potential when extracted from wood that is not used in pulp production and is refined in to higher refining ratio product other than ethanol.

Calculated internal return rates are low in some cases and every company has to make decision what is their desired internal return rate.

6 SUMMARY &CONCLUSIONS

Object of this thesis was to discover possibilities how preselected side streams found in UPM Kaukas could be utilized as a part of industrial symbiosis and what are the main points when implementing new technologies to existing pulp mill. The most important side streams were decided by the advisory board and they were lignin, hemicellulose, sludge and waste heat. Secondary objective was to inspect how UPM Kaukas compares to other eco-industrial parks and industrial symbioses.

Relevant industrial symbiosis theory was gathered with literature study. Pulp and paper industry has developed during the years to be very raw material efficient. Pulp and paper industry seems to work in a symbiotic way but current theory tells that more economic benefits could be achieved when working with outside partners and not only inside company.

Current waste treatment state in UPM Kaukas and side stream utilization situations in Kalundborg industrial symbiosis and similar kraft pulp mills in Finland were studied with literature review. Current waste management state of UPM Kaukas is considered to be good. Wastes are recycled and only difficult wastes are disposed to landfills. Evolution of Kalundborg industrial symbiosis can be used as reference how different production plants can be implemented into UPM Kaukas or to larger area such as municipality of Lappeenranta. Similar kraft pulp mills in Finland are implementing technologies reviewed in this thesis.

For every preselected side stream, a literature review of current techniques was conducted and with expert advice selected techniques were chosen. Lignin could be used in lime kiln to replace fossil fuels but if aim is to develop deeper industrial symbiosis then it could be sold to new possible business partner. Possible end products for lignin are multiple. Lignin extraction will increase chemical usage in the chemical recovery stage of the kraft process. When deciding the extraction percentage addition of chemicals has to be taken into special consideration.

Hemicellulose has great potential for high refining ratio and large economic advantage can be obtained if it’s extracted. Current extraction methods however can alter the quality of the pulp. If pulp quality cannot be changed consideration for waste wood to be utilized for the process should be considered.

Sludge can be used as fertilizer or it can be used to produce bio-methane or both. When used as fertilizer more in depth analysis of heavy metal content must be conducted. Current disposal method for sludge is to burn it in Kaukaan Voima boiler. When sludge is not burned effects on the boiler must be considered.

Organic Rankine Cycle would utilize waste heat flow that goes into Lake Saimaa. If environmental laws get stricter towards waste heat flow to Lake Saimaa Organic Rankine cycle could lower waste heat flow. Excess heat from Kaukaan Voima bio boiler can be used to dry biofuel but it is only advisable if it is not used in anything else.

Technoeconomic analysis was conducted for lignin extraction, hemicellulose extraction and Organic Rankine cycle. Internal return rates were calculated with 10-year payback time and sensitivity analysis was performed with end product market price and initial investment costs. Economically most viable options were lignin extraction and hemicellulose extraction. Organic Rankine cycle did not reach positive internal return rate due to fact of UPM Kaukas does not need to buy electricity.

In the future side stream utilization techniques with the highest potential should be implemented in to UPM Kaukas kraft pulp mill process. Best option that would not affect pulp quality would be lignin removal but hemicellulose extraction also has potential.

UPM as a company has committed to get rid of landfill wastes and it can be done in the future. Before that goal is accomplished possibility to share landfill with city of Lappeenranta could be considered. Even though UPM has their own landfill sharing one with city could help to lower the managing costs and would produce more land fill gas to be collected and to be used.

Economically beneficial symbiotic exchanges are present in UPM Kaukas eco-industrial park. Resources should be allocated towards discovering companies who are interested in using technologies presented in thesis. Before finding out new business partners more in depth calculations and documentation for side streams has to be done. This allows easier negotiations with new business partners when all the needed information is already gathered. Other important aspects when implementing new symbiotic relationships are presented in Annex I.

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Annex I

Important points in implementing new symbiotic connections

Logistics

- -Is there enough capacity to withstand new transportation traffic?
- -Enough parking space during construction?
- -Enough parking space during operation?

Technology

- Is the implemented technology true and tested?
- Is the production profitability location specific?
- Who takes the biggest investment risk?

During special circumstances

- Is the new symbiotic connection able to withstand pulp mill outages?
- It is important to have backup plan if the symbiotic partner can't perform?

Maintenance and upkeep

- How the symbiosis coordinates and pays maintenance and repair?
- Could the operation of the new facility be handled by UPM Kaukas