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Biotechnical methods for improvement of energy economy in mechanical pulping

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Abstract

Forest industry is a notable user of electric power in Finland. The main reason for this is mechanical pulping, which is very energy intensive. Energy savings in mechanical pulping will also affect indirectly emissions of greenhouse gases (GHG). The aims of the study were to a) study the potential for energy savings and reduction of GHGs by implementation of biotechnical methods in mechanical pulping, b) estimate their cost-efficiency and c) assess the environmental impacts of their adoption into TMP production using the LCA methodology. Two different biotechnical methods were considered, namely fungal pretreatment of chips (biopulping) and enzyme-aided refining, both of which have shown marked potential for energy savings in mechanical pulping. Biopulping has been studied intensively, but without experience in mill scale. Enzyme-aided refining was developed during 1990s in collaborative projects and the method has been succesfully verified in mill scale trials.

Cost-efficiency, adoption and effects on emissions of GHGs of the biotehnical methods as compared with other competing technologies were estimated by the EFOM model. Two different scenarios extending to 2030 were used. In the ´optimistic´scenario the new cleaner biotechnologies develop rapidly and they are adopted effectively into use, whereas in the ´realistic´ scenario new technologies reducing greenhouse gas emissions penetrate rather slowly into the energy and industrial systems.

The results showed that enzyme-aided refining was very competitive as compared with alternative methods and it has a potential of being largely applied in mechanical pulping. Biopulping, which is technically more difficult to control and also more expensive to invest and operate, could be largely adopted according to the optimistic scenario in 2020. It is shown by the LCA study that implementation of the biotechnical methods would reduce total emissions of GHGs. Acidifying emissions from production of bleaching chemicals would, however, increase due a need of extra bleaching for biopulped chips, but the portion of acidifying emissions from the total emissions were assumed to be low. Effects on wastewater loadings arising from the application of biotechnology were not assessed in this study due to lack of relevant data.

Preface

Evolution of energy use within the Finnish forest industry during the next decades has a great national impact. The basis for this study was to evaluate the benefits and costs of biotechnical methods if implemented into mechanical pulping in mill scale. The work included also careful assessment of environmental impacts of the biotechnical methods, if they were implemented in mill practice.

This project was a part of the national technology programme CLIMTECH funded mainly by the National Technology Agency (Tekes). The CLIMTECH technology programme aimed to contribute to technological choices, research, development, commersialisation and implementation to cleaner technologies in order to meet the emission restrictions of GHGs approved in the Kyoto protocol.

The work was carried out in collaboration between VTT Biotechnology and VTT Processes. The project group at VTT Biotechnology updated information on the biotechnical methods and designed the industrial biopulping process with the help of industrial partners. This information obtained from literature and discussions with the company representatives was the basis for the scenario and LCA studies, which were performed at VTT Processes.

The work was advised by the steering group representing both industry and administration. The streering group was included: Kari Luukko (chairman, Finnish Forest Industry Association), Pasi Heiskanen (Tekes), Jukka Honkasalo (UPM-Kymmene), Kimmo Lahti-Nuuttila (M-real), Ralf Lundell (AB Enzymes) and Ilkka Savolainen (co-ordinator, CLIMTECH- research programme). The project group wants to acknowledge the steering group for valuable comments and fruitful discussions during the work.

Several companies (Metso Paper, Roal Oy, Fläkt Oy, Tankki Oy) are thanked for valuable information used for cost analysis. Special thanks are adressed to UPM-Kymmene Rauma Paper Mills for data and help in the LCA study.

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Appendix

List of symbols

BOD	Biological oxygen demand
CBH	Cellobiohydrolase
COD	Chemical oxygen demand
GHG	Greenhouse gas
GW	Groundwood
LCA	Life cycle assessment
LWC	Light weight coated
SC	Super calandered
TMP	Thermomechanical pulp

1. Introduction

In order to respond to the challenges of sustainable development many nations, organisations and institutions have launched policies, strategies, programs and related activities for the development, and more rapid diffusion and uptake of cleaner technologies in industry. One such effort has been the ”*Clean World*” research program launched by VTT in 2001. This program focuses on the development of new cleaner technologies for small-scale energy production and the production of biochemicals from renewable materials; on technologies for mitigating climate change; on in-situ methods for remediation of polluted soils; and on the development of new building materials for securing safe and healthy indoor climate. The application of biotechnology plays a central role in many R&D-projects of the Program, one of them being this study, in which the application of biotechnical methods for the potential reduction of energy consumption in mechanical pulping is being assessed.

Improved industrial sustainability through biotechnology addresses many global environmental concerns. Generally one can state that biotechnology has clear environmental advantages and is economically competitive in a growing number of industrial sectors. It enables the reduction of material and energy consumption, as well as pollution and waste generation for the same level of industrial production. Continued R&D efforts, as well as new technical innovations are, however, vital for the wider utilisation of biotechnology by industry. Moreover joint government-industry action is needed to underpin the development and use of clean industrial products and processes /OECD, 1998/.

Gaps between the agreed-upon agenda of sustainable development, R&D needs and technical possibilities can be narrowed by alerting governments, industry and the public to biotechnology’s growing potential, but also to the bottlenecks, which still must be removed to bring this potential come to fruition. An example of a political push in favour of sustainable development and more rapid diffusion and application of biotechnology in industry is the Kyoto agreement on greenhouse gas reductions. In order to respond to the challenges connected with set GHG reduction targets, a national R&D program on technologies for climate change mitigation was launched in Finland in 1999. As a part of this CLIMTECH Program the present study assesses the GHG reduction potential of broader application of biotechnology in mechanical pulp production on a national level.

Although definitions of sustainable development generally are considered elusive, it is clear that any move towards industrial sustainability will affect all stages of a product’s or process’s life cycle. It will require new design principles based on a global and holistic approach to reducing environmental impacts; global because these impacts transcend national borders and holistic because short-term, piecemeal solutions to address a succession of issues in isolation will be less effective. One important means of integrating environmental issues into industrial design and operations is the adoption of Life Cycle Assessment (LCA), which so far is the best tool to measure cleanliness.

The LCA approach must always consider the boundaries, that is, the points in a multi-step process at which an LCA is to begin and end. LCA is confined to the material and energy balances, and environmental impacts of an activity, but socio-politic and economic criteria, which are also important for decision makers, do not fall within its scope. There is a high degree of consensus on the methodological framework of LCA, although the task of collecting the data can be very onerous and the method of weighting different environmental impacts is largely disputed. How do you judge *e.g.* the importance of CO_2 emissions against the BOD content of waste-waters? Because of limited availability of data on industrial scale application of biotechnical methods in mechanical pulping the LCA done in this study focuses mainly on the CO_2 reduction potential and respective impacts on the climate.

Research activity on biotechnology for the pulp and paper industry has been lively during the last two decades, but industrial implementation of new technology based either on enzymes or microbes has advanced slowly (Viikari, 2002). One reason might have been that in scientific papers economical reasoning and assessment of environmental impacts of a potential biotechnical application, which are important issues for industry, have been scarce. In this work two different biotechnical methods were considered, namely fungal pretreatment of chips (biopulping) and enzyme-aided refining, both of which have shown marked potential for energy savings in mechanical pulping. Their benefits and costs were assessed as compared with competing technology using scenario and LCA studies.

2. Aims of the study

The aims of the study were to

- study potential for energy savings and reduction of GHGs by implementation of biotechnical methods in mechanical pulping,
- estimate the possible costs and
- assess the environmental impacts of their adoption into TMP production using the LCA methodology.

This work was a part of the CLIMTECH technology programme of the National Technology Agency (Tekes). The general aims of CLIMTECH were a) to support the mitigation of climate change and the attainment of both national and international climate change mitigation objectives and b) to contribute to technological choices, research, development, commercialisation and implementation of cleaner technologies

The time scale for the technologies studied in the Programme extends to the year 2030.

Drawing from the objectives of the CLIMTECH programme, this work assessed the potential and possibilities of biotechnical methods from the present until 2030. The long time scale obviously induces many uncertainties in the estimates. The estimates presented are aimed to assess the possible future developments based on present knowledge. The possible future developments were assessed for two alternative scenarios:

- ‘Realistic’ development: International climate change mitigation measures evolve rather slowly. There are no significant changes in the support for the development and commercialisation of cleaner technologies. As a result, new technologies reducing greenhouse gas emissions penetrate rather slowly into the energy and industrial systems.

- ‘Optimistic’ development: As a result of accelerating climate change mitigation measures both internationally and within Finland, cleaner technologies develop rapidly and they are taken effectively into use. This assumes also increased support for the development and commercialisation of technologies reducing greenhouse gas emissions.

This general approach was requested by the CLIMTECH programme.

3. Mechanical pulping in papermaking

3.1 Prospects of paper production in the future

The Finnish forest industry is a worldwide player in production of paper and board. The production of paper and board in Finland has increased steadily from 1970's and in 2000 the annual production was over 1,350 000 t (Forest Industries Federation, 2002). Overall production of paper products has been predicted to grow during the next twenty years and the increment will largely be concentrated on wood containing paper and paperboards (Figure 1, Ministry of Trade and Industry, 2001a).

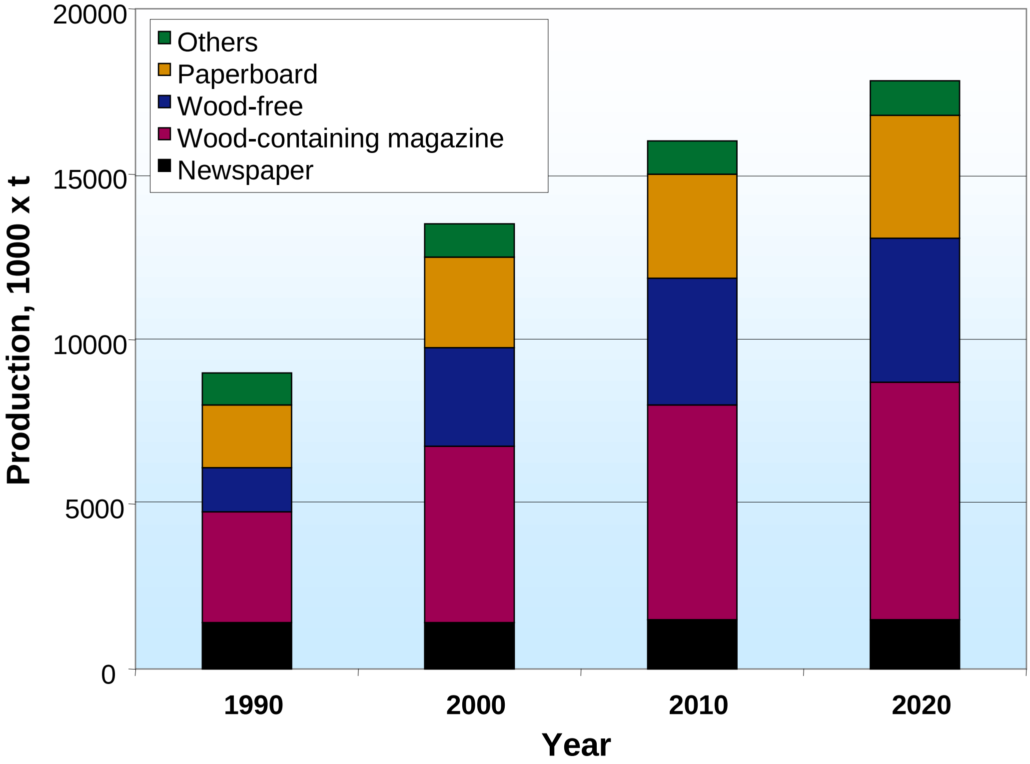

Figure 1. Predicted production of paper and board during 1990–2020 (Ministry of Trade and Industry, 2001a).

Competitiveness of the Finnish pulp and paper companies is in a large extent based on high quality wood-containing writing and magazine paper grades, like SC and LWC. This means that production of mechanical pulps, which are essential pulp components in these paper grades, will also increase (Figure 2). A growing portion of mechanical pulp is estimated to be produced as thermomechanical pulp (TMP) in stead of groundwood pulp (Ministry of Trade and Industry, 2001a). Production of groundwood pulp will increase only slightly and this shift in favor of TMP will have a clear energy related impact. This is due to the fact that thermomechanical pulping (TMP) to low freeness values, which is necessary for pulp furnishes to be used in SC or LWC, takes 30–40 % more energy than by grinding (Tienvieri *et al.*, 1999).

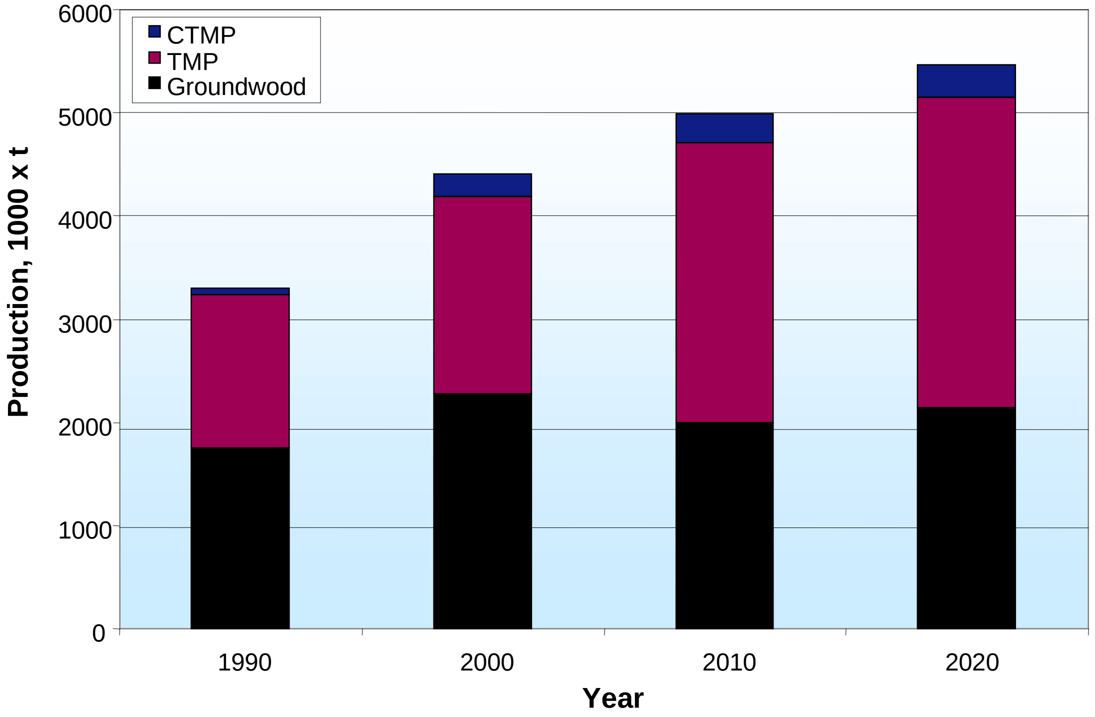

Figure 2. Predicted production of mechanical pulps in 1990–2020.

In 1998 consumption of electricity for mechanical pulping in Finland was 9.55 TWh, which corresponded to 40 % of the overall electricity consumed in forest industry (Ministry of Trade and Industry, 2001a). During the next decades annual consumption of electricity (GWh/a) is estimated to increase gradually in conjuction with paper and board production capacity (Figure 3).

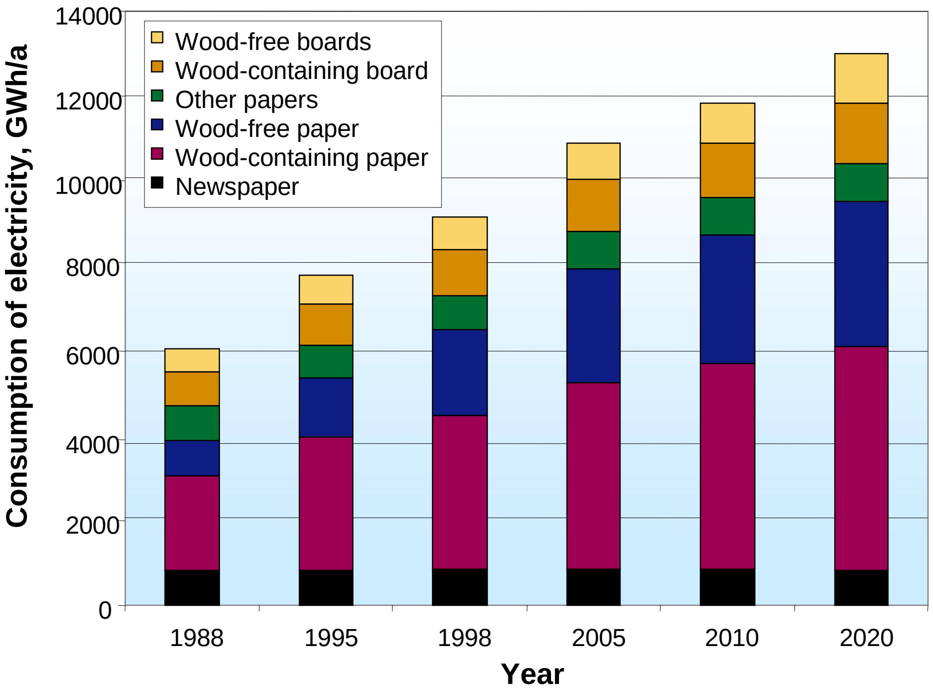

Figure 3. Estimated consumption of electricity in paper and board production till 2020 (Ministry of Trade and Industry, 2001a).

An average specific energy consumption (SEC) of TMP and GW has steadily increased during the last years (Figures. 4 a–b). This has been due to high quality requirements of writing and magazine paper grades, which has resulted in increasing needs of low freeness pulps to attain good surface and optical properties for these paper grades. A target freeness value is typically 30–40 ml and 80–100 ml for LWC base paper and for newspaper grades, respectively.

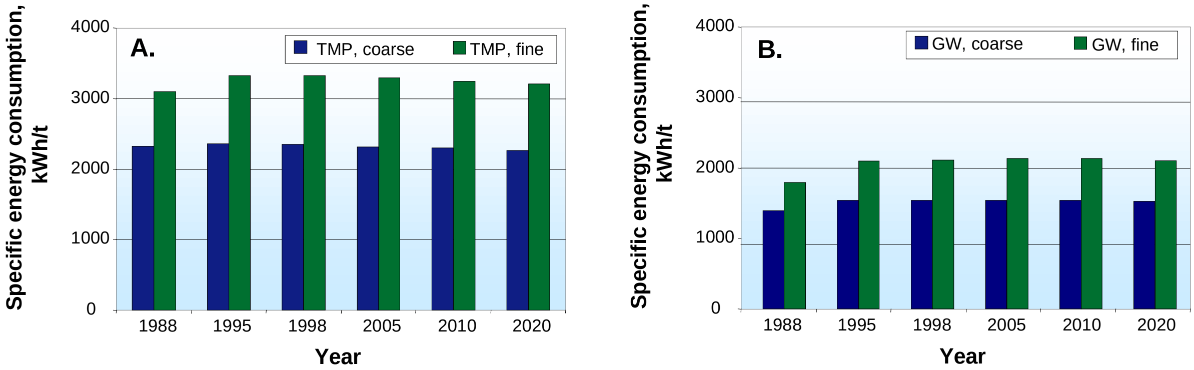

Figure 4. Specific energy consumption (SEC) of a) thermomechanicl pulping (TMP) and b) grinding (GW).

During the last decade plenty of research efforts have been focused on the reduction of SEC of mechanical pulping worldwide and also in Finland. Unfortenately, there is no clear sign of a new superior method or a technology leap in mechanical pulping

(Sundholm, 1999). It is evident that in the near future specific energy consumption in mechanical pulping and paper production will be improved within small steps, while new production machinery and technology are adopted. It is expected that via optimisation of the refining process and control system a decrease of SEC can be obtained within a few years (Ministry of Trade and Industry, 2001a). Implementation of new technology and production methods, including biotechnical methods, into mill processes will be based on cost efficiency as compared with prevailing and other competing technologies.

3.2 Mechanical pulping

3.2.1 Thermomechanical pulping (TMP)

Thermomechanical pulping (TMP) is based on refining of wood chips between two grooved metal plates (Figure 5). One (or both) of the plates, separated by a narrow gap, is rotating with high speed. When chips are fed axially into the center of the refiner, they are defibrated into shives and fibres by impacts of bars on opposite discs while the raw material is pressed outwards to the exterior of the plates. By altering the plate gap the refining process can be controlled to obtain a pulp of a desired freeness level. Refining is very energy intensive and a large portion of the energy input (as electricity) is transformed to heat and steam inside the refiner. However, recovered hot steam can be exploited in other stages of papermaking, *e.g.* in the drying section of a paper machine, improving thus the cost efficiency of the TMP process.

A simplified flow sheet for a TMP mill is shown in Figure 6. The process consists of the main and reject refiners, several screening steps and bleaching. First wood chips are refined to pulp in two stages and after screening a portion of the pulp, shieves and coarse fibres *i.e.* rejects, are refined further in reject refiners to obtain a pulp of desired properties. Thereafter, pulp is bleached and stored prior to use in the papermachine.

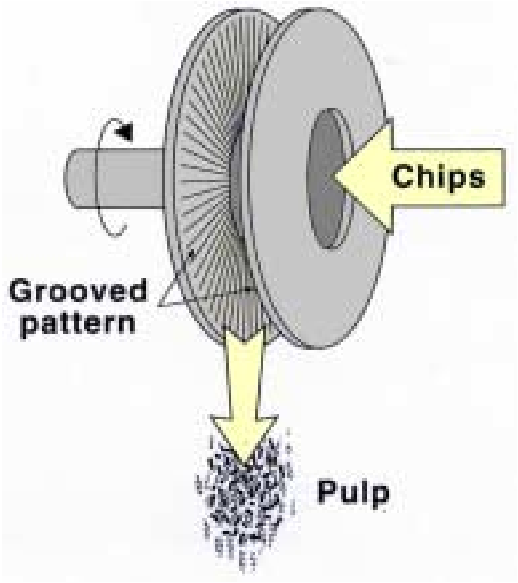

Figure 5. The principle of refiner mechanical pulping (Tienvieri et al., 1999).

The portion of pulp, which goes through reject refining, is mill and paper grade specific. In production of LWC or SC the reject ratio can vary between 30 and 50 %, whereas in production of newspaper the need for reject refining is less (reject ratio 10–20 %) due to a higher target freeness of the accept pulp. Share of power consumed in reject refining increases correspondingly as a function of the reject ratio. In TMP production for magazine papers, with high amounts of rejects, the share of energy consumed in reject refining is 30–40 % (of total), but only 10 to 20 % for lower paper grades, like newspaper and boards.

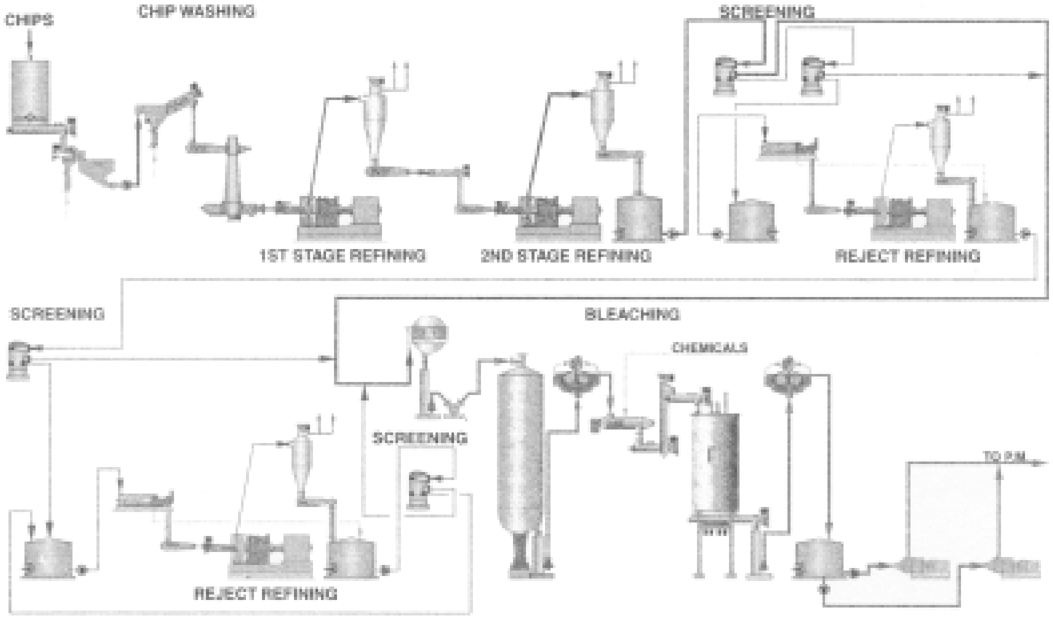

Figure 6. A flowsheet for a TMP mill (Tienvieri et al., 1999).

Production of TMP and mechanical pulp in general is straightforward so that residence times between process steps are short. Storage tanks between refining steps and bleaching are rather small and storage towers are only used for bleached accept pulp. The residence time in storage towers is several hours, but in intermediate tanks only tens of minutes rather than hours.

The temperature of whitewater is typically from 75 to 85 ^{O}C and it can be controlled rather easily. In whitewater the pH is slightly acidic (pH 4–6), when spruce is used as raw material and no chemicals are added to the process.

In northern countries Norway spruce (*Picea abies*) is the main raw material for TMP. In Canada and USA other spruce species and firs as well as aspen are also used as raw materials.

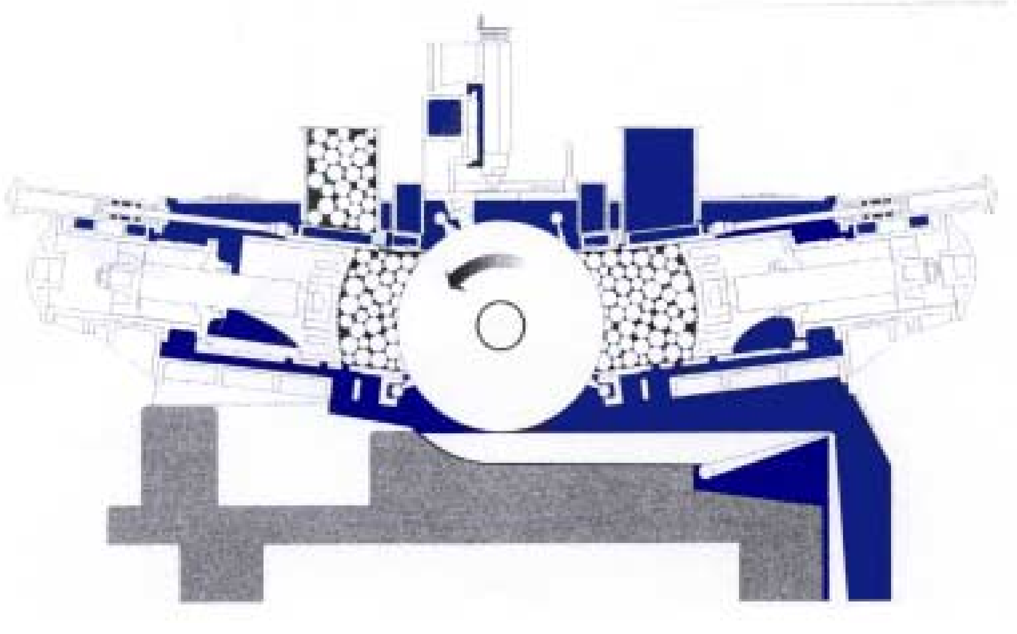

Figure 7. A modern atmospheric Valmet grinder (Liimatainen et al., 1999).

3.2.2 Grinding (GW; PGW)

In stone grinding wood logs, with a typical length of 1–1.5 m, are pressed against rotating pulpstone, while the stone surface is simultaneoulsy cleaned and cooled by water showers (Figure 7). In grinding wood is brought into a cyclic oscillating stress field and in consequence of absorbed mechanical energy wood structure loosens up and is finally defibrated. The surface layer of the pulp stone is hard and porous, and is properly sharpened to generate cyclic and compression pulses (Salmen *et al.*, 1999). Further enhancement of defibration of wood could be obtained when grinding was performed in pressurized conditions, *i.e*. in PGW process (Liimatainen *et al*. 1999).

Shower waters are essential for groundwood process acting as a cooling and lubricating medium between the grits and defibrating wood. By controlling the temperature and amount of shower water one can govern the grinding process and resulting pulp quality: too low shower water temperature tends to stiffen the fibres enhancing fibre breaking and fines generation whereas too high shower water temperature aids darkening of pulp (Salmen *et al.*, 1999). In the former case strength properties and in the latter case brightness of the pulp will be deteriorated.

PGW process can be finetuned suitable for different paper grades by varying grinding conditions (temperature and pressure). A flow scheme for a PGW70 plant is shown in Figure 8. After grinding the accept pulp and rejects are separated in successive screens. Larger pieces of wood and shives are shredded prior to screening and reject refining. Normally rejects constitute 15–20 % of the total pulp and the coarse rejects are further refined in a reject refiner.

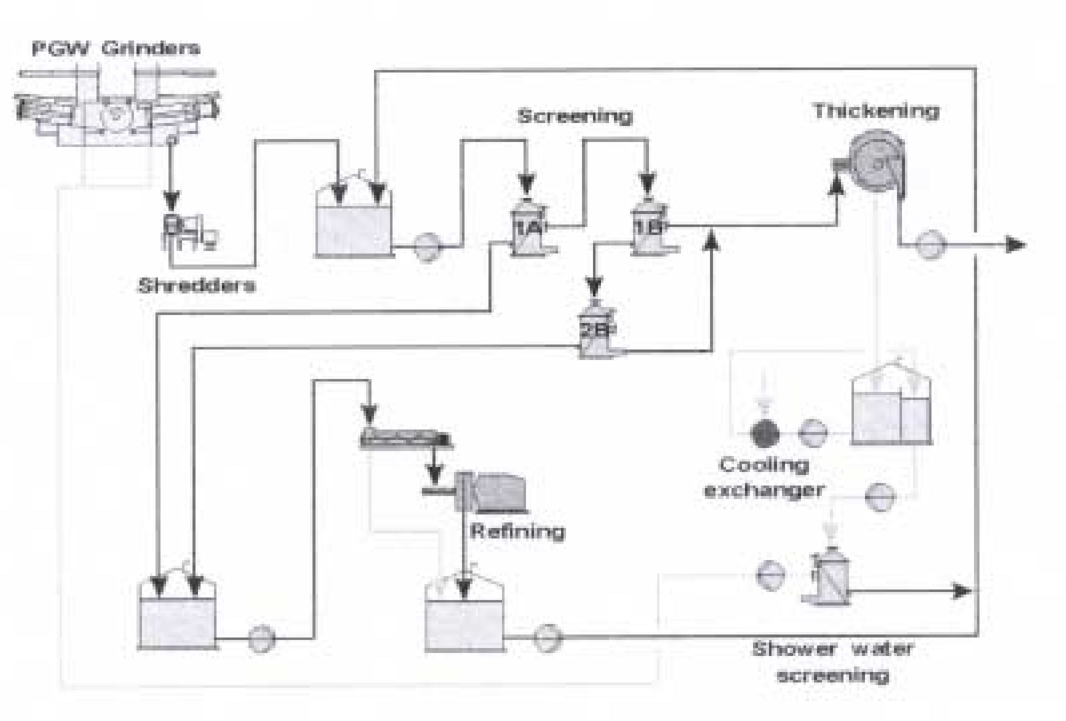

Figure 8. Flow scheme for a PGW70 plant (Liimatainen et al., 1999)

3.3 Environmental impacts of mechanical pulping

Environmental impacts of mechanical pulping originate from various stages of the manufacturing (Manner *et al.*, 1999). Defiberizing processes, grinding or refiner processes, together with screening, reject treatments, thickenings, and dilutions, *etc.*, are the main steps in mechanical pulping. They correspond to most of the energy input in the whole mill. They cause the greatest part of the wood fiber yield loss, all forms of which are subsequently found as environmental impact.

Residual of chemical additives, such as chemicals used in CTMP manufacture or reciduals of bleaching agents, can also form a noticable part of environmental impact (Manner *et al.*, 1999). Moreover chemical pretreatments or bleaching stages reduce yield. The wood material and the process chemicals which are released into process waters will end up in the mill effluents, if not carried away with the paper product or taken out as solid waste.

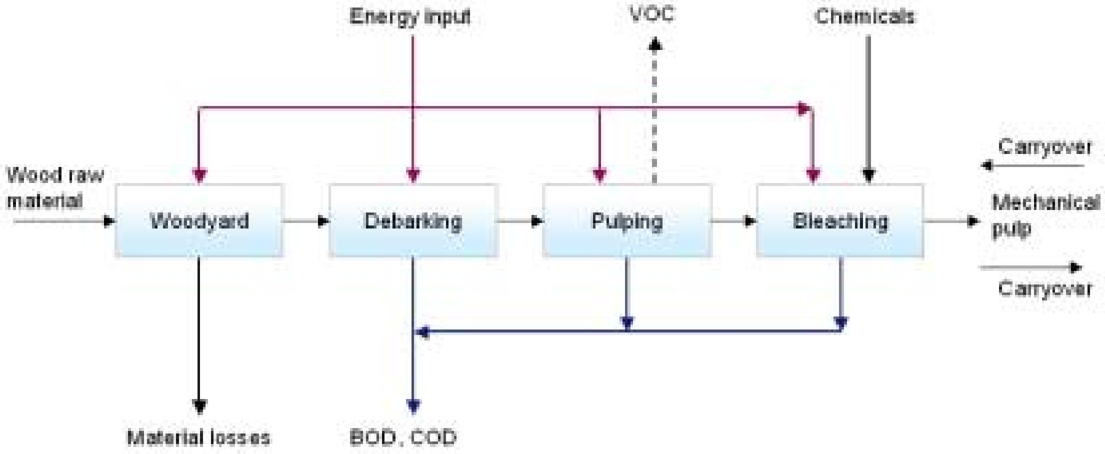

Figure 9. Main flows causing environmental impacts during mechanical pulping (Manner et al., 1999).

3.3.1 Wood and chip storage

Wood storage can cause changes in wood quality leading to changes in solubility of components, which consequently can influence the environmental impact (Manner *et al.*, 1999). In addition to changes in wood and fiber quality, yield loss is possible. The main changes in wood during storage in woodyards are due to bacterial and fungal activity and drying followed by accelerated oxidation. The main impact related to quality is loss of brightness.

3.3.2 Debarking

Bark, debarking loss of wood, sawdust, and chipping dust comprise most of the solid waste, whish is created during debarking (Manner *et al.*, 1999). A common practice is to use solid wastes as fuel and thus utilize their energy value. The effluent discharge of debarking is significant and can form one-third of the COD load of the whole paper mill. The effluent from debarking is kept separate from the water system of pulping and bleaching due to its toxic nature.

3.3.3 Release of wood components into water in mechanical pulping and bleaching

Dissolution of wood substances into the process waters varies depending on the pulping process used (Manner *et al.*, 1999). When wood is processed into mechanical pulp by conventional grinding or refining, 2 %–5 % of the wood material is dissolved, or disperced as colloidal particles, into process water. Characteristics of wastewater composition from different pulping processes using spruce as raw material in Nordic conditions are given in Table 1.

Table 1. Typical characteristics of waters from mechanical pulping of spruce in Nordic mills. TOC data calculated by TOC= 0.35xCOD (Franzén and Jantunen, 1993; Manner et al., 1999).

Pulping Process	**BOD_7 (kg/ton)**	**COD (kg/ton)**	**TOC (kg/ton)**	**Total P (g/ton)**	**Total N (g/ton)**
GW	10–12	30–40	10–14	20–25	80–100
PGW	12–15	40–50	14–18	20–30	90–110
TMP	15–25	50–80	18–28	30–40	100–130
CTMP	20–35	60–100	21–35	35–45	110–140

Bleaching with alkaline hydrogen peroxide causes an additional load of 5–15 kg BOD/ton and 15–40 kg COD/ton, which is the same magnitude as in mechanical pulping itself (Franzén and Jantunen, 1993). The discharges of phosphorus and nitrogen also increase. Reducing dithionite bleaching does not notably increase the amount of dissolved organic material.

The main components of the dissolved and colloidal substances are hemicelluloses, lipophilic extractives, lignans, and lignin related substances. Table 2 gives typical amounts of substances released from TMP of Norway spruce (Manner *et al.*, 1999).

Table 2. Typical amounts of dissolved and colloidal substances in 1 % suspensions of mill-produced spruce (Picea abies) TMP. Bleaching of the TMP was made with alkaline hydrogen peroxide (3 % on dry pulp basis) in the laboratory. The TOC values of these waters were 214 and 288 mg/l, respectively (Thornton et al., 1991, 1993; Holmbom et al., 1991; Thornton, 1993).

Component group kg/ton TMP)	**Unbleached TMP**	**Peroxide-bleached TMP**
Hemicelluloses	18	8
– Galactoglucomannan	16	4
– Other hemicelluloses	2	5
Pectins (galacturonans)	2	4
Lignans	2	1
Other lignin-related substances	7	11
Lipophilic extractives	5	4
Acetic acid	1	20
Formic acid	0.1	4
Inorganic constituents	<1	5

In addition to these wood originated components, residuals of processing chemicals, and leakages from machinery constitute dissolved and dispersed material released into process waters. This material includes carryover of residuals of papermaking chemicals, organic and inorganic substances in fresh water and carryover of dissolved and dispersed material from debarking.

Mechanical pulping effluents are toxic to water organisms. The toxic components and the toxicity levels differ substantially between wood species (O'Connor *et al*., 1992). Much of the toxicity of softwoods pulping effluents is due to the resin acids (Lavallée *et al*., 1993). Well-operated biological treatment can eliminate most of the toxicity of mechanical pulping effluents (Gibbons *et al.*, 1992).

3.3.4 Evaporation of compounds in mechanical pulping

Some materials losses take place by evaporation (Manner *et al.*, 1999). A part of wood extractives and fragmented wood polymers are evaporated during processing. Those volatile organic compounds (VOCs) are removed with exhaust steam flows or condensed back into liquid phase. Incineration of waste residues results in burning exhausts.

3.3.5 Final environmental emissions

The final environmental emissions from mechanical pulp manufacture after all system closings, recovery, and purification steps can be listed as follows (Manner *et al.*, 1999):

- Bark and other wood-based residues that are recovered as a valuable fuel.
- Biosludge, which is usually treated together with primary sludges, originate from internal and/or external wastewater treatment.
- Oxygen-consuming organic substances, nutrients, and various other organic and inorganic impurities in the outlet effluent from watewater treatment.
- Air emissions, from different stages of the operation.
- Noise
- Heat excess from defibration

4. Biotechnology and mechanical pulping

4.1 Biopulping technology

In biopulping, wood chips are treated with a selected micro-organism prior to mechanical pulping in order to obtain energy savings in refining and quality improvements of pulp. The selected biopulping organism, normally a white rot fungus, grows and attacks on wood lignin (and carbohydrates) resulting to softening of wood chips. This results in energy savings in refining. Depending on the organism and wood species, the reported energy savings have been in the range of ca. 20–40 % after a two-week treatment and up to 47 % after a four-week treatment (*Ceriporiopsis subvermispora* on aspen chips) (Leatham *et al.*, 1990; Akhtar *et al.*, 1992; 1998). Additionally, paper strength properties have shown to be improved after biopulping. The main drawbacks of biopulping are related to losses in yield and brightness.

Research in biopulping started already in the 1970's. One of the first microorganism studied for biopulping was a white-rot fungus *Phanerochaete chrysosporium*. It was efficient and selective on degradation of wood lignin and in addition competitive on unsterile chips partly due to its high growth temperature optimum (39 °C). However, it was found to be ineffective on softwoods. The other white rotter, *Ceriporiopsis subvermispora,* was later found to be effective both on softwoods and hardwoods. The growth optimum for this fungus is 27–32 °C and therefore biopulping with *Ceriporiopsis* had to be performed with sterilized chips (Akhtar *et al*., 1998).

Research aiming at isolating effective biopulping organisms suitable for northern climate has been done in Finland for several years. Promising results have been obtained with new microbial strains decreasing the energy consumption in mechanical refining (Tekes report, 2002). In Finland scale-up of the biopulping process to industrial or larger pilot scale has not been done, the largest scale of the experiments being about 10 kg (d.w.) of spruce chips.

This study is based on the results obtained with *Ceriporiopsis subvermispora* because of the large amount of treatment results available. However, new and efficient micro-organisms are studied at the moment. *E.g. Phlebia subserialis* has recently shown better properties than *C. subvermispora*: The fungus does not increase the compressibility of wood chips as much as *C. subvermispora* and the effects in mechanical pulping are still comparable (Akhtar *et al.*, 1998).

4.1.1 State-of-the-art of biopulping

4.1.1.1 Main research results

First studies of biopulping with *C. subvermispora* were carried out with aspen (Akhtar *et al.*, 1992). Up to 47 % decrease in the refiner energy consumption was obtained after four weeks treatment at laboratory scale. Shorter tretments also showed the efficiency of fungal tretment. Two weeks' treatments of loblolly pine chips decreased the refiner energy consumption by up to 36 % (Akhtar *et al.*, 1997). For spruce chips the decrease was 24% at laboratory scale (Scott *et al.*, 1998).

Spruce chips have been treated succesfully at a larger scale, too (Scott *et al.*, 1998). On 4–40 tons' scale of chips, 26–38 % energy savings in refining of refiner mechanical pulp were obtained. At the production of thermo mechanical pulp, energy saving of 31 % was obtained. Pretreatment of spruce wood chips with *C. subvermispora* improved paper strength properties (Akhtar *et al.*, 1998). Burst index, tear index and tensile index improved by 35 %, 52 % and 26 %, respectively as compared to the control treatment.

Biopulping fungi can also reduce the content of extractives in wood chips (Fisher *et al.*, 1994). On softwood chips *C. subvermispora* was equally effective in reducing extractives as the albino strain of sapstain fungi *Ophiostoma piliferum*, which is commercially used for depitching (Table 3). The reduction in the amount of wood extractives was about 30 % by *C. subvermispora*.

Table 3. The effect of different fungi on softwood dichloro methane extractives in two weeks' cultivation.

	Loblolly pine (*Pinus taeda L.*) Resin content (%)	**Spruce (*Picea abies*) Resin content (%)**
Control	2.64	1.2
C. subvermispora	1.93	0.8
O. piliferum	2.16	0.9
P. chrysosporium	–	0.9

Sykes (1994) studied the effect of biopulping on the toxicity and biological oxygen demand of effluents from aspen pulps. The effluents from untreated pulps were significantly more toxic than those of (Table 4) biotreated pulps. BOD for effluents from fungal treated pulps were, however, higher than for refiner mechanical pulp (RMP) of raw aspen chips. COD for effluents from fungus-treated pulps were considerably higher than for RMP of raw chips, probably because of the release of lignin-related products.

Table 4. Effluents from the first refiner pass of raw aspen chips, chips after control treatment and chips after fungal treatment. The treatment time was 4 weeks. (Sykes, 1994).

Treatment	**BOD** (g/kg pulp)	**COD** (g/kg pulp)	**Toxicity** (100/EC_{50})
Raw aspen chips	18	40	33
Control (+ nutrients)	40	74	17
C. subvermispora (+ nutrients)	36	100	4

Fungal pretreatment of wood chips significantly reduces the brightness of the resulting mechanical pulp. To gain the same level of brightness as that of normal mechanical pulp, fungal treated pulps need additional bleaching. Scott and Swaney (1998) have estimated a 15 % increase in the consumption of bleaching chemicals.

Biopulping with *Ceriporiopsis subvermispora* can not be performed with unsterile chips (Akhtar *et al.*, 1998). The indigenous micro-organisms inhibit the effect of this fungus in biopulping. Bisulfite treatment or short steaming of wood chips prior to inoculation of chips has been shown to allow the proper growth of the fungus on chips.

The amount of the required inoculum could be reduced from 3 kg/t to 0.25 g/t (of dry wood chips) by a nutrient addition (Akhtar *et al.*, 1997). Good results were obtained by combining the inoculum with corn steep liquor (5 kg/t of dry wood chips), which is a cheap nutrient available *e.g.* in USA.

4.1.1.2 Biopulping processes

Large scale biopulping experiments with *C. subvermispora* have been carried out in Madison, USA (Scott *et al.*, 1998). 40 tons of chips have been treated in a continuous process consisting of steaming, cooling and inoculation before a two-week treatment in an aerated chip pile. The throughput of the chip steaming, cooling and inoculation system was about 2 tons/h.

Industrial scale biopulping processes have not yet been reported. However, a corresponding process (Cartapip) for pitch removal and controlling of unwanted coloured micro-orgnisms on wood chips has been used for several years on industrial scale (Breuil *et al.*, 1998). In the Cartapip process the inoculated fungus does not modify wood in a such way, which could result in energy savings in mechanical pulping. Additionally, decontamination of chips and aeration of chip piles are not practiced with Cartapip. The process consist only of mixing the Cartapip powder with water and then spraying the suspension on chips while they are tumbled in a screw conveyor before being blown into the chip yard.

4.1.1.3 Open questions and research needs

Scale-up

The scale-up of biopulping technology into a continuosly operated industrial process rises several open questions. The control of optimal conditions for fungal growth inside the chip pile or silo may be difficult because of the large size and formation of subzones in terms of *e.g.* temperature, moisture and oxygen availability. Growth of fungus is endogenic and large quantities of heat must be removed from chips during the treatment. This can be performed with compressed air. The air blown through the pile or silo will simultaneously dry the chips and therefore humid conditions inside pile/silo must be taken care of ensuring adequate growth of fungus. Probably this can be done by moistening the inlet air and by adding water sprays at proper locations. The compression and softening of chips due to fungal growth will probably increase the aeration costs.

Continuous day-to-day operation on pilot or mill scale, providing homogenous material for pulping needs still to be demonstrated.

Inoculum and nutrients

The production of fungal inoculum of *e.g. Ceriporiopsis subvermispora* for biopulping has not been reported on a large scale. *Ceriporiopsis* is not a sporulating fungus and thus the stability of the fungal product may be a problem. A ready-to-use product based on *Ceriporiopsis* or another biopulping fungus with high stability and long shelf life should be developed. Corresponding fungal products are, however, available for *e.g.*

biocontrol applications, and no major difficulties next to those included in the normal product development work for living microbial preparations are anticipated.

The amount of inoculum could have been reduced to a cost-effective level by the nutrient addition. Corn steep liquor (CSL) which is a cheap nutrient in USA has generally been used. If imported to Finland it will however make up a substantial part of the processing costs. An alternative Finnish waste material with high nutrient content (especially nitrogen) should be searched for and developed in further studies.

Winter operation

A day-to day operation of a large-scale industrial process in northern climate can prove to be problematic. During the winter months, freezing of chips should be prevented to ensure steady performance of the biopulping organism. Nevertheless heterogeneous quality of chips might be resulted, especially if growth conditions, *i.e.* temperature, humidity, for the biopulping organism were not uniform in the exterior and inner parts of the pile/silo. Handling of high volumes of moist air might result in unwanted ice formation in the equipments, conveyors etc.

Strain development

In the long term, major improvements to the performance of the biopulping process can be obtained by screening new and better strains for chip treatment. Key items to focus on include:

- Improved selectivity of the fungi; leading to decreased yield losses and improved fibre quality
- Competitive strains on unsterilised chips, resulting in a more simple and economic process, as steaming of the chips can be omitted
- Strains that cause less darkening of the chips, resulting in the reduced need of additional bleaching of pulps prepared from fungi-treated chips

4.1.2 Description of the process

In the biopulping process with *Ceriporiopsis subvermispora,* wood chips are steamed, cooled, inoculated and then incubated two weeks at 27–32 °C temperature (Scott *et al.*, 1998). The biopulping process was further developed and designed especially for Nordic conditions. Design of the process was partly based on the following facts and assumptions, which were derived from published data of several experiments carried out on pilot or large laboratory scale:

- The amount of inoculum needed is 0.5 g/ton (dry) wood chips (Akhtar *et al.*, 1997)
- The amount of corn steep liquor used as additional nutrient is 5 kg/ton (dry) wood chips (Akhtar *et al.*, 1997)
- The yield loss during biopulping (2 weeks) is 2 % of wood chip material.
- The heat generation during the fungal treatment is 0–400 W/m^3 (Scott *et al.*, 1998).
- Consequently, the aeration rate required for cooling is 0–0.4 m^3/m^3/min (Scott *et al.*, 1998).
- Other details are based on discussions with Finnish equipment manufactures (*e.g.* Metso Woodhandling Oy, Oy Fläkt Ab) and on literature data (*e.g.* Akhtar *et al.*, 1997, Scott *et al.*, 1998)

4.1.2.1 Steaming, cooling and inoculation

Wood is chipped and conveyed to the biopulping process. The biopulping process diagram is presented in Figure 10.

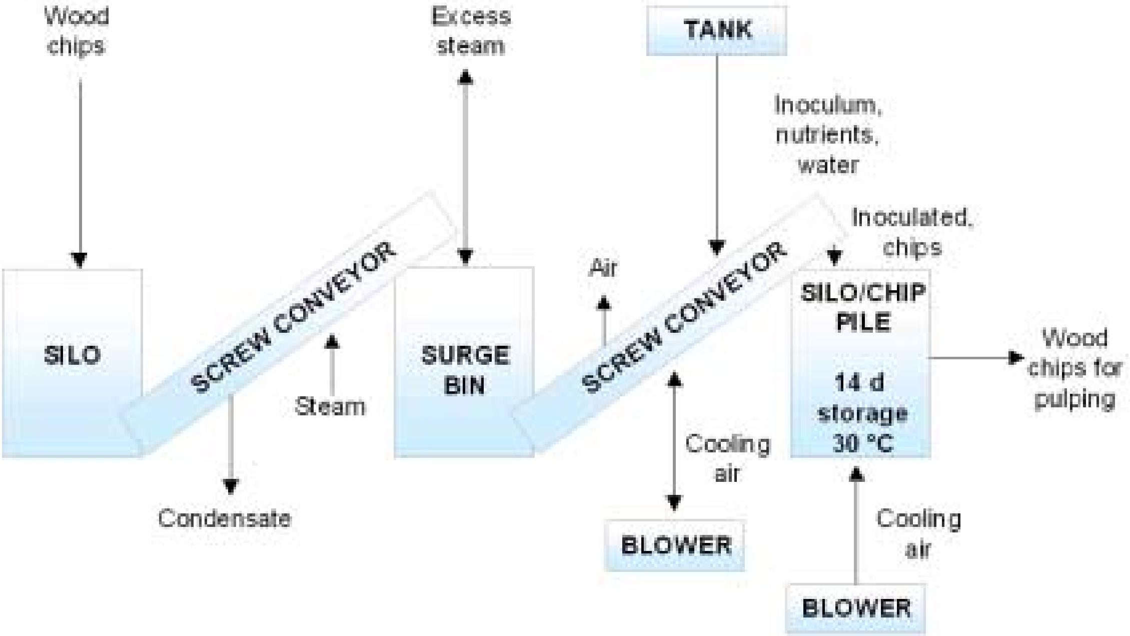

Figure 10. Biopulping process.

The chips are stored for a short time (max 5 h) in a silo before being conveyed to steaming. Steaming will be carried out in a screw conveyor, where steam is injected near to its upper end. Steam will condensate and the surface of the chips will heat up to 100 °C temperature. Condensing water will be drained off at the lower inlet end of the conveyor. After steaming, the chips will be dropped to a surge bin. The surge bin is needed for buffering the process and also for holding the chips in a high temperature for a time long enough for decontamination.

After steaming, the wood chips must be cooled down before the inoculation step. The chips will be conveyed from the surge bin by a screw conveyor, which is ventilated with air in order to cool the wood chips. Cooling air is ventilated with a blower. The air enters the conveyor in the middle section, flows through the stretch of chips and comes out at the lower position near the inlet of the conveyor. The cooling air is blown countercurrently against the conveyed chips to make the cooling more efficient. During this, some water from chips will evaporate. The outcoming warm air is blown to the outdoor air or is recycled elsewhere in the process.

After cooling the temperature of chips is below 50 °C and they can be inoculated with the fungus. The inoculation will take place in the same conveyor as cooling. The fungal preparation of inoculum and additional nutrients are mixed with water and stored in a tank. This suspension containing the fungal preparation, additional nutrients (*e.g.* corn steep liquor) and water will be sprayed with a pump and mixed to chips in a screw conveyor. Thereafter inoculated chips will be conveyed to a silo or a pile.

4.1.2.2 Chip treatment in silo

Inoculated wood chips will be conveyed and loaded into a silo through the top. The capacity of each silo is the volume that is required for two day's pulp production of the mill. In the first two days the heat generation rate of fungi is small but during the following days it will increase rapidly. During the first two days the silo might need some warming, otherwise the temperature of the chips might be suboptimal for the onset of fungal growth. Laater on heat generation by the fungal metabolism increases and the chips should be aerated at a rate sufficient to keep the temperature at optimal level (*e.g.* 27–32 °C for *Ceriporiopsis subvermispora*). The air will be fed with a blower at the bottom of the silo, possibly moistened and after flowing through the chips it will come out from the top of the silo. The chips will be incubated in the silo for 14 days. The silo will be unloaded by a conveyor from the bottom of the silo and the chips conveyed to the pulping process.

4.1.2.3 Chip treatment in pile

Wood chips will be conveyed to a pile after inoculation and stored in a annular shaped pile for 14 days, in similar environmental conditions as in the silo treatment. Chips will be fed with moving conveyors to a sector of the annular pile. At the same time chips treated for 14 days will be unloaded by conveyors at the other sector of the pile. The pile will be aerated through the bottom with the aid of blowers. The pile will be divided into separate sections in terms of ventilation arrangements and in order to enable different aeration levels of chips during the treatment stages.

4.1.2.4 Preparation of inocula

The process schema of inoculum production for biopulping was based both on literature data and on the pilot scale experience of microbial cultivations performed at VTT Biotechnology for several customers. Information on production of inoculum was applied in the LCA study. The production of fungal inoculum for biopulping consist of several process steps. Active fungal cell mass is produced by cultivating the microorganism in a fermentor on a defined culture medium. After cultivation, fungal cells are separated from the culture medium by filtration and the cell mass is dried in a freeze dryer. Stabilizing agents are added to the cell mass prior to drying in order to maintain viability and adequate shelf life. The dried product is packed and transported to a paper mill for use. The final product containing the active fungus should probably be transported and stored in the cold chain (+4 °C), to guarantee stability. It is estimated that the dried industrial fungal product should have the shelf life of several months, and high viability when suspended to water and nutrients prior to use in the mill.

4.1.2.5 The effects of biopulping on mechanical pulping

Sofar scaling up of the biopulping process to pilot scale has been succesful and improvements in the efficiency of the treatment has been obtained (Scott *et al.* 1998). Based on the literature reports with *C. subvermispora* and results obtained in a national project ("Pretreatments of wood chips in pulping processes"/Finnish Forest Cluster Research Programme) it is assumed that net energy savings of 20 % in specific energy consumption (SEC) could be attained. It is also assumed that the effectiveness of the treatment can further be improved in the future.

4.1.2.6 The effects of biopulping on paper manufacture

It has been shown that biopulping affected on the strength properties, the brightness, and the content of extractives of the pulp produced, and thus also have consequences on the paper manufacturing.

Fungal treatments of wood chips have shown to improve paper strength properties (Akhtar *et al.*, 1998). Burst, tear and tensile indexes improved by 35 %, 52 % and 26 %, respectively over the control. The improvement of the strength properties of mechanical pulp by microbial pretreatment provides a possibility to replace kraft pulps with biomechanical pulp in the wood-containing paper grades.

Biomechanical pulps need additional bleaching to gain the same brightness level as normal mechanical pulp. Scott and Swaney (1998) have estimated an increase of 15 % in the consumption of bleaching chemicals. However, this estimate is based on the brightness results gained with the blends of chemical pulp. The amount of bleaching chemicals needed to reach the same brightness level for biopulp as for normal mechanical pulp is much higher. Based on the results obtained in the research project "Pretreatments of wood chips in pulping processes" (Tekes report, 2002), a 400 % increase in hydrogen peroxide consumption in bleaching of biopulped pulp as compared to conventional mechanical pulp was estimated. Sodium hydroxide cosumption was assumed to increase to 250 % (Lindholm, 1999). The darkening effect of fungi was assumed to be reduced and the bleachability of biomechanical pulp improved in the future.

The amount of wood extractives can be reduced by fungal treatment of wood chips. Consequently, the problems associated with wood extractives, *e.g.* breaks at paper machines, stickies and specks on paper products and toxicity of effluents can be reduced, if biomechanical pulps are used for paper manufacture.

Effects of biopulping on environmental emissions from the pulping process have not been studied throughly. In biopulping, additional process steps (steaming, cooling, inoculation and storage of chips) are implemented to the normal pulping process. These new process steps may have unexpected impacts on quantity and quality of waste water and gaseous emissions (Figure 11).

Steaming of chips might induce increased release of volatile and/or soluble compounds from wood chips (*e.g.* exractives, carbohydrates) into air or water. After steaming, the chips are cooled by compressed air resulting in evaporation of volatile compounds as well as water. Extra need for cleaning of equipments due to inoculation of chips may arise, which can slightly increase the amount of waste water. Microbial modification of chips as well as added nutrients will probably affect on the BOD and COD loads of waste water due to enhanced leaching of soluble components from wood during fungal treatment.

In normal chip storage microbial activity causes carbon dioxide formation, but occasional methane release may also happen due to anaerobic conditions in the pile. In biopulping this can be avoided by aeration, but intensive fungal growth may cause odorous emissions.

In refining, higher BOD and COD levels in the circulation water might occur, when biopulped chips are used as raw material. Evidently, this is due to fungal biomass itself and increased leaching of wood components caused by fungal modification of wood. On the other hand, removal of extractives from chips by fungi may decrease the toxity of water. At bleaching, increased consumption of bleaching chemicals will cause increased waste water loads.

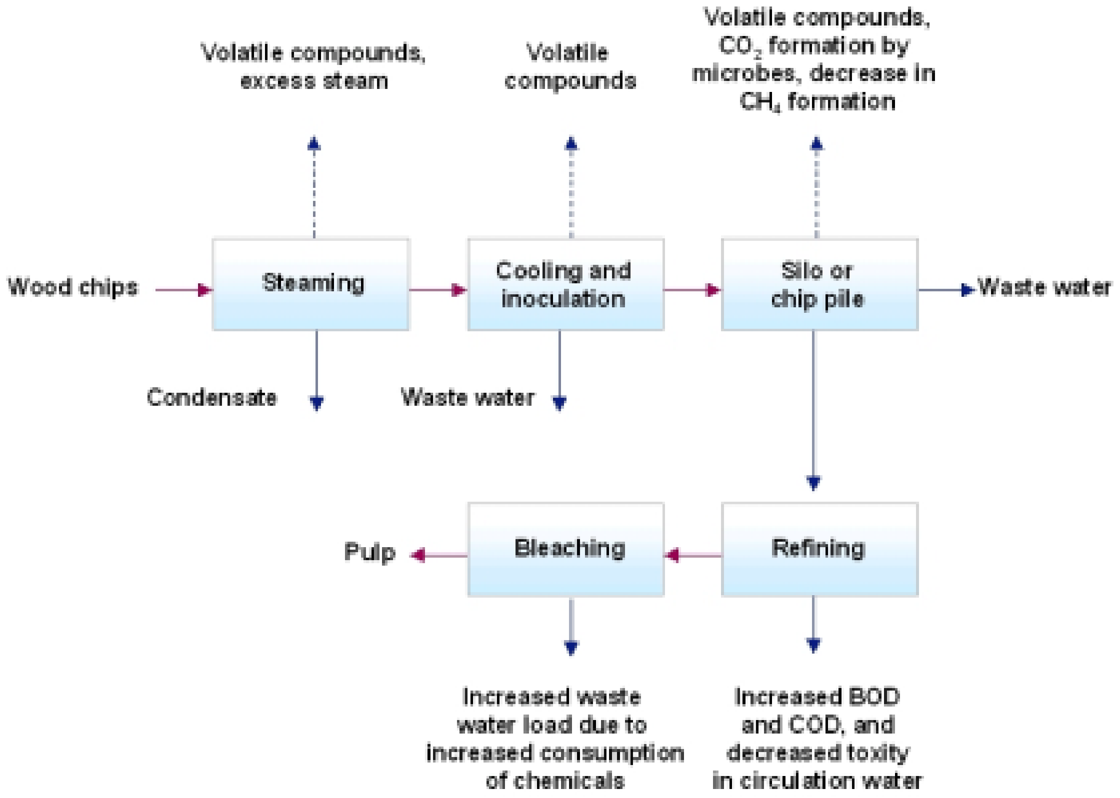

Figure 11. Environmental effects of biopulping in mechanical pulping process.

4.2 Enzyme-aided refining of mechanical pulp

In addition to microorganisms enzyme preparations can also be applied in modification of wood raw material prior to mechanical pulping. In biopulping, exogenous enzymes secrected by the inoculated fungus during growth in the interior of chips soften and loosen the wood structure, which essentially reduces mechanical energy needed for chip defibration. In enzyme-aided refining an enzyme preparation, free of living cells, is used for modification of coarse pulp or rejects prior to reject refining (Figure 12).

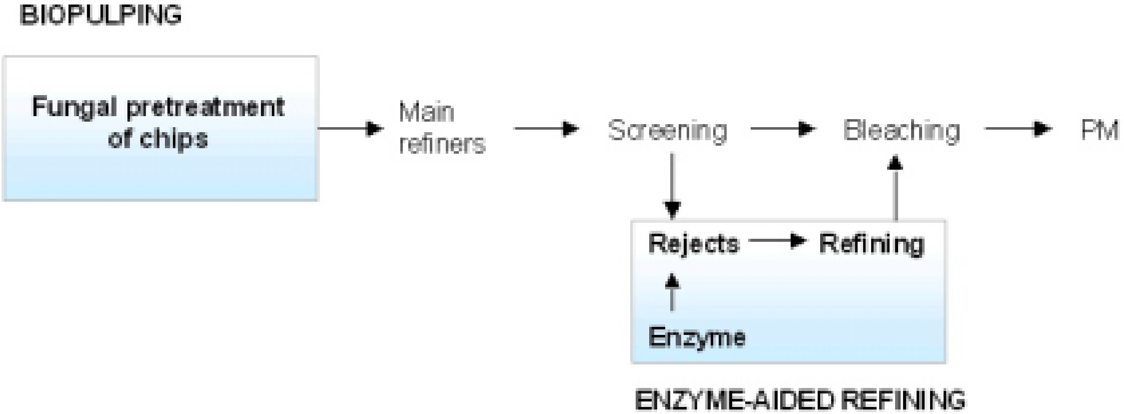

Figure 12. Principles of the biotechnical methods for mechanical pulping.

Ultimately, both of these biotechnical methods end up to documented benefits in mechanical pulping, namely, in reduction of SEC and in improvement of sheet properties. However, from biotechnical and process technical points of view these two processes differ considerably (Table 5). Biopulping involves application of a living fungus on heterogenous chip material in high amounts, which makes it sensitive to disturbances and difficult to control for cell growth and activity during rather long incubation time. Treatment time needed for enzymatic modification of pulp is on the contrary short, only a few hours (2–4 hours). However, the enzyme preparation must be designed and tailored for the raw material in question, taking into account prevailing conditions (temperature, delays etc) in the mill.

Table 5. Characteristics of the biotechnical methods for mechanical pulping.

Method	**Treatment of**	**Action of**	**Process characteristics**	**Benefits**
Bio-pulping	Chips	A growing fungus	Treatment time, 2–3 weeks Chip piles or towers Semicontrolled process	Reduction of SEC, 20–40 % Improved strength properties of paper
Enzyme-aided refining	Pulp or rejects	Enzyme(s)	Treatment time, 2–4 hours Reject tanks Controlled process	Reduction of SEC, 5–10 % Good sheet properties

The main benefit of both methods is energy saving. However, the potential for energy savings is higher in biopulping than in enzyme-aided refining, because in the latter case only part of the pulp is treated after defibration in the main refiners (Figure 13). In main refiners 60–70 % of the total specific energy consumption (SEC) is formed. Energy savings of 10–15 % in reject refining will therefore end up to net energy savings of 3–8 % depending on reject ratio in production of TMP (main + reject refiners).

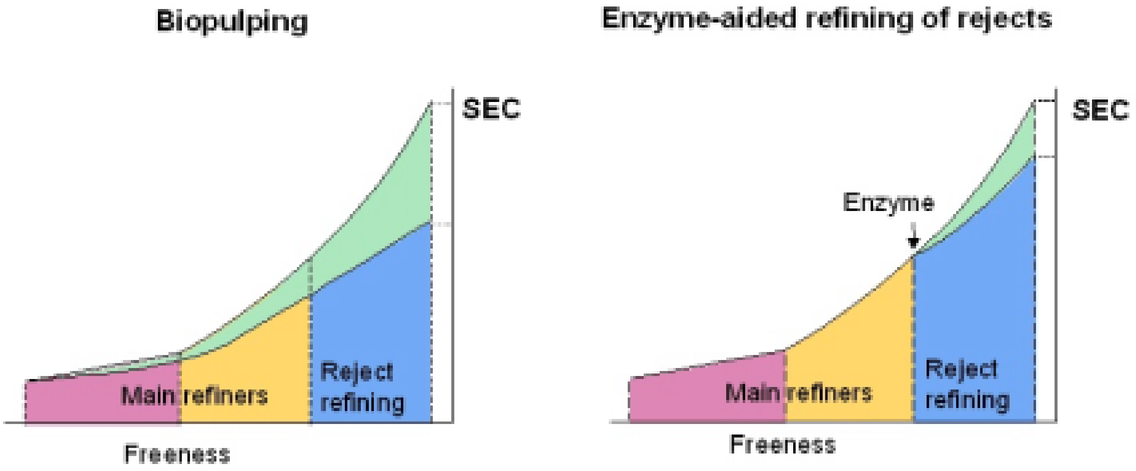

Figure 13. Energy savings in biopulping and enzyme–aided refining. The shaded areas represent potential energy savings obtainable by the two different methods.

4.2.1 Development of the method

The concept of enzyme-aided refining was developed during 1990's at VTT Biotechnology in collaboration with the Laboratory of Pulping Tecnology at HUT. The main aim was to obtain energy savings in refining while retaining good pulp properties. The study started with screening of suitable enzyme(s) for pretreatment of coarse pulp, prior to laboratory scale refinings with a disk-refiner. The main attention was paid to enzymes acting on carbohydrates, *i.e.* cellulases and different types of hemicellulases (xylanases, mannanases, pectinases), in stead of lignin modifying enzymes.

As a result of the screening and testing of several purified enzymes and their mixtures in laboratory scale refinings a cellulase, namely cellobiohydrolase I (CBH I), was found to be most promising. When coarse TMP (CSF 400–600 ml) was pretreated with CBH I for a few hours, energy savings between 15 and 20 % were obtained in a successive reject refining (Pere *et al.*, 1996, 2000). One primary advantage of the method as compared with the competing technologies was that a reduction in SEC was obtained without any harmful effects on pulp quality. In fact, improvement of strength properties of pulp was demonstrated when coarse rejects devoid of fines (CSF 600–650 ml) were treated. In addition, no deterioration of sheet optical properties, *e.g.* decrease of brightness, was detected due to the enzymatic pretreatment. Soon afterwards the potential of the enzymatic method was also tested in pilot scale trials at Keskuslaboratorio Oy. Results of the pilot trials verified the main laboratory findings, but the competitiviness of the method had to be improved in order to be a viable alternative in mill conditions. Firstly, to be economically feasible the dosage of enzyme had to be lowered and secondly, optimal conditions for the treatment had to be found, because acceptable retention times are short in the mills. Through optimisation of treatment conditions, *e.g.* pulp consistency and mixing, and composition of the enzyme preparation, effective dosage of the enzyme could be reduced substantially from that, which was used in the preliminary laboratory and pilot scale experiments.

4.2.2 Mill scale trials

Industrial scale refinings on a TMP line were performed at UPM-Kymmene/ Rauma Paper mills for final verification of the results obtained on laboratory and pilot scales (Pere *et al.*, 2002). The trials consisted of experimental periods with enzyme addition (1–2 weeks) and of reference periods prior to and after the experimental periods. Throughout the trials the raw material, process conditions (white water characteristics, screening) and refiners were kept as stable as possible. On-line information on refiner loads, specific energy consumption (SEC) and freeness (CSF) of the pulp were collected during the trials.

Layout of the TMP line of a capacity for 200 tons/d is shown in Figure 14. The enzyme was mixed with the reject pulp in a storage tank prior to the two-stage reject refining. During the trials the freeness (CSF) of the unrefined reject pulp varied between 200–250 ml. The temperature of the white water was set to 70 °C and the reaction time of the pulp with the enzyme was between 6 and 8 hours. A semi-commercial enzyme preparation, rich in cellobiohydrolase activity (CBH), was used in the trials. Dosing of the enzyme (based on protein) was varied between 0.1 kg/t and 0.4 kg/t according to the daily output of rejects.

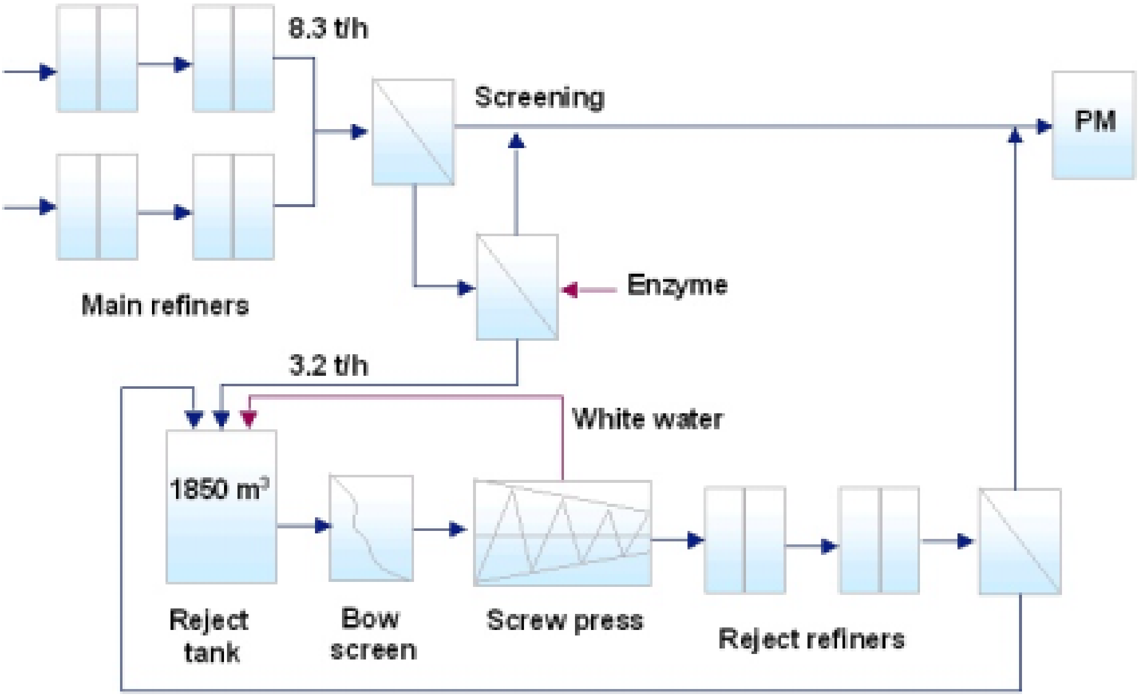

Figure 14. A schematic presentation of the TMP plant at UPM-Kymmene Rauma paper mill.

After the start-up of a trial enzymatic activity in the process was followed by taking samples of white water from the bow screen and analysing them for soluble carbohydrates. Concentration of soluble carbohydrates in the white water began to increase within 5-8 hours after the start-up of the enzyme addition. Organic solubles in white water corresponded very well to the enzyme loading and responded within a few hours to changes in the enzyme dosage. At the dosage of 0.1 kg/t concentration of reducing sugars in the white water exceeded the background level by 20-30 %. Thus yield loss due to the enzymatic treatment can be expected to be rather low, when the enzyme will be loaded at a relevant level (≤ 0.1 kg/t) in continuous use.

Simultaneously with the appearance of soluble carbohydrates in the white water, an increase in motor load of the two reject refiners was detected. Within few hours the refiner loads reached a level, which was 10–15 % higher than before enzyme addition.

While the refiners were normally run for a constant freeness, the increased refiner load enhanced fiber development and consequently, a decrease in CSF was observed. The reduction in CSF was compensated by opening of plate gaps. Thereafter, the CSF of the pulps started to increase back to the set values. The plate positions could be kept open till the cessation of enzyme addition, but thereafter they were tightened in order to maintain the target freeness.

As a consequence of the plate gap opening, the specific energy consumption (SEC, MWh/t) of the reject refiners decreased by 10–15 %, as compared with the periods without enzyme addition. This is shown in Figure 15, where the SEC of the reject refiners is shown for the second experimental period. First, SEC started to rise due to increased motor load, but decreased clearly after release of the refiner plates. Thereafter, the SEC was retained at a reduced level even with the lowest enzyme dosage used (0.1 kg/t). According to these results, 0.1 kg/t was a sufficient make-up dose of enzyme to generate and maintain boosting of refining. After termination of the enzyme feed the SEC reached the original level, indicating a gradual dilution of the residual enzyme activity out of the system.

The quality of accept pulp was maintained good during the trials, and differences between the experimental and reference pulps were rather small. Improvements in strength properties of laboratory sheets were not detected unlike previously in the laboratory refinings, in which the unrefined reject was characterised by a high freeness, 600 ml CSF (Pere *et al*, 2002). Obviously, the main reason for this negative result was a low CSF of the unrefined reject pulp (200–250 ml CSF), which reduced the modifying power of the enzyme. Also fines originally present in the unrefined reject adsorbed part of the enzyme, diminishing its effects on the long fibres.

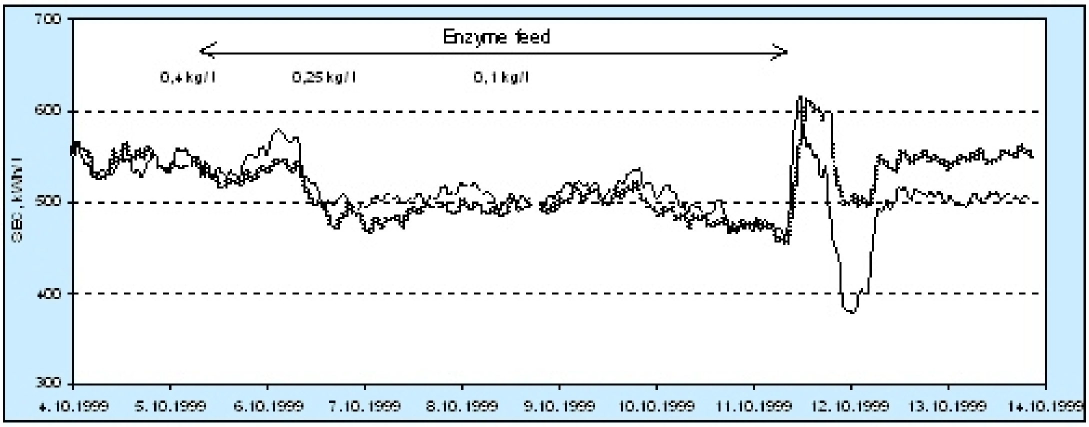

Figure 15. The specific energy consumption (SEC) of the reject refiners during the second trial.

The following conclusions could be made according to the mill trials:

- enzyme-aided refining is a viable and applicable method in mill conditions
- energy savings of 10–15 % were realised in reject refining
- energy savings were obtained wihout loss of strength or brightness of pulp
- no disturbances in the normal operation of the TMP line or the paper machine was noted
- activity of the enzyme could be easily followed by analysing the concentration of reducing sugars in the white water

4.2.3 Selection and specifications for an enzyme preparation for refining

Operational conditions in the whitewater of TMP mills are rather harsh and therefore a commercial enzyme preparation has to fulfill several conditions:

- thermotolerance at 80 ^{O}C for several hours
- high activity
- reliable operation in varying process conditions
- low yield loss (soluble carbohydrates) in the enzymatic treatment

The temperature of whitewater varies from mill to mill, but temperatures between 70 and 80 ^{O}C are usual. Lately there has been a trend of rising temperatures of the whitewaters, due to the closing of water circulation systems inside the mills. In a TMP mill the temperature of whitewater can be controlled by fresh steam, which is not possible in the GW process. This control over temperature of whitewater gives some flexibility for choosing an enzyme preparation, but long-term reduction of the temperature by several degrees to fit for an enzyme is not a viable alternative.

A proper enzyme should also maintain its (hydrolytic) activity in elevated temperatures. High activity combined with good thermotolerance will mean lower enzyme dosage, which has a positive effect on the operational economy by decreasing the amount of effective enzyme needed in the system.

Whitewater contains mainly wood derived components, like carbohydrates, lignans, and extractives, but accumulation of process chemicals in circulation waters must also be considered. These include *e.g.* residual bleaching chemicals, which might be inhibitive to action of enzymes. Additionally, contamination of whitewater with process chemicals used in the paper machine, especially during shutdown periods, might be possible.

Therefore daily control of enzyme activity in the whitewater is necessary, for example by analysing the concentration of soluble hydrolysis products in the whitewater.

No commercial cellulase preparation with such qualifications is available at this moment. New cellulases for extreme conditions are under development, but today the upper limit for thermotolerance is about 70 ^{o}C for the best CBH type cellulase.

'Cellulase' is a general item for a set of enzymes acting on cellulose and having unique modes of action. For example, from the fungus *Trichoderma reesei*, one of the most efficient saprophytic microbe, genes have been cloned that encode seven different cellulases, two cellobiohydrolases and five endoglucanases, in addition to 10 hemicellulases representing different enzyme activities (Penttilä and Saloheimo, 1999, Margolles-Clark *et al.,* 1997). Cellobiohydrolases act exo-wise liberating mainly cellobiose from cellulose chain ends, whereas endoglucanases hydrolyse internal linkages of cellulose molecule.

A purified cellulase, free of other contaminating enzyme activities, has a characteristic mode of action giving therefore rise to individual effects on pulp fibre properties (Pere *et al.,* 1995). Noteworthy, loss of strength due to hydrolytic action of endoglucanases has been documented even in the case of lignified mechanical pulp fibres (Pere *et al.*, 2000). Another very important feature of cellulases is that when applied as a mixture they act synergistically, which means enhanced hydrolytic action on fibrous matrial as compared with a situation when acting individually (Teeri, 1987).

5. Cost estimate of the biotechnical methods

5.1 Biopulping

5.1.1 Investment costs

An advantage of a silo based biopulping system is the improved control of operational conditions, especially in the northern climate. The major drawback is, however, its high investment cost. The costs of the chip pile systems would be lower and the system more flexible. However, proper control of the process is more difficult to attain. Biopulping treatments of chips both in silo and in pile systems need new process equipment. The investment costs are estimated for the following equipments (Table 6). It is assumed that the inoculum is purchased and therefore there are no capital costs associated with its production.

Table 6. Equipments needed for biopulping process of 600 t/d chips (dry weight) (Scott et al., 1998, Metso Woodhandling Oy, Fläkt Oy).

Silo treatment	**Chip pile treatment**
Silos and conveyors	**Silos and conveyors**
7 silos á 9350 m^3, 1 silo á 2000 m^3, screw conveyors for unloading the silos, screw conveyor for steaming, surge bin á 6.2 m^3, screw conveyor for cooling and inoculation, elevator, belt conveyors, bridges for belt conveyors	1 silo 2000 m^3, screw conveyors for unloading the silo, screw conveyor for steaming, surge bin, 6.2 m^3, screw conveyor for cooling and inoculation, elevator, belt conveyors, bridges for belt conveyors
Blowers, motors	**Blowers, motors**
Cooling of chips in conveyor after steaming	Cooling of chips in conveyor after steaming
7 blowers for the aeration of silos	7 blowers for aeration of the chip pile
Accessories	**Accessories**
Dispenser for feeding nutrient and dry inoculum to the tank	Dispenser for nutrient and dry inoculum feed to tank
Tank for mixing inoculum and nutrients with water	Tank for mixing inoculum and nutrients with water
Pump for inoculum feed	Pump for inoculum feed

The equipment and investment costs for silo or chip pile treatment systems are presented in Table 7. The most expensive equipments are silos, conveyors, and blowers. Investment costs consist of additional costs of piping, instrumentation, electricity, foundation, steel constructions, insulation, painting, site arrangements, design, and start-up, if not included in equipment costs (Metso Woodhandling Oy, Holland and Wilkinson, 1997). Foundations for silos and chip piles are the highest additional costs.

Table 7. Equpment and investment costs for biopulping tretment in silo or chip pile system.

	Silo treatment	**Chip pile treatment**
Price for equipments (€)	8 000 000	3 500 000
Investment costs (€)	14 400 000	7 200 000
Investment costs (20 % provision for accuracy of estimation) (€)	17 300 000	8 600 000

5.1.2 Operating costs

Operating costs of biopulping consist of raw material costs (inoculum, corn steep solids, hydrogen peroxide), of other variable operating costs (*e.g.* steam and electricity), and of fixed operating costs (*e.g.* wages and salaries, assurances, rents, management, research and development, quality control, health and safety). Summary of the operating costs are shown in Table 8.

Inoculum

This kind of fungal inoculum has not been produced on large scale for the same use. The price for inoculum is approximated to be similar to other dry and formulated fungal inocula. Verdera Oy's (earlier Kemira Agro) *Gliocladium catenulatum* -fungus containing biocontrol product Prestop Mix is sold for 300 €/kg (Verdera Oy, Heikki Pulkkanen). The consumption of inoculum is estimated at 0.52 g/t and thus the cost is 0.155 €/t.

Corn Steep Solids

The price of corn steep solids (94.5 % dry matter) is 1 € /kg (Chemec Oy, Hannu Laine and 1998 price from internet, http://home3.inet.tele.dk/starch/isi/market/products.htm). Similar or resembling domestic material having high nutrient composition may be more economical and practical to use on production scale. The consumption of corn steep solids is estimated at 5.2 kg/t. The corresponding cost is thus 5.45 €/t.

Steam and electricity

Steam for decontaminaton of chips in biopulping is needed (158 kWh/t).

Additional electricity consumption in the biopulping process consists of electricity needed for *e.g.* blowers, conveyors and mixers and is estimated at about 213 kWh/t. For chip pile system the consumption is 187 kWh/t. Mainly electricity is consumed by the blowers ventilating the silo or chip pile.

Hydrogen peroxide

Additional bleaching for pulps made of fungally treated chips is needed. The current price for hydrogen peroxide (100 %) is 430 €/t (Kemira Pulp and Paper Chemicals). The current trend for the price is decreasing.

Maintenance and repair was estimated to be 2 % of the equipment costs. For silo treatment the cost is 0.79 €/t and for chip pile treatment 0.34 €/t.

Variable operation costs (without steam and electricity and hydrogen peroxide) for silo sytem are 6.40 €/t and for chip pile system 5.95 €/t.

Fixed operation costs (*e.g.* additional personnel costs, insurances) for silo treatment are 932 000 €/a and for chip pile system 823 000 €/a.

Table 8. Operation costs for biopulping process.

Type of cost	**Costs, €/t**
Fungal inoculum	0.15
Nutrients (Corn steep solids)	5.45
Bleaching chemicals	12.72 (3.18 reference)
Electricity	6.5 (silo), 5.6 (pile)
Fixed operation costs	932 000 €/y (silo), 823 000 €/y (pile)

5.2 Enzyme-aided refining

Extra costs for the enzymatic treatment are due to an investment in a storage tank or tower, if not available, and due to costs of enzyme preparation. The enzyme needs a residence time of a few hours (2–3 hours) to act on pulp fibres. Quite often reject tanks are designed for a shorter residence time and therefore additional capacity for pulp storage and enzymatic treatment might be necessary. Increasing pulp consistency reduces the capacity of a storage tank needed. Because enzymatic activity is also enhanced as a function of increasing pulp consistency, it is beneficial to place the storage tank after a screening step (*e.g.* bow screen) in the TMP line.

Investment costs for a storage tower were estimated for a TMP daily capacity of 400t/d of reject pulp (Metso Paper). The estimation was based on the following design values:

- residence time, 3 hours
- consistency 3 %

Investment costs:	Storage tower + mixer	**300 000€**
	Additional costs	**200 000€**
	Total	**500 000€**

Costs for enzyme preparation will form the main part of operating costs. Estimation of the enzyme dosage was obtained from the mill trials (see section 4.2.2). According to these trials a constant dosage of 0.1 kg/t was sufficient to boost reject refining. At mill conditions the effective enzyme dosage is dependent on characteristics of the enzyme preparation (enzyme activity) and on the recirculation of whitewater containing active enzyme. Momentary concentration of active enzyme in the whitewater is determined as a sum of addition of fresh enzyme and the rate of inactiviation of the enzyme in recycled whitewater. Enrichment of active enzyme in the whitewater could be demonstrated during the mill trials. A short loop for recirculated whitewater is obviously beneficial for maintaining 'residual' enzyme activity in the whitewater as long as possible.

A price of **2 €/t** of pulp was estimated for the first enzyme products tailored for this application (AB Enzymes Oy). After a few years the unit price for the enzyme can be expected to decrease substantially due to successful R&D efforts by the enzyme companies, and assuming that the technology remains viable and that there is increased industrial demand for it. This type of decreasing price curves has been noted for *i.e.* xylanase preparations used for boosting of bleaching.

6. Potential role of biotechnical methods in the energy-economy of mechanical pulping and in climate change mitigation measures

The purpose of this part of the project was to estimate the potential future role of biotechnical methods in energy saving and in the reduction of greenhouse gas emissions on a national level in Finland. As shown in the previous chapters biotechnical methods can offer significant energy savings in mechanical pulp production. Due to the high energy-intensity of pulping with conventional methods, this may also have a significant effect on the total greenhouse gas emissions of the pulping industry and on the energy-economy on a national level.

6.1 Electricity generation and greenhouse gas emissions in Finland

In the Kyoto protocol Finland has committed herself to a stabilization of greenhouse gas emissions at the 1990 level. The target is challenging, as the total energy consumption in Finland has grown during 1990’s by 1 6%, and the growth has been estimated to continue also in the future. In 2001, CO_2 emissions from fuel combustion were 60 million tonnes CO_2, whereas in 1990 they were 53.9 million tonnes CO_2 (Statistics Finland, 2002). A decreasing trend in CH_4 and N_2O emissions kept the Finnish total greenhouse gas emissions below the Kyoto target during 1990’s. The situation for 2001 for other gases and sectors than CO_2 from combustion is not known at the moment of writing. Figure 16 shows the greenhouse gas emission trends in Finland during 1990–2000.

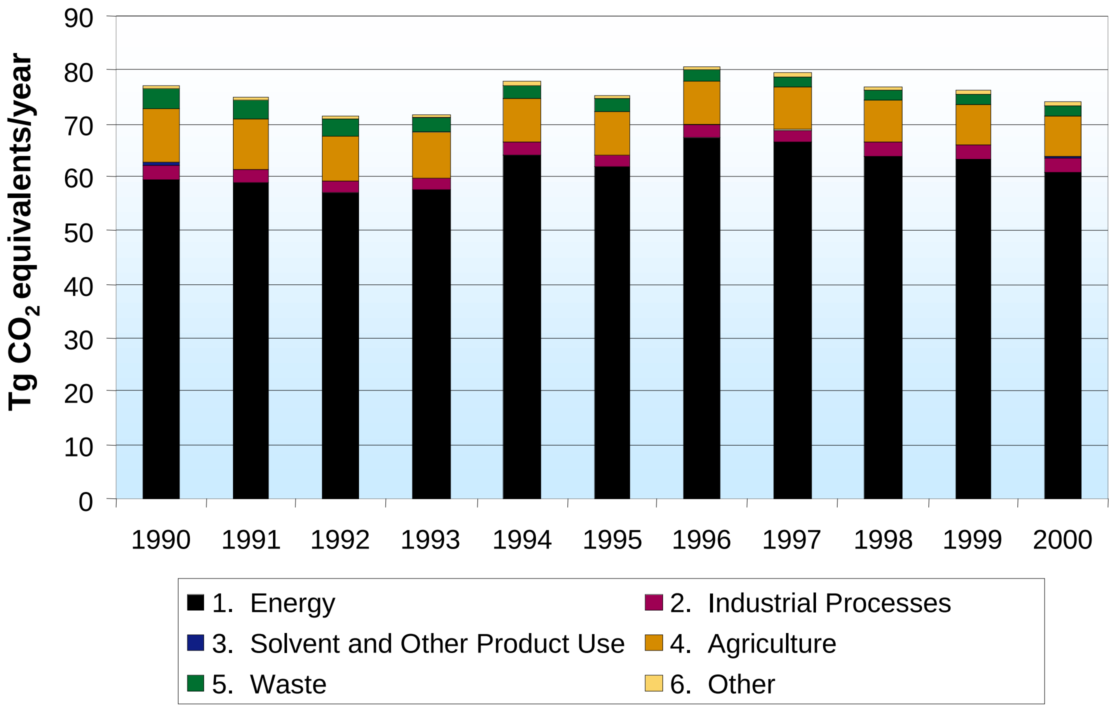

Figure 16. Finnish greenhouse gas emissions (excluding land-use change and forestry) by sector. Source: VTT, SYKE.

Figure 17 shows that energy from combustion is the dominating source of greenhouse gas emissions in Finland. (This includes also *e.g.* transportation and residential use of energy). Figure 17 illustrates the relative importance of CO_2 emissions from combustion in the energy and industrial sectors in total greenhouse gas emissions in Finland. The Industrial sector is the second largest single CO_2 emitting sector in Finland.

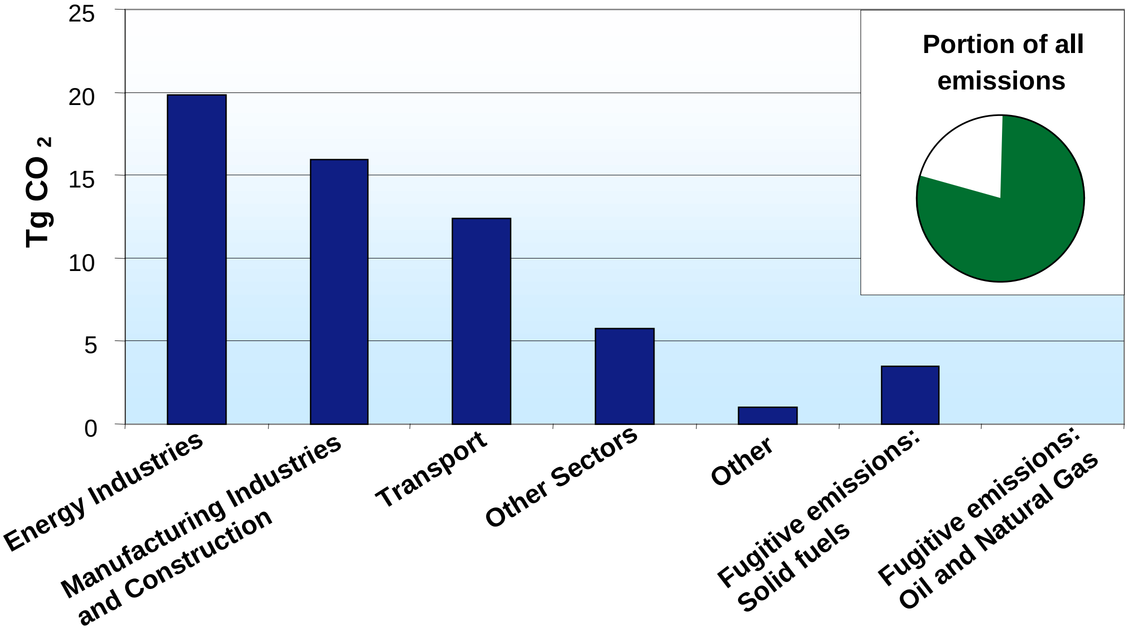

Figure 17. CO_2 emissions (58.5 Tg) in the Energy sector by main source categories and their portion of all anthropogenic greenhouse gas emission in Finland in 2000. Source: VTT, SYKE.

The efficiency of energy and electricity saving measures in reducing greenhouse gas emissions depends on the fuel structure used. For instance, if electricity for the process is produced with coal, electricity savings result in a reduction of of CO_2 emissions by about about 800–900 gCO_2/kWh. In the other extreme, if the energy used in the process is produced by carbon-free sources, such as (sustainable use of) biomass or hydropower, there would not be any direct benefit in CO_2 emissions. The fuel structure is also prone to change over time, thus changing the CO_2 reduction efficiency as well. Figure 18 shows the electricity generation sources in Finland during 1990–2000.

In Finland, energy saving measures affect mainly the amount of electricity bought from outside. The energy needs of the process industry are quite even throughout the year. The energy saving measures thus reduce the amount of marginal condensing power needed. In the Nordic countries, the marginal condensing power used is presently mainly coal power with specific CO_2 emissions at about 800–900 gCO_2/kWh. If energy saving measures reduce the use of natural gas in combined cycle power plants, the specific CO_2 emission savings are about 300 gCO_2/kWh.

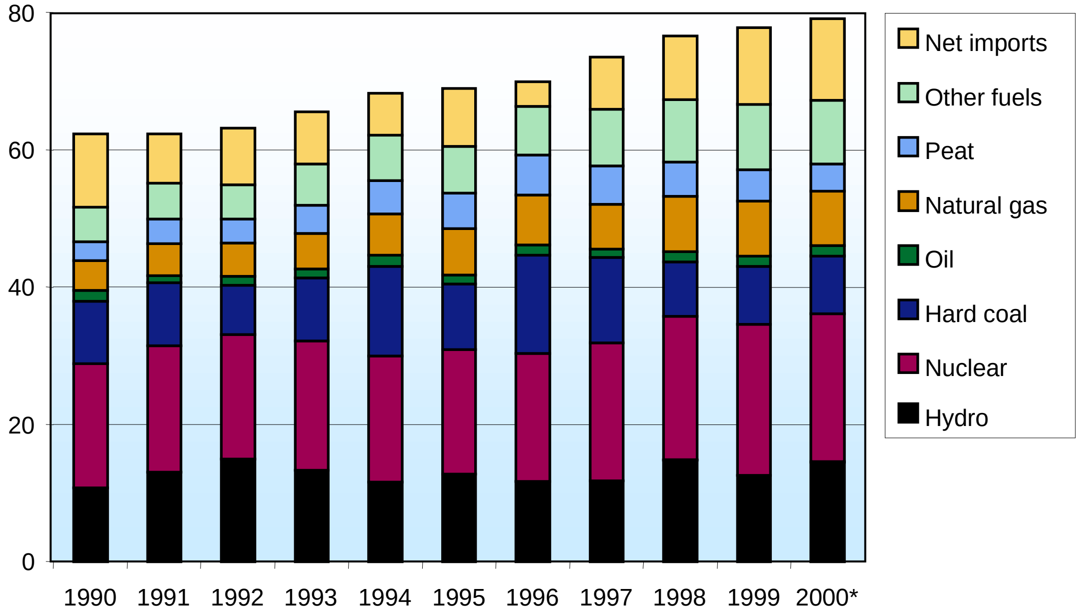

Figure 18. Electricity generation by energy source in Finland (in TWh). Source: Statistics Finland, 2001.

6.2 Energy system model EFOM-ENV for Finland

In this project the effect of biopulping techniques on greenhouse gas emissions in Finland was assessed using the EFOM-ENV energy system model. The EFOM-ENV is a linear optimizing energy system model used at VTT Processes (Lehtilä and Pirilä 1996, Lehtilä and Tuhkanen, 1999). The EFOM model calculates energy supply and demand with user-defined pre-conditions and constraints, such as fuel prices or total energy demand. The model determines for any study period the cost-optimal mix of fuels and technologies with given boundary conditions, such as emission limits. Figure 19 shows the basic structure of the EFOM model.

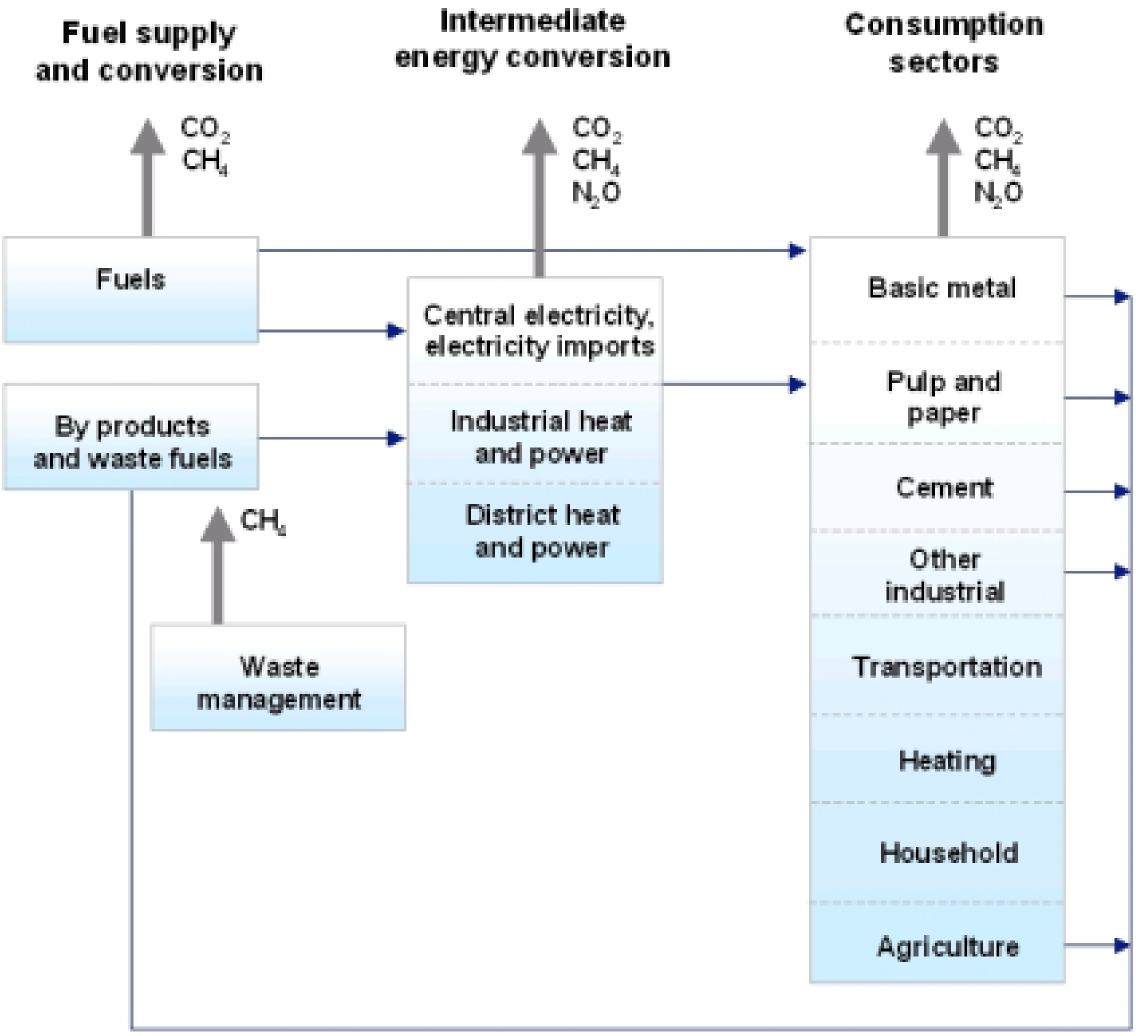

Figure 19. The structure of the EFOM model. The model includes separate subsystems. for the primary energy supply and fuel conversion, electricity and heat production and final energy use.

The EFOM model has been frequently used in national-scale studies supporting energy policy planning and reduction strategies for greenhouse gas emissions (*e.g.* Lehtilä and Pirilä, 1993, 1996, Kemppi *et al.*, 2001, Kara *et al.*, 2002). In this work, EFOM was used to analyse the cost-effectiveness of biotechnical pulping methods as a greenhouse gas reduction measure in comparison to other available measures. An energy system model is required in order to comprehensively assess all the reflections of single additional techniques on the whole energy system.

The EFOM model was used in this project for the time period extending from the present to the year 2030. The future time horizon was defined by the CLIMTECH Technology Programme.

6.3 Scenario assumptions

In the scenario modeling work, the assumptions of the KIO2 scenario of the recent National Climate Strategy of the Finnish Government were used (Ministry of Trade and Industry, 2001a–b). Table 9 presents a short summary of the general economic development and other background assumptions used.

Table 9. General economic developments and changes in the energy system assumed in the scenarios studied (Ministry of Trade and Industry, 2001b).

	1998–2005	**2005–2010**	**2010–2020**	**2020–2030**
GDP growth (%/year)	3.3	2.3	2.1	2.1
Population (million)	5.2	5.2	5.3	slow decrease
Technological progress	Rapid	Rapid	Rapid	Rapid
Energy taxation compared to present	Increases in the EU	Increases in the EU	Increases in the EU	Increases in the EU
Natural gas network in Finland	No expansion	To South West Finland	To South West Finland	No expansion
Nuclear capacity	No expansion	1300MW more	Constant	Constant
Use of coal	Decreases	Decreases	Decreases	Decreases
Electricity Imports (TWh/year)	8–12	6	6	6

In the scenarios it was assumed that Finland would meet the Kyoto obligation on the reduction of greenhouse gases, which is the stabilization of greenhouse gas emissions at the 1990 level during the period 2008–2012. After this period it is assumed that the emissions should be further reduced. A reduction target of –20 % from the 1990 level has been set for the year 2030. In the model study, it was assumed that after 2010 the energy taxation structure would be gradually transformed towards CO_2–based taxation instead of the present structures.

The EFOM model was used to find the cost-optimal path for reaching the emission targets. The penetration of biotechnical methods in mechanical pulping was determined by their cost-effectiveness in comparison to other greenhouse gas emission reduction options. In other words, biotechnical methods were not 'forced' to enter the market unless they proved cost-effective in comparison to other methods available in the total energy system.

Tables 10 and 11 show the assumptions on the development and penetration of biotechnical methods used in the EFOM model calculations. The potential of biopulping was mainly investigated with the Chip pile option, which has considerably lower investment costs than the Silo treatment option.

Table 10. Parameters describing the future development and penetration of ***enzyme-aided pulping*** *used in the EFOM model calculations. All percentage figures are given as shares of total capacity in Finland. Ton refers to tons of product pulp.*

	2005	**2010**	**2020**	**2030**
Technical lifetime	30 years	30 years	30 years	30 years
Usability (days/year)	350	350	350	350
Energy saving (kWh/ton)	100	100	100	100
Enzyme need (kg/ton)	0,1	0,05		0,05
Enzyme price (€/kg)	20	10	5	5
Investment (€/capacity ton)	500	450	450	450
Conventional scenario				
Maximum possible penetration	5 %	20 %	30 %	50 %
Optimistic scenario				
Maximum possible penetration	5 %	30 %	60 %	85 %

Table 11. Parameters describing the future development and penetration of ***biopulping*** *(with the chip pile option) used in the EFOM model calculations. All percentage figures are given as shares of total capacity in Finland. Ton refers to tons of product pulp.*

	2005	**2010**	**2020**	**2030**
Investment (€/capacity ton)	14825	14825	14825	14825
Additional fixed costs (€/ton)	4,04	4,04	4,04	4,04
Add. moving operation costs (€/ton)	5,95	5,95	5,95	5,95
Technical lifetime (years)	35	35	35	35
Usability (days/year)	350	350	350	350
Conventional scenario				
Maximum possible penetration	0 %	8 %	25 %	30 %
Additional bleaching need	400 %	400 %	300 %	300 %
Bleaching cost (€/ton)	12,98	12,98	9,74	9,74
Net electricity saving (compared to normal process)	13%	13%	18%	18%
Optimistic scenario				
Maximum possible penetration	0 %	20 %	50 %	75 %
Additional bleaching need	300 %	300 %	200 %	200 %
Bleaching cost (€/ton)	9,74	9,74	6,49	6,49
Net electricity saving (compared to normal process)	13 %	18 %	23 %	23 %

In the EFOM scenario calculations, it was assumed that the biopulping technique would be applicable also in the production of coarser grades, *e.g.* newspaper. For newspaper use, it was assumed that the whiteness requirements would not be as strict as with finer grades, and the additional bleaching needs would be half of the estimates given in Table 11.

6.4 Results

6.4.1 Cost-efficient penetration of biotechnical methods

With the conventional assumptions on the development of biotechniques and the required chemical uses, only the enzyme-aided pulping turned out to be cost-effective in comparison to other methods available in the total energy system until the year 2020. By 2030, also biopulping in newspaper production would become economical in the 'Conventional' scenario. This is due to the lower additional bleaching costs assumed in comparison to finer paper grades.

When the 'Optimistic' scenario on the development of biotechnical methods was assumed, biopulping started penetrating rapidly to the sector in 2020. Figure 20 shows the cost-effective penetration of the different methods with both scenarios and the total mechanical mass production scenario assumed calculated with the EFOM model (Forest Industries Federation, 2002; Ministry of Trade and Industry, 2001a–b).

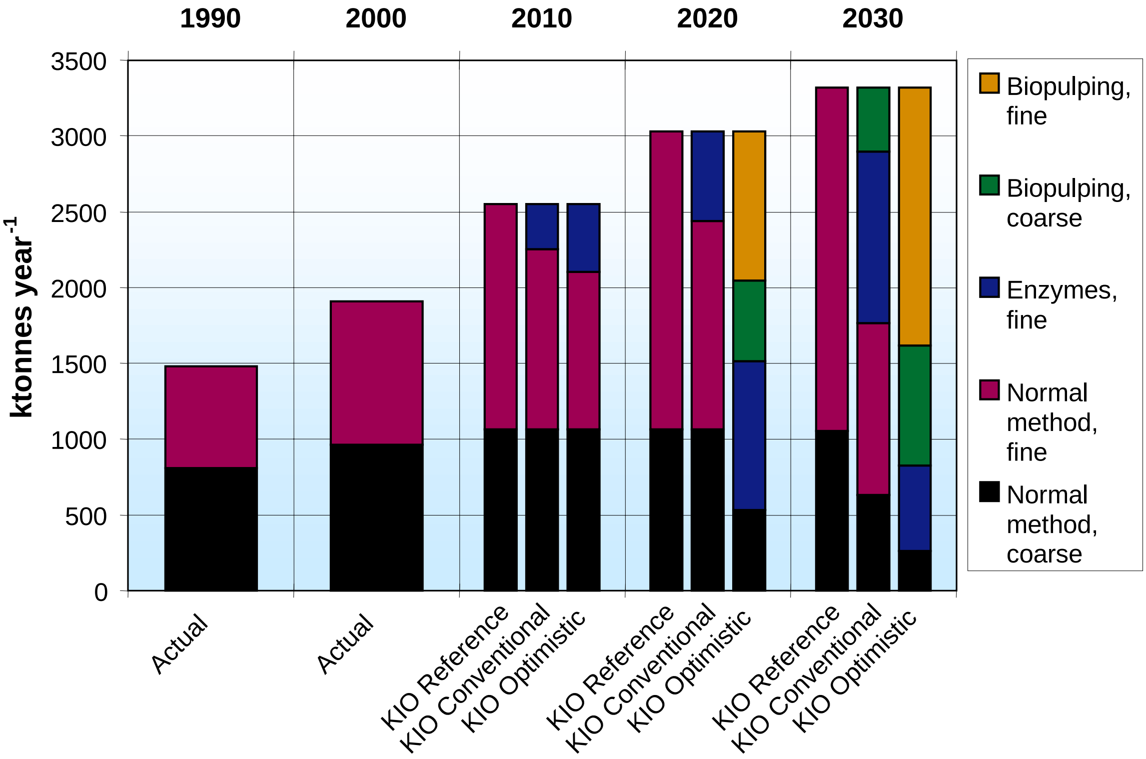

Figure 20. Development of mechanical pulp production in Finland during 1990–2030 and penetration of the different methods in the scenarios studied.

6.4.2 Electricity savings and CO_2 emissions

The resulting electricity savings are shown in Figure 21. The total electricity consumption increases from 30.5 TWh in 2010 to 34.1 TWh in 2030 in the absence of biotechnical methods (Ministry of Trade and Industry, 2001b). The conventional scenario for biotechnical methods would yield about 1% savings in the total electricity consumption of the total forest industry sector in Finland by 2030. The optimistic scenario for biotechnical methods results in about 5 % savings in the total electricity consumption of the whole forest industry sector in Finland by 2030.

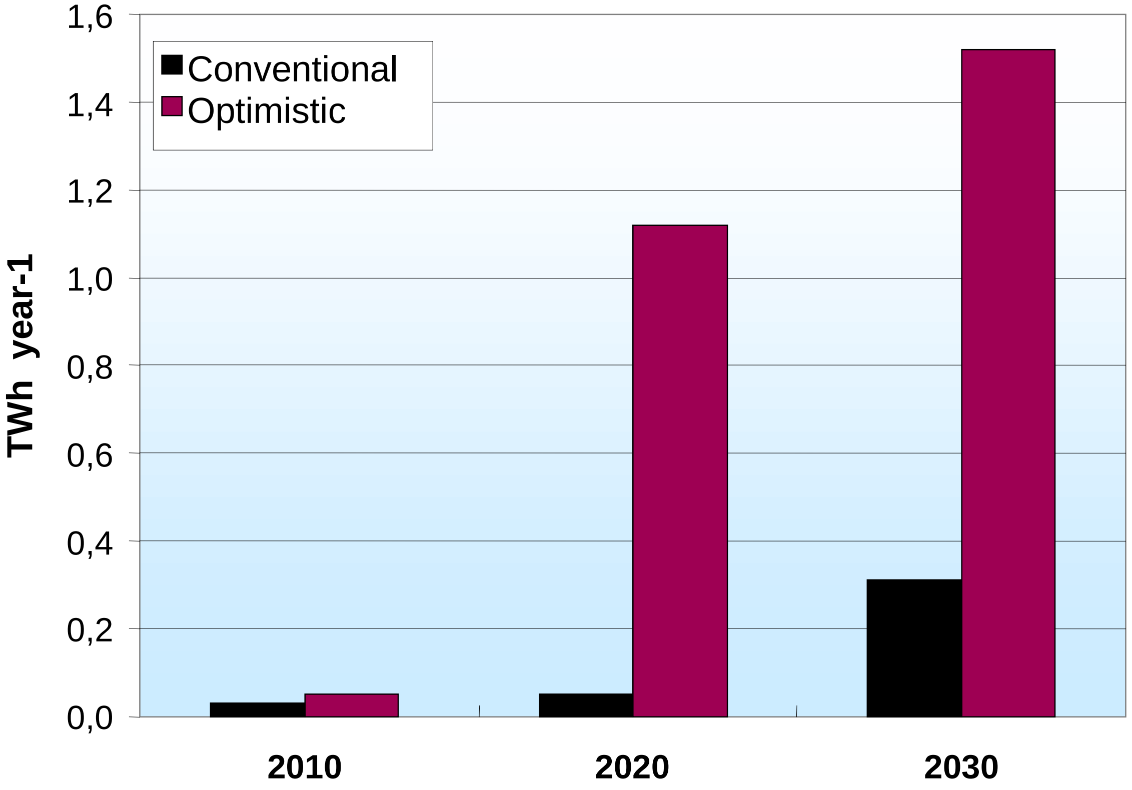

Figure 21. Electricity savings in forest industry with the scenarios studied.

In the scenario study with the EFOM model, the goal was to find out how cost-effective the biotechnical methods are in relation to other greenhouse gas emission reduction technologies in the total Finnish energy system. This was done by investigating a plausible long-term scenario of greenhouse gas reductions in Finland, *i.e.* a 20 % reduction from 1990 by 2030. In the model study the biotechnical methods compete with all the reduction options, and in the cost-optimal solution the introduction of biotechnical methods may allow to leave out some of the most expensive reductions in other sectors of the society.

In the scenarios studied, the biotechnical methods allowed to leave out mainly some of the expensive emission reduction options in the service sector. As a result of this substitution effect, the net impact on Finland's total emissions remains much smaller than the impact in the forestry sector alone. Instead, the main net impact ia a decrease in the average emission reduction costs. The total greenhouse gas emission reductions in Finland were 0.1 $TgCO_2$ with the conventional technology scenario and 0.6 $TgCO_2$ with the optimistic technology development scenario, *i.e.* 0.2 % and 1.0 % of total greenhouse gas emissions and 0.2 % and 1.1 % of total CO_2 emissions in Finland in 2030 in the scenario studied. Figure 22 shows the Finnish greenhouse gas emissions during 1990–2030 in the scenarios studied.

The total emission reduction costs (discounted to the present value) during the period studied decreased with biotechnical methods by about 33 million € in the 'Conventional' scenario and by about 62 million € in the 'Optimistic' scenario. The marginal costs for further greenhouse gas emission reductions with the biotechnical methods available were about 47 €/ton CO_2–eq. Figure 22 shows the development of Finnish greenhouse gas emissions in the scenarios studied.

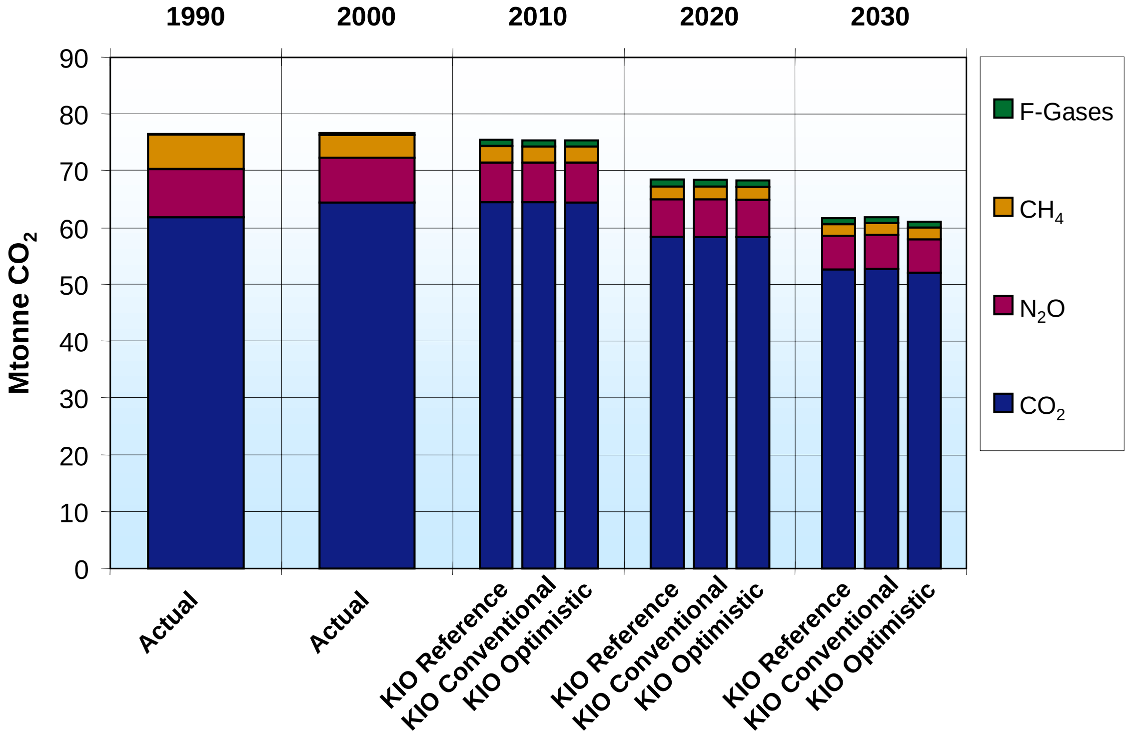

Figure 22. Finnish greenhouse gas emissions during 1990–2030 in the scenarios studied.

6.4.3 Comparison with other electricity saving options in pulp and paper production

The cost-effectiveness of biotechnical methods can also be judged from a single enterprice’s view by calculating the costs for the achieved electricity savings. This calculation could also contain a price for the avoided CO_2-emissions. For clarity and comparability with earlier studies, the costs for electricity savings were in this case calculated not taking into account the probable future value of avoided CO_2 emissions.

Using the parameter values given in Tables 10 and 11 and assuming a 15 years payback time with 5 % interest rate, entzymatic refinement provides an opportunity for electricity savings with costs around 0,6 cnt/kWh. The costs of electricity savings with biopulping of fine grades (again calculated for 5 % interest rate and 15 years payback time) range between 3,0–6,7 cnt/kWh (Chip pile option) and 3,7–7,9 cnt/kWh (Silo option). The high end of the range reflects the assumed present situation, and the low end describes the assumed development by 2020–2030. (All prices are given as present-day values).

If a payback time of 35 years is assumed for biopulping investments (with 5 % interest rate), the costs of electricity savings are between 2,8–6,4 cnt/kWh (Chip pile option) and 3,3–7,2 cnt/kWh (Silo option).

For grades with lower extra bleaching needs, the prices for electricity savings with biopulping techniques are about 15-20 % less in all cases.

In practise, biotechnical methods compete with other electricity saving measures available in the forest industry sector. The implementation of biotechnical methods may reduce the economic potential of other energy saving measures for the same process, or other methods with better cost-efficiency might reduce the economic potential of biotechnical methods. Table 12 presents a summary showing an approximate cost-effectiveness classification of different methods available (Ministry of Trade and Industry, 2001a). It should be noted that the cost-effectiveness of different methods is highly case-specific.

Table 12. Summary of main options available for the reduction of energy consumption in forest industry. All values are calculated for 15 years investment payback time. The costs of biotechnical methods are based on estimates developed in this project (Tables 10 and 11). Other estimates are from (Ministry of Trade and Industry, 2001a; Pöyry, 2000).

Economically profitable measures (costs less than 30 €/MWh)	**Measures with moderate additional costs** (between 30 €/MWh and 40 €/MWh)	**Measures with considerable additional costs** (between 40 €/MWh and 60 €/MWh)
Use of recycled paper and board	Improved process control in mechanical pulp production	New blade concepts in mechanical pulp production
Modernisations in refined mechanical pulp production	Adjustments in the rotation speed and temperatures of the refining process	Grindstone coatings
Improvements in pumps and mixers in chemical mass production	Reduction of radial velocity in groundwood pulping	New defibering and bleaching techniques in chemical pulping
Improvements in pumps and mixers in board production	Improvements in pumps and blowers in chemical mass production	Further improvements in paper and board machines
Enzyme-aided refining of mechanical pulp	Improvements in pumps and blowers in printing paper production	Biopulping of fine paper grades
	Improvements in pumps and blowers in board production	
	Biopulping in Chip piles for newspaper production	

6.5 Conclusions

The following conclusions can be made from the EFOM model studies:

- In a long-term scenario with a significant greenhouse gas emission reduction requirement imposed on the Finnish energy and industrial system, the biotechnical methods studied turn out to provide potential cost-effective means for the reduction of electricity consumption and greenhouse gas emissions on a national scale.

- Enzyme-aided refining can provide an opportunity for electricity savings with costs around 0,6 cnt/kWh (calculated for 5 % interest rate and 15 years payback time, no price assigned for CO_2 emissions).

- The costs of electricity savings with biopulping for fine grades (calculated for 5 % interest rate and 15 years payback time) range between 3,0–6,7 cnt/kWh (Chip pile option) and 3,7–7,9 cnt/kWh (Silo option). The high end of the range reflects the assumed present situation, and the low end describes the assumed development by 2020–2030. (All prices are given as present-day values, no price is accounted for avoided CO_2 emissions). If a payback time of 35 years is assumed (with 5 % interest rate), the costs of electricity savings are between 2,8-6,4 cnt/kWh (Chip pile option) and 3,3–7,2 cnt/kWh (Silo option). For grades with lower extra bleaching needs, the prices for electricity savings are about 15-20 % less in all cases.

- The cost-effectiveness of biopulping is highly dependent on the assumptions made concerning the future development of investment and operation costs, including the need for extra bleaching.

7. Environmental impacts of mechanical pulping

The life cycle assessment (LCA) methodology (SFS-EN ISO 14040, 14041, 14042, 14043) was applied to study environmental loads and impacts of mechanical pulping (TMP). This LCA study on TMP includes production of energy, bleaching chemicals and biotechnical products connected with the main phases of mechanical pulping. The main phases of TMP production are debarking, chipping, refining and bleaching.

7.1 Goal and scope of the LCA study

The goal of the life cycle assessment (LCA) was to produce information on the environmental impacts of the chosen biotechnical methods if implemented in traditional TMP production. Especially the clarification of the significance of environmental loads and impacts concerning production chains of additives and chemicals was the goal of the study. Energy issues, greenhouse gases and water emissions are relevant focal targets of the LCA study. The reference method used in all comparisons and calculations was traditional mechanical pulping. The biotechnical methods assessed were biopulping prior to mechanical pulping and enzyme-aided mechanical pulping prior to reject refining. Principles of both methods are described thoroughly in the earlier chapters and the calculation bases of the systems are presented in this chapter. A further goal of the study is to generate more profound basis for key environmental arguments concerning the different systems and to interpret the results.

7.1.1 Mechanical pulping systems considered in the LCA study

The traditional TMP process serves as a reference for the modified processes, *i.e.* enzyme-aided refining (ENZYME) and biopulping (BP REAL and BP OPT). The LCA analysis is performed according to the two different scenarios, realistic (BP REAL) and optimistic (BP OPT) mentioned in the earlier chapters. The results were calculated corresponding to one metric ton (t) of bleached mechanical pulp. The system boundaries began from the wood yard and end before papermaking, where mechanical and chemical pulps are mixed with paper additives.

A clear disadvantage of the biopulping method was an estimated increase of bleaching chemicals in doses of hydrogen peroxide and sodium hydroxide. In the enzyme-aided method, the bleaching chemicals were assumed to be at the same level as in the TMP system. Both biotechnological methods were assumed to decrease the use of electric power in refining.

7.1.2 Environmental loads and impacts considered in the LCA study

The environmental loads are divided into emissions causing global warming, acidification, eutrophication, oxygen depletion and photochemical formation of tropospheric ozone. In this study the greenhouse gases causing global warming are CH_4, CO_2 and N_2O according to IPCC 1995. The emissions causing acidification are H_2S, HCl, HF, NH_3, NO_x, SO_2, NH_4+ and NH_4-N. The emissions causing photochemical formation of tropospheric ozone are CH_4, CO, HC and NO_x.

The emissions causing eutrophication and oxygen depletion (BOD and COD) were omitted in this study due to unavailability of data for the enzyme and biopulping systems. In biopulping fungal treatment of chips and increasing use of chemicals may have effects on wastewater loads and on the treatment process for wastewaters.

The global warming potentials were calculated as kg CO_2 eq/kg. The acidification potentials were calculated as kg H+ eq/kg and photochemical formation potentials of tropospheric ozone are calculated as kg C_2H_4 eq/kg.

7.2 System boundaries and the functional units of mechanical pulping systems

The main functional unit of the mechanical pulping system was 1000 kg bleached mechanical pulp. All the results were calculated corresponding to this functional unit.

The system boundaries define the processes, which are included in the life cycle assessment. The life cycle of the mechanical pulping system began from receiving of the logs at plant and ended with papermaking, where mechanical and chemical pulp are mixed with additives. Chemical pulping and papermaking were outside the system boundaries of this study.

The treatment of logs at the plant site included barking and chipping with corresponding energy consumption. Transportation of logs and any forest operations were not included in the study. The amount of logs needed is calculated based on a production of 1000 kg bleached mechanical pulp in all systems considered. The mechanical pulping included main refining of wood chips, screening of pulp after the main refining, reject storing and reject refining. The bleaching process included use of chemicals and their production chains. The biopulping chain included the production chain of the fungal product, feeding of fungal product and storing of treated chips with respective energy consumptions. The enzyme-aided mechanical pulping included the whole enzyme production chain, feeding of enzymes into the reject storage tank and refining of treated reject pulp with respective energy consumptions. Overviews of the mechanical pulping systems are presented in the following Figures 23, 24 and 25.

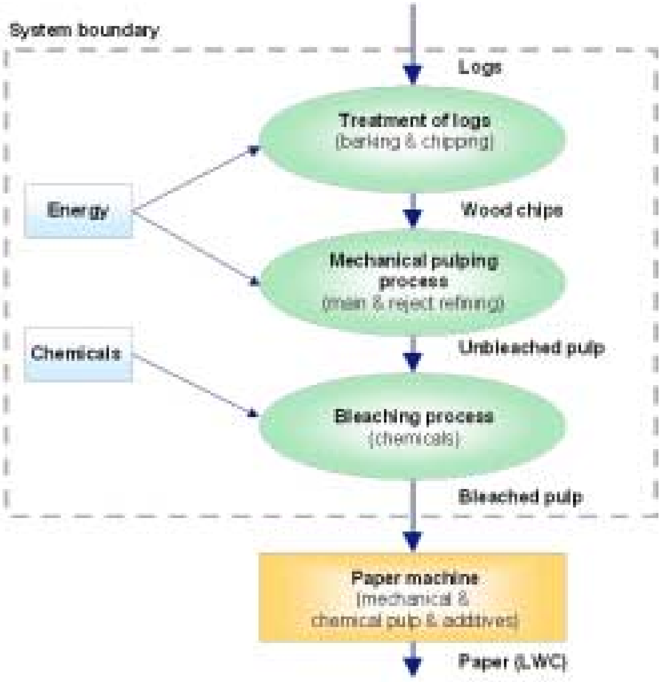

Figure 23. The system boundaries of mechanical pulping (TMP).

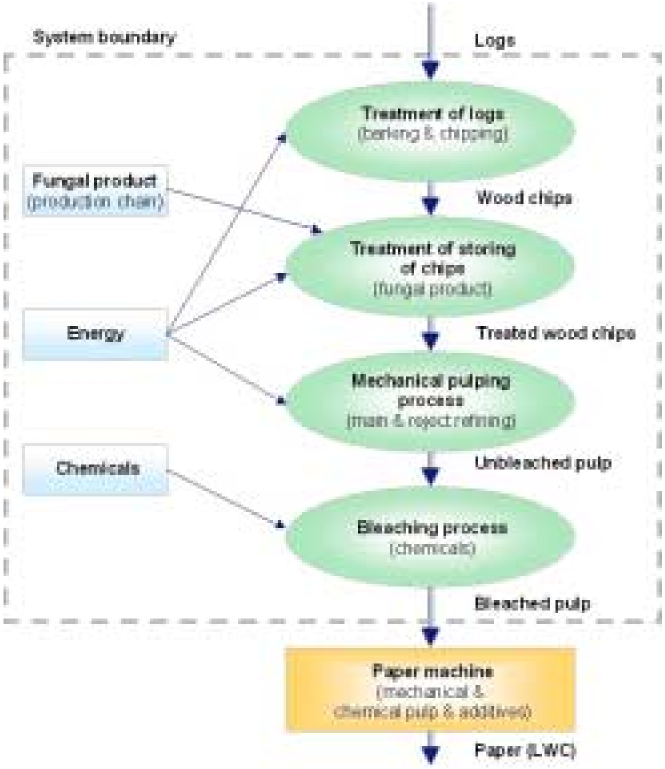

Figure 24. The system boundaries of biopulping (BP REAL and BP OPT).

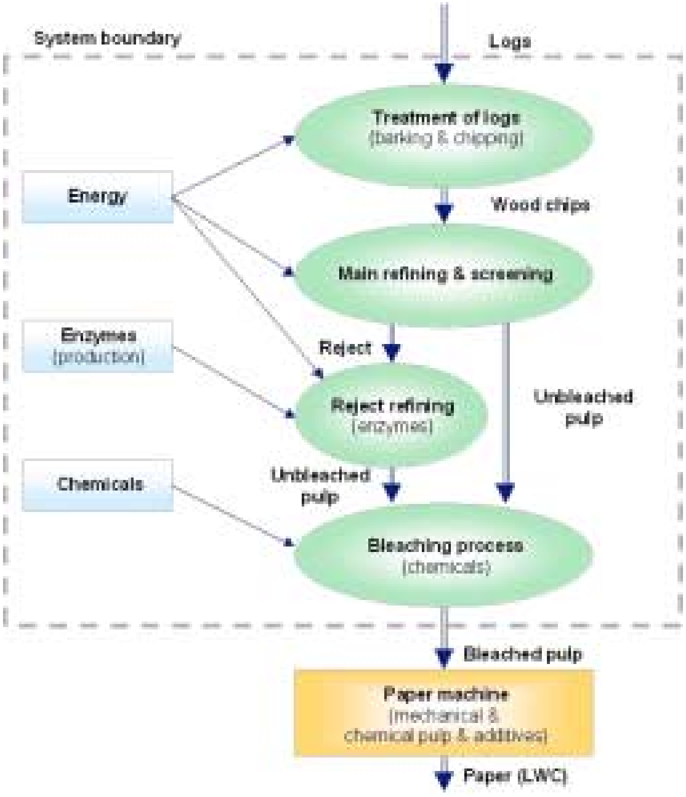

Figure 25. The system boundaries of enzyme-aided mechanical pulping (ENZYME).

7.3 Data and data sources

The data for the biotechnical unit processes were obtained from VTT Biotechnology, the literature and relevant companies, whereas information on the TMP process was mainly from UPM-Kymmene Rauma Paper Mills. The main data sources for the studied systems are given in the following Table 13.

Table 13. Sources of data information for the unit processes assessed in the LCA study.

Unit process	**Year**	**Source**	**Remarks**
Barking plant	2000	UPM-Rauma	Available: logs, electric power, water, bark Not available: air and water emissions, wastes, losses
Chipping of logs	2000	VTT Database	Available: logs, electric power, chips Not available: air and water emissions, wastes, losses
Main refining Reject refining	2000	UPM-Rauma	Available: pulp, electric, power, steam recovered, water, pulp losses Not available: air and water emissions, wastes, losses
Bleaching process	2000	UPM-Rauma	Available: pulp, chemicals, selected water emissions Not available: air and water emissions, pulp losses
Production of enzyme	2002		Available: enzyme, energy, chemicals, raw materials, water
- Energy		ROAL Ab	
- Process		VTT BEL	Not available: air and water emissions, wastes, production of chemicals and raw materials
Production of fungal product	2002	VTT BEL	Available: fungal products, energy, chemicals, raw materials, water Not available: air and water emissions, wastes, production of chemicals and raw materials
Bleaching chemicals		UPM-Kymmene	Available: products, energy, chemicals, raw materials, water, energy chains
- DTPA	Unknown	IDEA Database	Not available: air and water emissions, wastes, production of chemicals and raw materials
- H_2O_2	1998	IDEA Database	
- NaOH	1998	Kemira	
- SO_2	1998	UPM-Kymmene	
- Sodium silicate	Unknown		
Transportation	1995	KCL-ECO	Available: modes of conveyance, fuels, selected air emissions Not available: production of fuels, water emissions
Rauma power plant	2000	UPM-Kymmene	Available: energy, energy sources, fuels, selected air emissions, wastes Not available: water emissions
UPM-Energy	Average	UPM-Kymmene	Available: electric power, energy sources, fuels, selected air emissions Not available: energy sources, fuels, water emissions, wastes
Finnish electricity	Average	VTT Database	Available: electric power, energy sources, fuels, raw materials, chemicals, water, air, air and water emissions, wastes Not available: production of chemicals
Wood energy plant	2000	VTT Database	Available: energy, energy sources, fuels, air emissions Not available: water emissions

7.4 Energy issues

The energy calculations are often complicated for the forest industry. Usually there is a big complex of plants closely linked to each other and including among others logs treatment, chipping, mechanical pulping, chemical pulping, papermaking and energy production. They all need energy in different forms (electric power, heat and steam) and recovered energy is normally utilised in other plants. Heat and steam recovered from processes are also sold outside the factory. Wood based fuels are by-products of wood handling, pulping and papermaking processes, and they are used in energy production. Energy production uses also other fuels like peat, coal and oil. The produced electric power does not cover all needs and electric power is also bought. Proper allocation of energy and emissions to different plants is thus not always possible. Good detailed data is needed to model the energy systems and to calculate replacement assumptions of produced energy, recovered energy and purchased power.

7.5 Inventory results

Inventory results included consumptions of bleaching chemicals and energy, as well as emissions causing global warming, acidification and photochemical formation of tropospheric ozone (IPCC 1995, Lindfors *et al*. 1995, Hauschild and Wenzel 1998). The results deal only with emissions to air, because at the time of the study there were no available data on eventual wastewater loads caused by the biotechnical methods.

The calculations of the systems are mainly based on data from the year 2000. The ENZYME system included electric power saving in reject refining (Table 14). The biopulping systems are divided into realistic-conventional and optimistic scenarios taking into account energy savings of refining and increasing use of bleaching chemicals (Tables 15 and 16). The calculation bases of the considered systems are presented in the following Tables 14, 15 and 16.

Table 14. Changes in consumptions of electric power and bleaching chemicals in the traditional mechanical pulping system and the enzyme-aided system.

Systems	**TMP 2000**	**ENZYME 2000–2030**
Electric power saving	0 %	–15 %
Increase of chemicals	0 %	0 %

Table 15. Changes in consumptions of electric power and bleaching chemicals in the realistic-conventional scenarios of the biopulping systems.

BIOPULPING Realistic-conventional scenario	**REAL 2005**	**REAL 2010**	**REAL 2020**	**REAL 2030**
Electric power saving	–20 %	–20 %	–25 %	–25 %
H_2O_2-increase	400 %	400 %	300 %	300 %
NaOH-increase	250 %	250 %	200 %	200 %

Table 16. Changes in consumptions of electric power and bleaching chemicals in the optimistic scenarios of the biopulping systems.

BIOPULPING Optimistic scenario	**OPT 2005**	**OPT 2010**	**OPT 2020**	**OPT 2030**
Electric power saving	–20 %	–25 %	–30 %	–30 %
H_2O_2-increase	300 %	300 %	200 %	200 %
NaOH-increase	200 %	200 %	150 %	150 %

Consumptions of bleaching chemicals in the different mechanical pulping systems are presented in Figure 26. A significant increase of bleaching chemicals (126 %) can be noted in the beginning of implementation of biopulping technology, but due to successful R&D efforts it is estimated to decrease later (42 %). This concerns especially increasing doses of H_2O_2 and NaOH chemicals. The enzyme-aided refining does not affect the consumption of bleaching chemicals. Increase of chemicals caused also more environmental loads and impacts, which was reflected in the inventory results. DTPA, H_2O_2, NaOH, SO_2 and sodium silicate are used in bleaching of pulp.

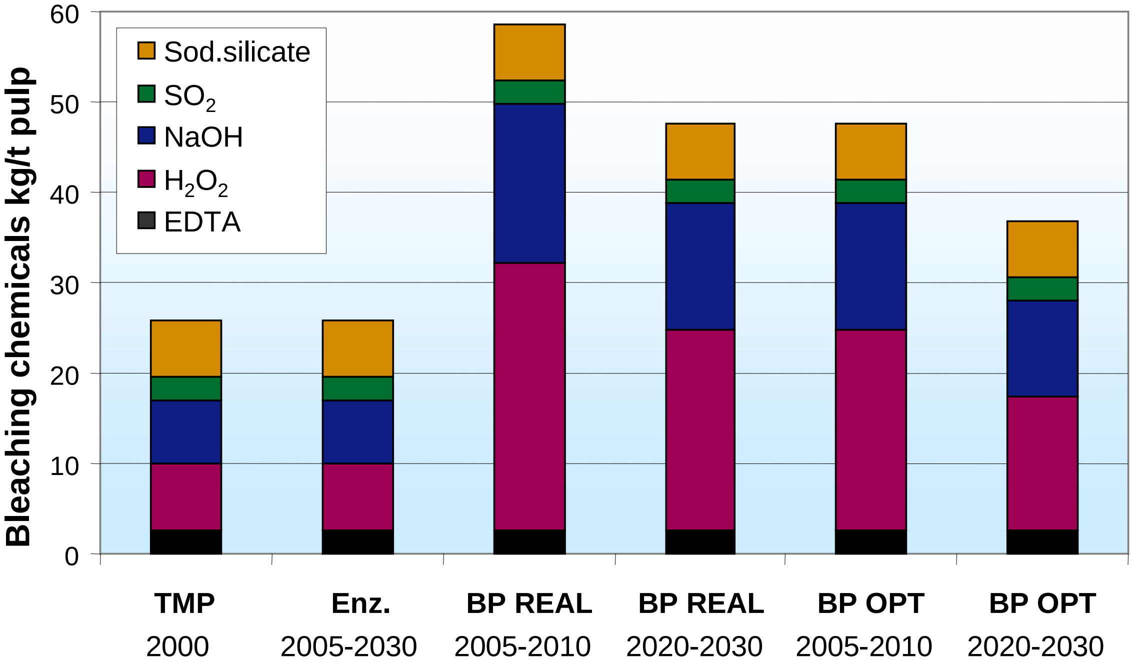

Figure 26. Estimated use of bleaching chemicals (kg/t of bleached pulp) in different mechanical pulping systems.

The system models used and calculated in LCA are presented in appendices 1–10.

7.5.1 Energy

Energy was the most effective element in the results of the air emissions including greenhouse gases. Almost all air emissions and impacts of the systems reflected changes in the energy consumption. UPM-Kymmene Rauma Paper Mills used in 2000 2200 GWh electric power, of which 1900 GWh was bought from UPM-Energy. The electric power of UPM-Energy was produced 35,6 % by hydropower, 49 % by nuclear and 15,4 % by coal and peat (UPM-Kymmene Rauma, 2000).

Energy consumption calculations were based on a production of 1000 kg of bleached pulp. The enzyme-aided mechanical pulping indicated electricity savings of 4 % compared with the traditional mechanical pulping system. Both biopulping scenarios BP REAL and BP OPT indicated electricity savings of 10–20 % compared with the traditional mechanical pulping system. However, these assumptions of electricity savings concerned savings in refining and did not include production chains of bleaching chemicals, fungal product, enzymes nor transportation fuels. The effects of the production chains were estimated with the LCA methodology.

The recovered steam energy from refining and compensation heat energy from Rauma power plant were calculated according to available data and energy production processes. Bark from debarking plant is used in Rauma power plant together with the other fuels and the direct compensation of energy and emissions was done according to the available models of the energy production. The recovered steam from refining depends on the electric power of refining. The recovered energy was less in the biopulping systems than in the traditional mechanical pulping system.

The biotechnical steps, *i.e.* the fungal treatment of chips, comprised 12–14 % of the total energy use of the considered systems (Figure 27). The energy savings were in the order of 0,13–0,6 MWh/t of bleached pulp when taking into account the steam energy needed in the fungal treatment of chips in biopulping systems. The electric power savings were in the order of 0,13–0,75 MWh/t of bleached pulp in the different pulping systems assessed (Figure 28).

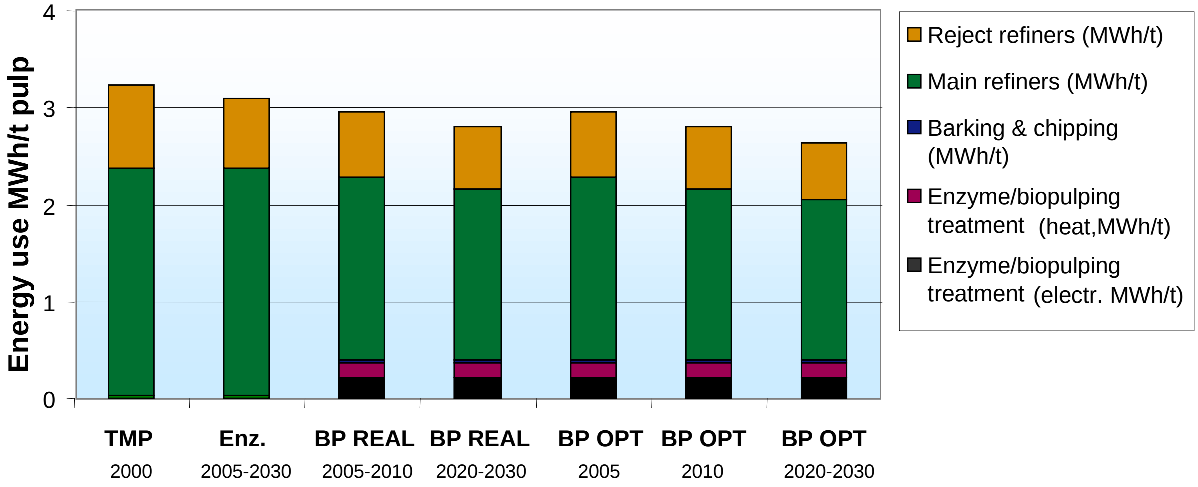

Figure 27. Estimated consumption of electricity and heat (MWh/t) in the different mechanical pulping systems.

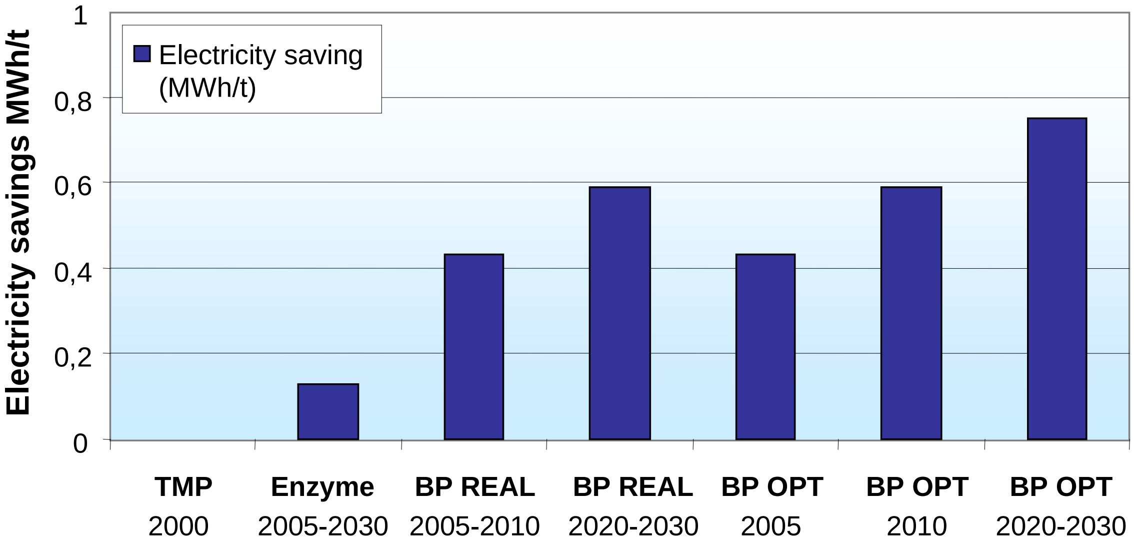

Figure 28. Electricity savings MWh/t bleached pulp in the different mechanical pulping systems.

7.5.2 Greenhouse gases causing global warming

The greenhouse gases (CH_4, CO_2, N_2O) originated mainly from burning of fossil fuels (coal, oil, natural gas and peat) for energy production and only minor shares from the transportation of chemicals (Figure 29). CH_4 emissions came mainly from energy production chains of bleaching chemicals. NaOH and H_2O_2 had the most energy intensive production chains among the ones used for production of bleaching chemicals for the systems. CO_2 emissions originated mainly from burning of fossil fuels in energy production. CO and N_2O emissions evolved mainly from production chains of bleaching chemicals.

In the traditional mechanical pulping process 86 % of CO_2 emissions related to the production of bleaching chemicals came from the production chains of NaOH and H_2O_2 (Figure 30). Logs treatment and refining caused, however 96 % of total CO_2 fossil emissions of the system and the share of the bleaching chemicals is only 4 %.

The CO_2 emissions of the alternative systems are presented in Figure 31. In biopulping, the fungal treatment of chips caused about 10 %, refining 77 % and the bleaching chemicals about 13 % of the total CO_2 emissions of the system (Figure 32). The shares of the N_2O and CH4 emissions were small and they originated almost totally from energy production chains of bleaching chemicals. The electricity savings in refining reduced the total emissions. It can be emphasised that the production chains of the enzyme and fungal inoculums formed only a minor part of the total greenhouse gas emissions released in mechanical pulping systems. However the increased use of energy in fungal treatment of chips causes emissions.

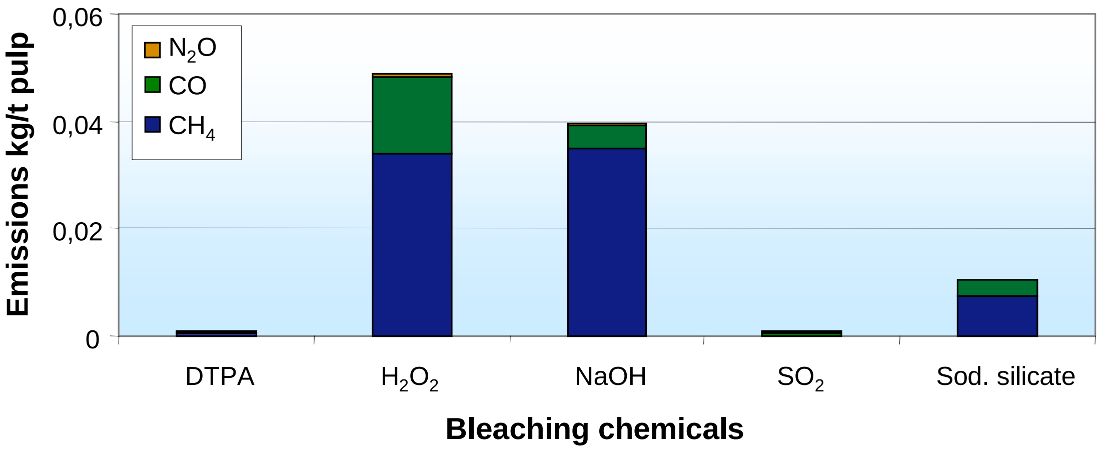

Figure 29. Greenhouse emissions (N_2O, CO and CH_4) of the production chains of bleaching chemicals in the traditional TMP process calculated to one ton of bleached pulp.

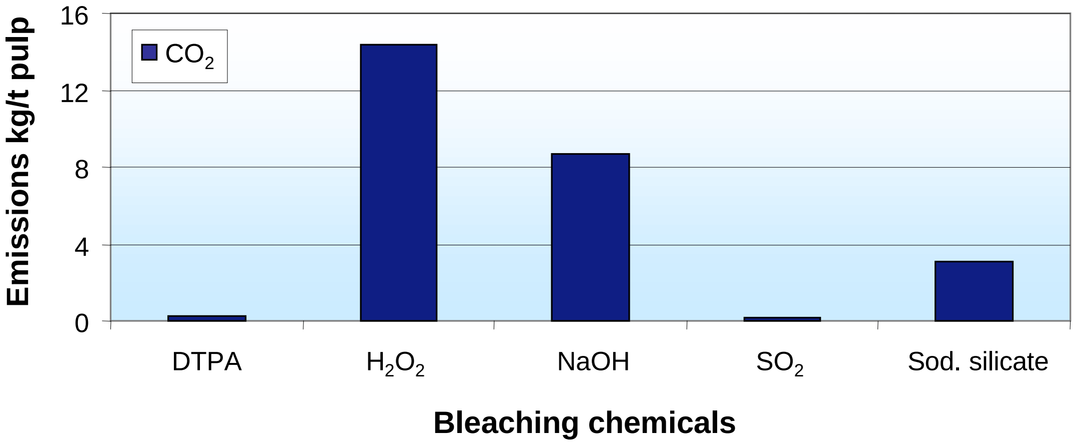

Figure 30. Greenhouse emissions (CO_2) of the production chains of bleaching chemicals in the traditional TMP process calculated to one ton of bleached pulp.

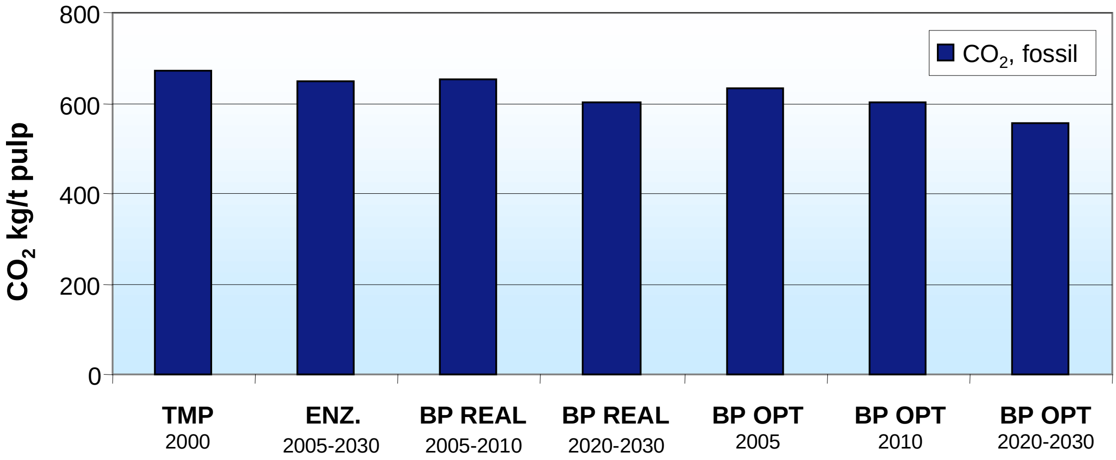

Figure 31. CO_2 emissions as kg/t of bleached pulp in the mechanical pulping systems.

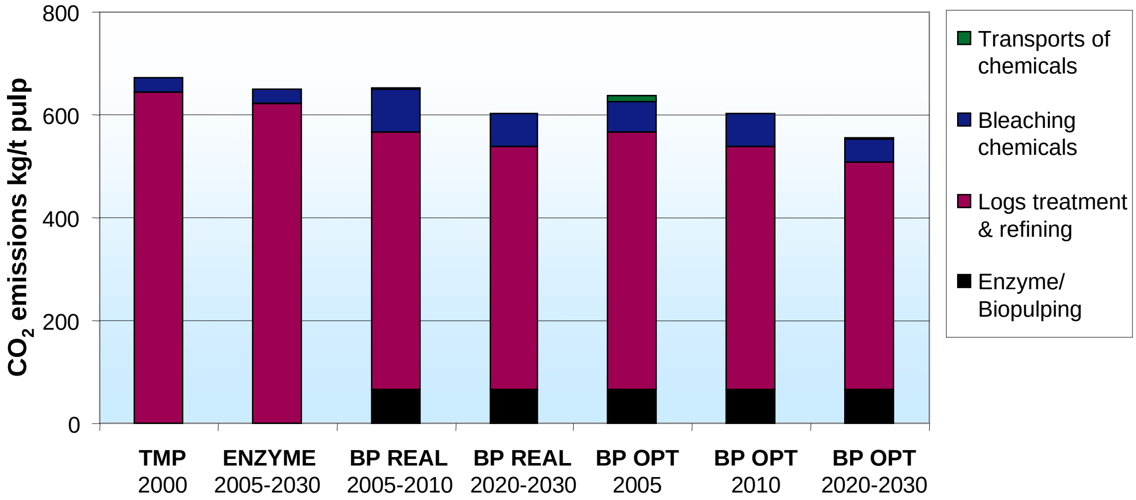

Figure 32. CO_2 fossil emissions (kg/t) of subsystems of mechanical pulping.

7.5.3 Acidic emissions

The emissions causing acidification (H_2S, HCl, HF, NH_3, NO_x, SO_2, NH_4) follow almost the same trend as the emissions of greenhouse gases. The SO_2 and NO_x emissions originated mainly from the energy production. Energy was used in refining, fungal treatment of chips and production chains of chemicals (Figures 33, 34 and 35). NH_3 emissions come mainly from DTPA (bleaching chemical). Only minor shares come from transportation of chemicals.

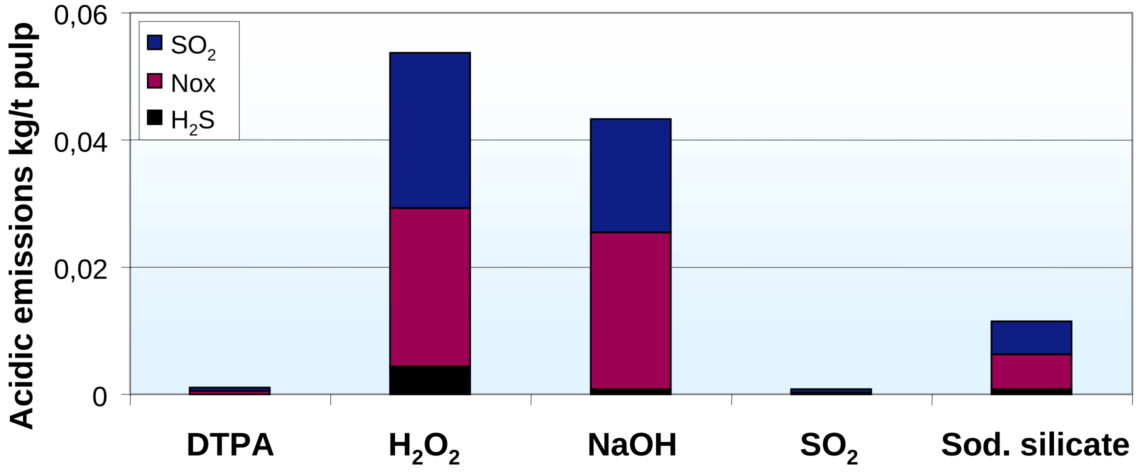

Figure 33. Acidic emissions of bleaching chemicals without NH_3 in the traditional TMP process calculated to one ton of bleached pulp.

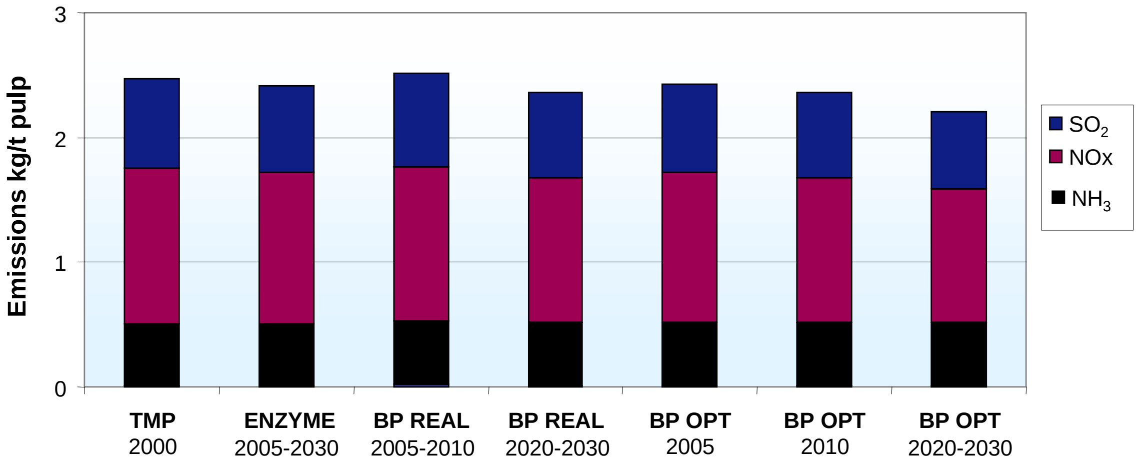

Figure 34. Acidic emissions of SO_2, NO_x, NH_4, NH_3, HF, HCl and H_2S as kg/t of bleached pulp in the mechanical pulping systems. Production of DTPA generates the biggest portion of the NH3 emissions.

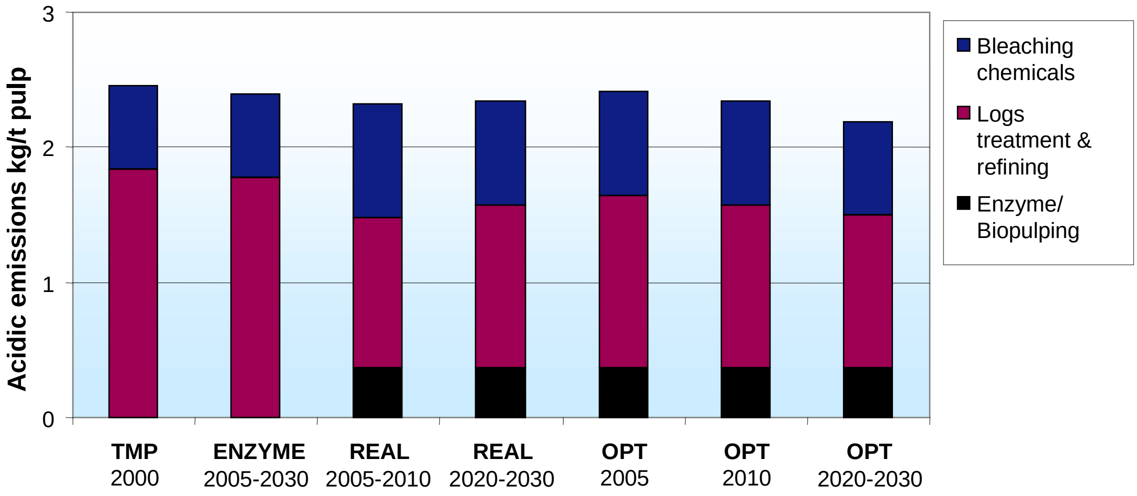

Figure 35. Acidic emissions expressed as kg/t of bleached pulp divided into different phases of the mechanical pulping systems.

7.5.4 Photochemical formation of tropospheric ozone

The emissions causing photochemical formation of tropospheric ozone are CH_4, CO, HC and NO_x. NO_x emissions form over 90 % of the total emissions in this category. They evolved mainly from energy production for refining, fungal treatment of chips and production chains of chemicals. Only minor shares came from transportation of chemicals (Figures 36, 37 and 38). CH_4, CO, HC emissions evolved mainly from production chains of bleaching chemicals.

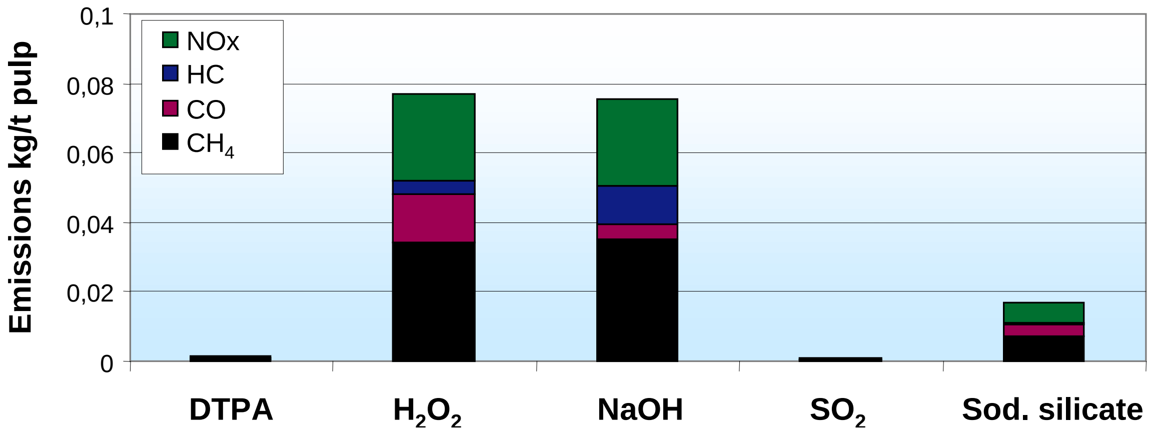

Figure 36. NO_x, HC, CO and CH_4 emissions expressed as kg/t of bleached pulp from the production of bleaching chemicals causing photochemical formation of tropospheric ozone in the different mechanical pulping systems.

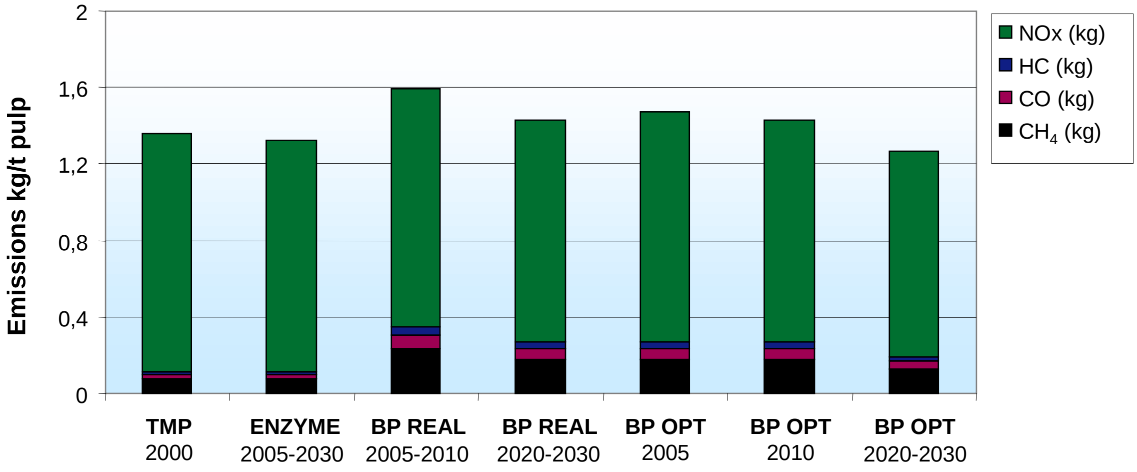

Figure 37. NO_x, HC, CO and CH_4 emissions causing photochemical formation of tropospheric ozone as kg/t of bleached pulp in the different mechanical pulping systems.

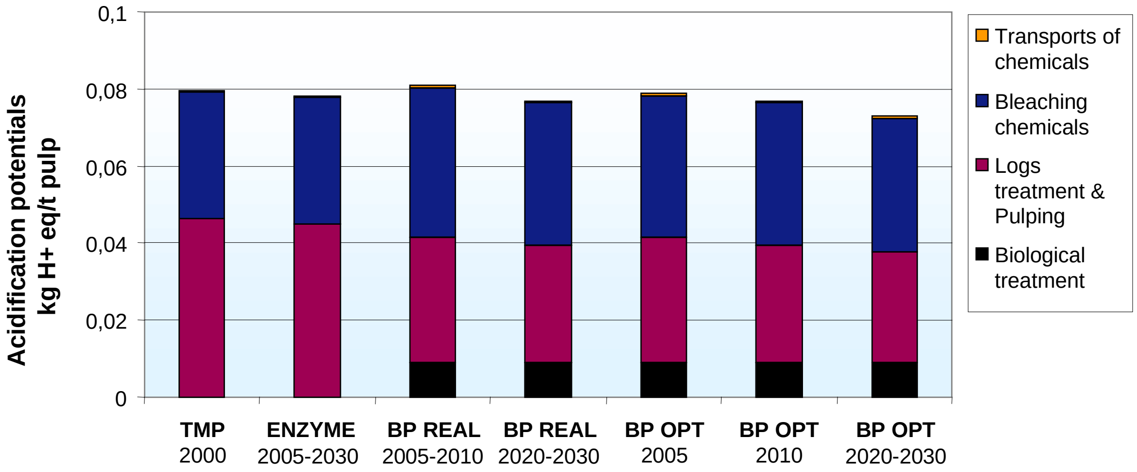

Figure 38. Emissions causing photochemical formation of tropospheric ozone as kg/t of bleached pulp divided into different phases of the mechanical pulping systems.

7.6 Impact assessment results

7.6.1 Global warming

The most important greenhouse gases causing global warming are water vapour, carbon dioxide, methane, nitrous oxide, tropospheric ozone, halogenised hydrocarbons, and sulphur hexafluoride. There are indirect greenhouse gases and compounds like volatile hydrocarbons, nitrogen oxides, carbon monoxide, and aerosols, which cause also global warming, but they are not normally included in the calculations in order to avoid double counting of gases. Emissions of greenhouse gases and aerosols due to human activities continue to alter the atmosphere in ways that are expected to affect the climate. The global average surface temperature has increased over the 20th century by about 0,6 °C. Snow cover and ice extend have decreased. Global average sea level has risen and ocean heat content has increased. (IPPC, 2001)

Global Warming Potentials (GWPs) are a measure of the relative radiative effect of a given substance compared to CO_2, integrated over a chosen time horizon. The GWP has been defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas (CO_2). In the following Table 17 are presented the specific potentials of the emissions causing global warming as kg CO_2 eq/kg. (IPCC, 1995)

Table 17. Global warming emissions and related specific potentials as kg CO_2 eq/kg CO (IPCC, 1995).

Global warming emissions	**Type of emission**	**Coefficient**	**Specific potentials kg CO_2 eq/kg**
CH_4	Air emission	21	(2.10E+01 kg CO2 eq/kg)
CO_2	Air emission	1	(1.00E+00 kg CO2 eq/kg)
N_2O	Air emission	310	(3.10E+02 kg CO2 eq/kg)

The global warming potentials were calculated as equivalents of CO_2 (Figure 39). The share of transports of chemicals was small as compared with the share of logs treatment and refining. The shares of bleaching chemicals and enzyme/biopulping were of the same magnitude forming each 9–13 % of the total greenhouse gas emissions. The calculated potentials of global warming followed the same trend as the corresponding total emissions. The need of steam and electricity in storing of chips and fungal treatment increased emissions and environmental impacts in biopulping as compared to enzyme-aided pulping. In biopulping also the production chains of bleaching chemicals generated emissions, but later developments of the biopulping technology is expected to lower the need of bleaching chemicals and thus lower the impacts under the present level.

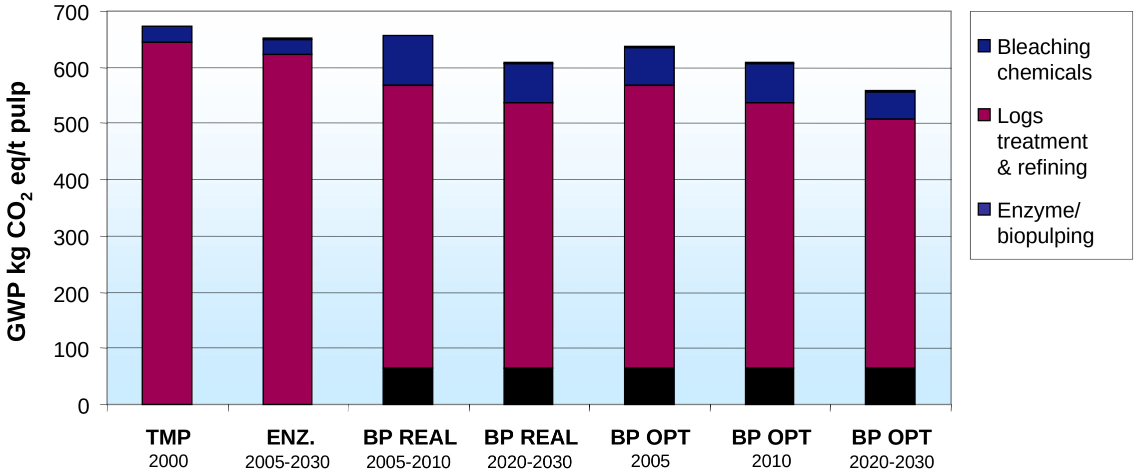

Figure 39. Global warming potentials expressed as equivalents of kg CO2/t of bleached pulp in the different phases of the mechanical pulping systems.

7.6.2 Acidification

Acidification is a regional effect, because the atmospheric life of the acidifying substances is limited. The most important emissions causing acidification are oxides of sulphur and nitrogen, which come mainly from energy production using fossil fuels, industry, and traffic. Acidification of soil or aquatic ecosystems can be defined as an impact, which leads to a fall in the system's acid neutralizing capacity. Specific acidification potentials of emissions are presented in the following Table 18.

Table 18. Acidification emissions and related specific potentials expressed as kg H+ eq/kg (Lindfors et al., 1995).

Acidification Emissions	**Type of emission**	**Coefficient**	**Specific potentials kg H+ eq/kg**
H_2S	Air emission	0,059	(5.88E-02 kg H+ eq/kg)
HCl	Air emission	0,028	(2.75E-02 kg H+ eq/kg)
HF	Air emission	0,050	(5.00E-02 kg H+ eq/kg)
NH3	Air emission	0,059	(5.88E-02 kg H+ eq/kg)
NOx	Air emission	0,022	(2.19E-02 kg H+ eq/kg)
SO_2	Air emission	0,031	(3.13E-02 kg H+ eq/kg)
Acid (H+)	Water emission	1,000	(1.00E+00 kg H+ eq/kg)
NH_4+	Water emission	0,111	(1.11E-01 kg H+ eq/kg)
NH_4-N	Water emission	0,143	(1.43E-01 kg H+ eq/kg)

The share of logs treatment and refining was biggest in the TMP and ENZYME scenarios. In the biopulping (BP REAL and BP OPT) scenarios the shares of bleaching chemicals and logs treatment and refining were of the same magnitude forming each 39–47 % of the total acidification potentials (Figure 40). The share of the fungal treatment of chips formed about 11 % of the total potentials. The share of transports of chemicals was small. The calculated potentials followed the same trend as the corresponding total emissions. The need of steam and electricity in storing of chips and fungal treatment increased emissions and environmental impacts in biopulping as compared to enzyme-aided pulping, but however the total emission of the production chain were clearly decreased. In biopulping also the production chains of bleaching chemicals generated emissions, but later developments of the biopulping technology was expected to lower the need of chemicals and also lower the impacts under the present level.

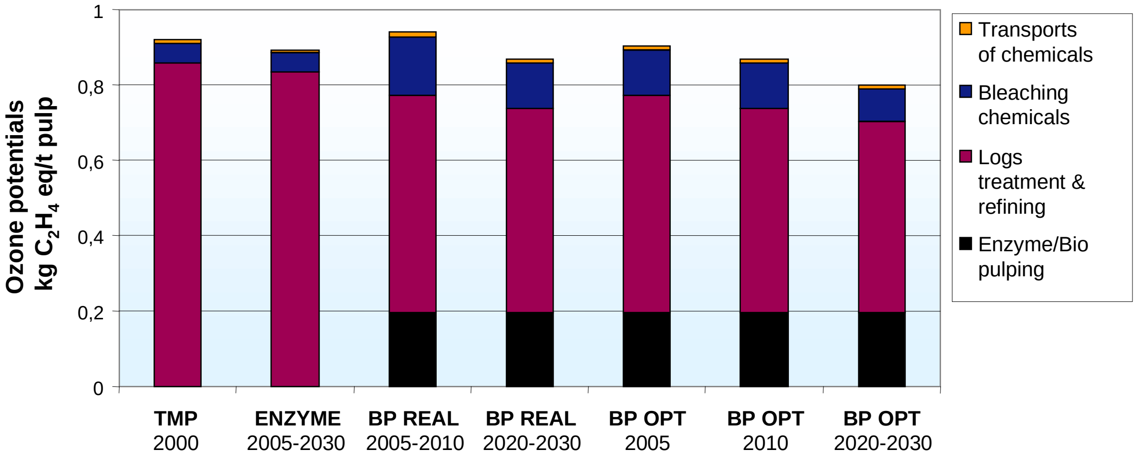

Figure 40. Acidification potentials expressed as equivalents of kg H+/t of bleached pulp in the different phases of the mechanical pulping systems.

7.6.3 Photochemical formation of tropospheric ozone

Increased air concentration of reactive substances, photo-oxidants, which are injurious to the health of living organisms, can arise via photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the troposphere. The conversion of VOCs and CO to ozone also requires sunlight and the presence of NO_x, which have a catalytic effect. The ozone formation potentials are presented in the following Table 19. (Hauschild and Wenzel, 1998)

Table 19. Acidification emissions and related specific potentials expressed as kg H+ eq/kg (Hauschild and Wenzel, 1998).

Photochemical formation of tropospheric ozone	**Type of emission**	**Coefficient**	**POCP, specific potentials as kg C_2H_4 eq/kg**
CH_4	Air emission	0,007	(7.00E-03 kg C_2H_4 eq/kg)
CO	Air emission	0,030	(3.00E-02 kg C_2H_4 eq/kg)
HC (Unspecified)	Air emission	0,600	(6.00E-01 kg C_2H_4 eq/kg)
NO_x	Air emission	0,732	(7.32E-01 kg C_2H_4 eq/kg)

The share of logs treatment and refining was over 60 % of the total potentials in all scenarios. In the biopulping (BP REAL and BP OPT) scenarios the share of bleaching chemicals was about 11–16 %. The share of fungal treatment of chips was about 20–25 % of the total potentials (Figure 41). The share of transports of chemicals was small. The calculated potentials followed the same trend as the corresponding total emissions where NO_x emissions form over 90 % of the total emissions of this category.

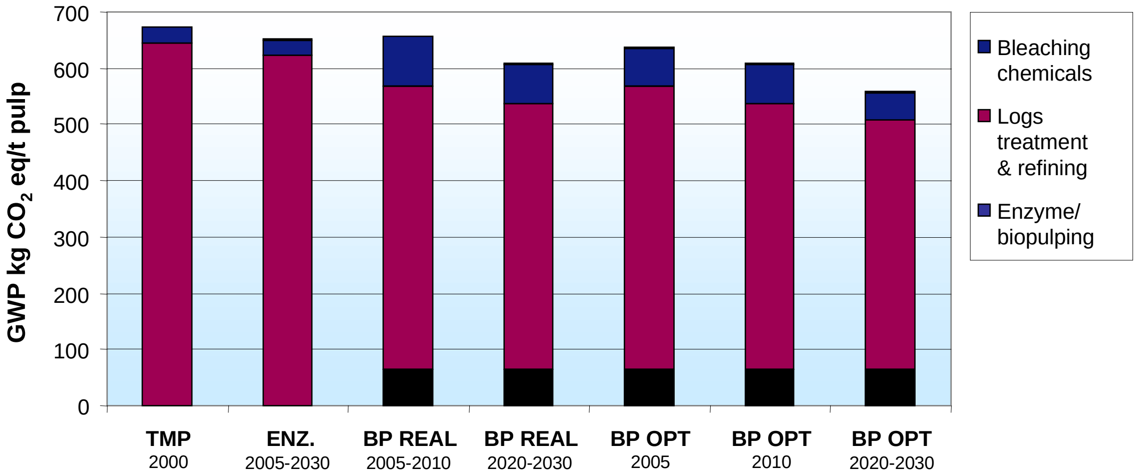

Figure 41. Photochemical formation potentials of tropospheric ozone expressed as equivalents of kg C_2H_4/t of bleached pulp in the different phases of the mechanical pulping systems.

7.7 Conclusions of the LCA study

Based on the LCA study the following conclusions can be made:

- Total air emissions decreased due to implementation of biotechnical methods
- Air emissions from the production chain of the enzyme and fungal product were low in relation to total emissions
- The fungal treatment of chips caused emissions due to increased need of energy in the treatment itself but the total emission of the production chain were clearly decreased
- Air emissions from the production chains of bleaching chemicals increased due to increased use of H_2O_2 and NaOH in the biopulping system
- Wastewater loads were expected to increase due to biopulping, but the calculations were omitted due to unavailability of relevant data at the moment
- Large-scale trials are needed in order to assess wastewater loads and to improve the quality of the data on the environmental burdens when utilising biotechnical methods in mechanical pulping

8. Discussion and conclusions

The EFOM model calculations assumed a 30 years lifetime for the investments in enzymatic pulping and 35 years for biopulping. This approximate technical lifetime is a considerably longer time horizon than what enterprises usually base their investments on. Therefore, the cost-effectiveness results given in Chapter 7 should be viewed from the point of national economy rather than that of a single enterprise.

The international mitigation of climate change is expected to change the energy and industrial systems profoundly in the long run. Already in the short term with the recent EU proposal on greenhouse gas emission trading within the EU, envisaged to start in 2005, CO_2 emissions may develop into an article of trade with a market price. In this case, cost-effectiveness calculations of energy-saving investments should take into account also the value of the CO_2 emissions avoided (as was done in the EFOM model calculations).

The potential of biopulping was mainly investigated with the Chip pile option, which has considerably lower investment costs than the Silo treatment option. With the 'Conventional' scenario, it is unlikely that the biopulping technique with the Silo treatment would have become cost-effective. In the 'Optimistic' scenario, biopulping techniques penetrated to their maximum share allowed. As the investment costs are discounted over the whole payback time and other costs (such as the extra bleaching needed) form a significant part of the total cost per tonne produced, also the Silo treatment option could become cost-effective in the long run, especially if pilot experiments indicate that a better mass quality or shorter treatment times can be achieved with Silo treatment.

Drawing from the objectives of the CLIMTECH programme, this work assessed the potential and possibilities of biotechnical methods in mechanical pulping from the present until 2030. The long time scale obviously induces many uncertainties in the estimates. As this study considered partly technologies which have not been demonstrated yet on a mill scale in Nordic conditions, the actual future potentials depend on the actual suitability of the processes. Pilot tests of especially biopulping will be needed for more accurate estimates.

Advances obtained, *i.e.* in energy economy, in new refining technology are often compensated by deterioration of pulp technical properties, especially strength properties. This is not the case with the biotechnical methods in question. It is very well documented in literature that pulp quality could be improved by both of the biotechnical treatments in laboratory scale. However, this improvement of pulp quality, *i.e.* mainly in strength properties, obtained by the application of the biotechnical methods were not included into the scenario study. This was justified by the facts that improvement of pulp quality was diffucult to assess in economical terms and it's paper grade and mill specific. Evidently, economical benefits obtained by the compensation of expensive chemical pulp by mechanical pulp in production of a wood containing paper grade can be remarkable for a certain mill.

In the scenario studies enzyme-aided refining was only assessed for the production of thermomechanical pulp, *i.e.* in refining. Basicly the same technology can be applied in the treatment and successive refining of rejects from grinding (GW, PGW), too. Rejects arise in lower amounts in grinding (15–20 %, GW, PGW) than in refining (30–50 %, TMP). Currently and likely also in the future, production of mechanical pulp by grinding will be broad in Finland and there exists a marked and potential site for the application of enzymes. However, due to lack of experimental data, enzyme-aided refining of GW rejects was not included in the study. Likewise novel biopulping of wood logs in stead of wood chips might be a potential option for future energy savings in the future.

The LCA study shows that implementation of biotechnical methods in mechanical pulping reduce the total air emissions including GHGs due to decreased energy use in refining. However, the air emissions from the production chains of bleaching chemicals and from the fungal treatment of chips increase due to increased needs of chemicals and energy in the biopulping system. The air emissions from the production chains of the enzyme and fungal products are however low in relation to total emissions. More knowledge, continued research efforts and large-scale trials are still needed in order to assess wastewater loads and to improve the quality of the data on the environmental burdens when utilising biotechnical methods in mechanical pulping.

It is very likely that wastewater loadings in terms of BOD and COD would increase in some extent if the biotechnical methods were implemented in TMP production. One would expect a minor increase of BOD in the case of the enzyme-aided refining, because the yield loss is low (<0.2 %) and almost totally composed of easily degradable carbohydrates. In biobulping leaching of wood derived compounds would perhaps be more extensive containing also recalcitrant compounds from lignin, which are resistant against microbial degradation during activated sludge treatment. Therefore the main consequence of biopulping would be an increased COD loading into wastewater, which might cause extra expenses in wastewater treatment to meet the limits of effluent discharges. One can expect that activated sludge plants could rather easily handle the increased BOD loading evolved from the biotechnical process steps.

9. Summary

The aims of the study were to a) study the potential for energy savings and reduction of GHGs by implementation of biotechnical methods in mechanical pulping, b) estimate their cost-efficiency and c) assess the environmental impacts of their adoption into TMP production using the LCA methodology. Two different biotechnical methods were considered, namely fungal pretreatment of chips (biopulping) and enzyme-aided refining, both of which have shown marked potential for energy savings in mechanical pulping. Cost-efficiency, adoption and effects on emissions of GHGs of the biotehnical methods as compared with other competing technologies were estimated by the EFOM model. Two different scenarios extending to 2030 were used. In the 'optimistic' scenario the new cleaner biotechnologies develop rapidly and they are adopted effectively into use, whereas in the 'realistic' scenario new technologies reducing greenhouse gas emissions penetrate rather slowly into the energy and industrial systems. The results showed that enzyme-aided refining was very competitive as compared with alternative methods and it has a potential of being largely applied in mechanical pulping. Biopulping, which is technically more difficult to control and also more expensive to invest and operate, could be largely adopted according to the optimistic scenario in 2020. It is shown by the LCA study that implementation of the biotechnical methods would reduce total emissions of GHGs. Acidifying emissions from production of bleaching chemicals would, however, increase due a need of extra bleaching for biopulped chips, but the portion of acidifying emissions from the total emissions were assumed to be low. Effects on wastewater loadings arising from the application of biotechnology were not assessed in this study due to lack of relevant data.

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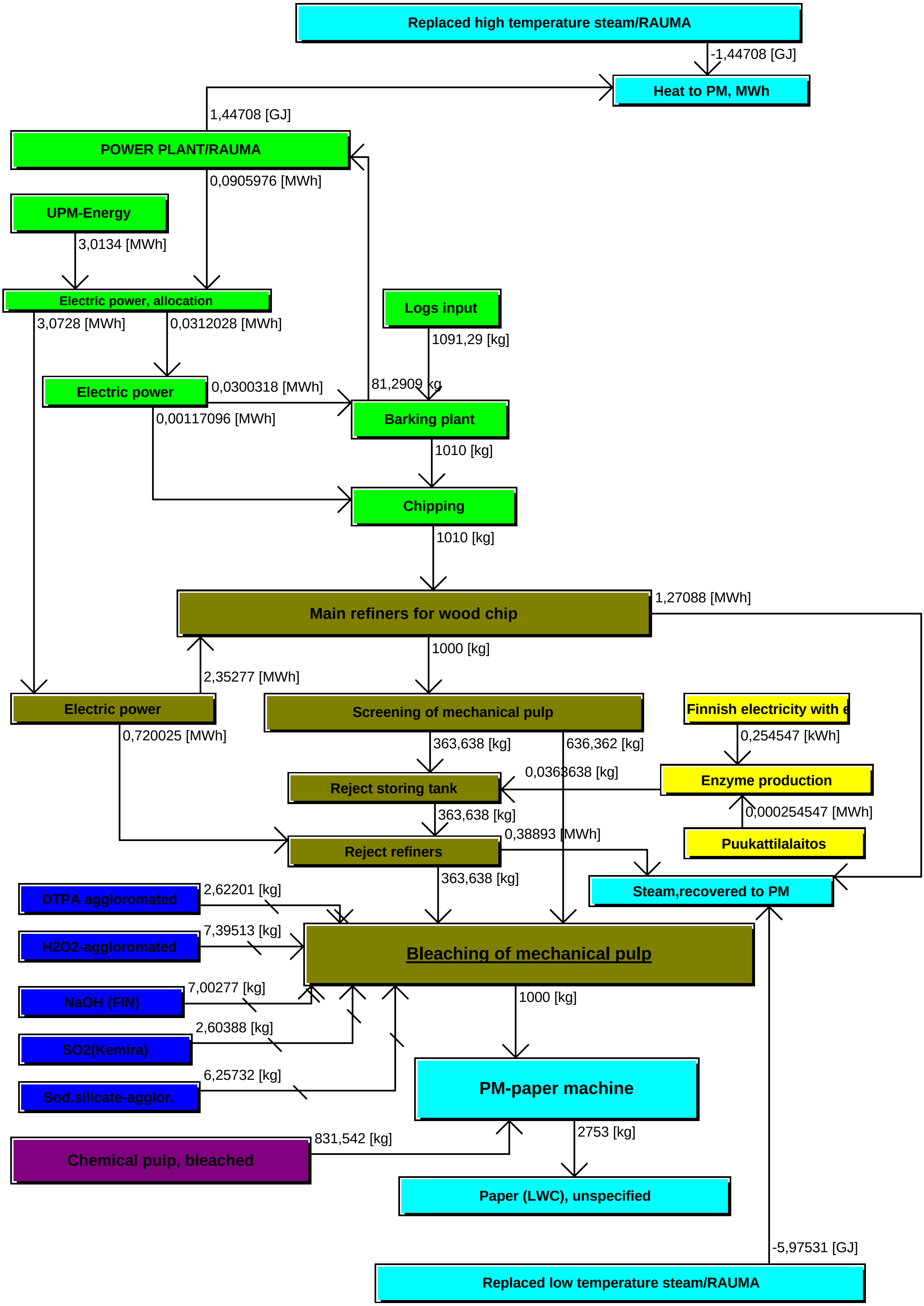
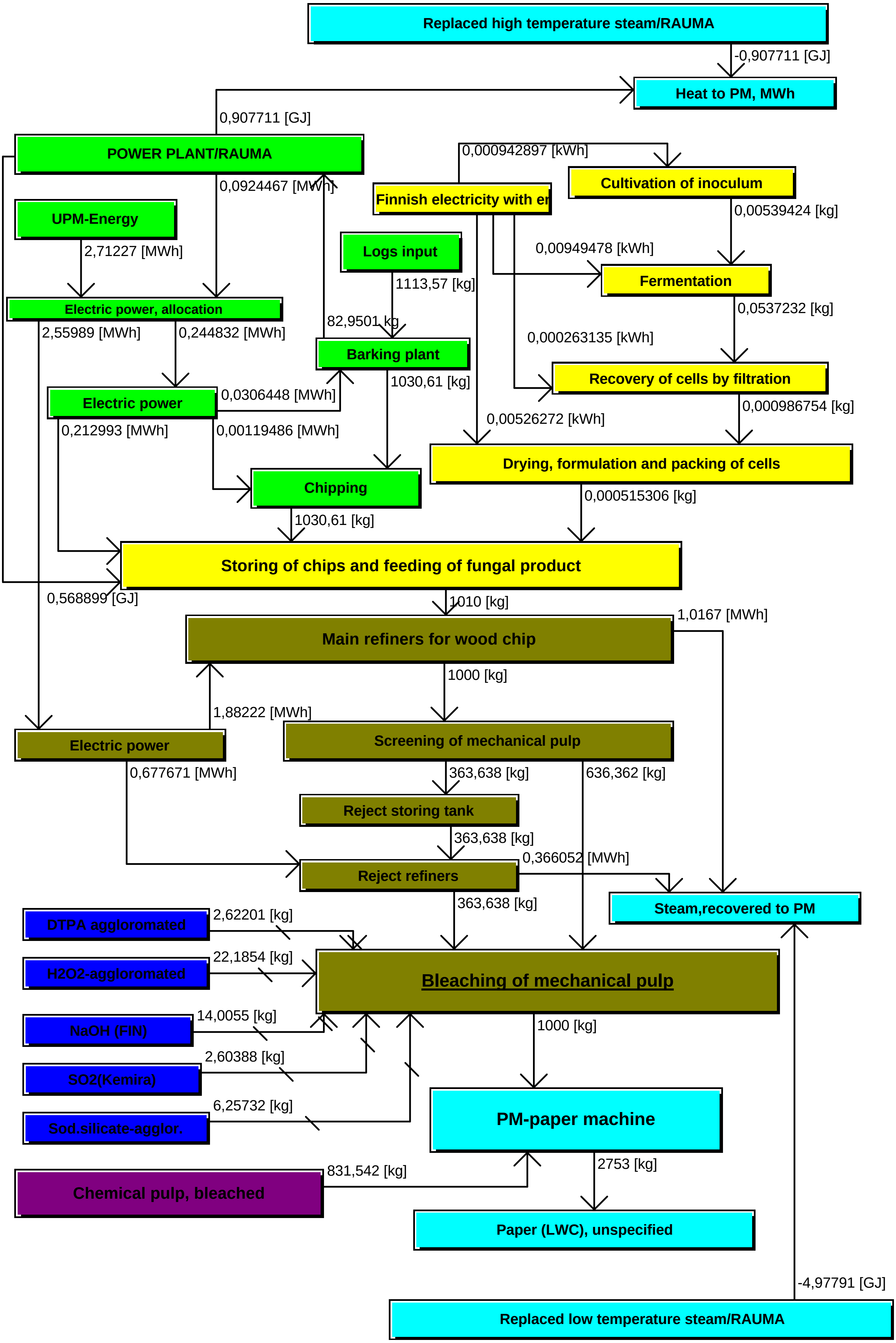
TMP4 - Enzym (0,1 kg/1000kg pulp), -15 % energy saving in reject refining



TMP4 - OPTIMI 2005 electricity -20 %, H2O2 3+300%, NaOH + 200%



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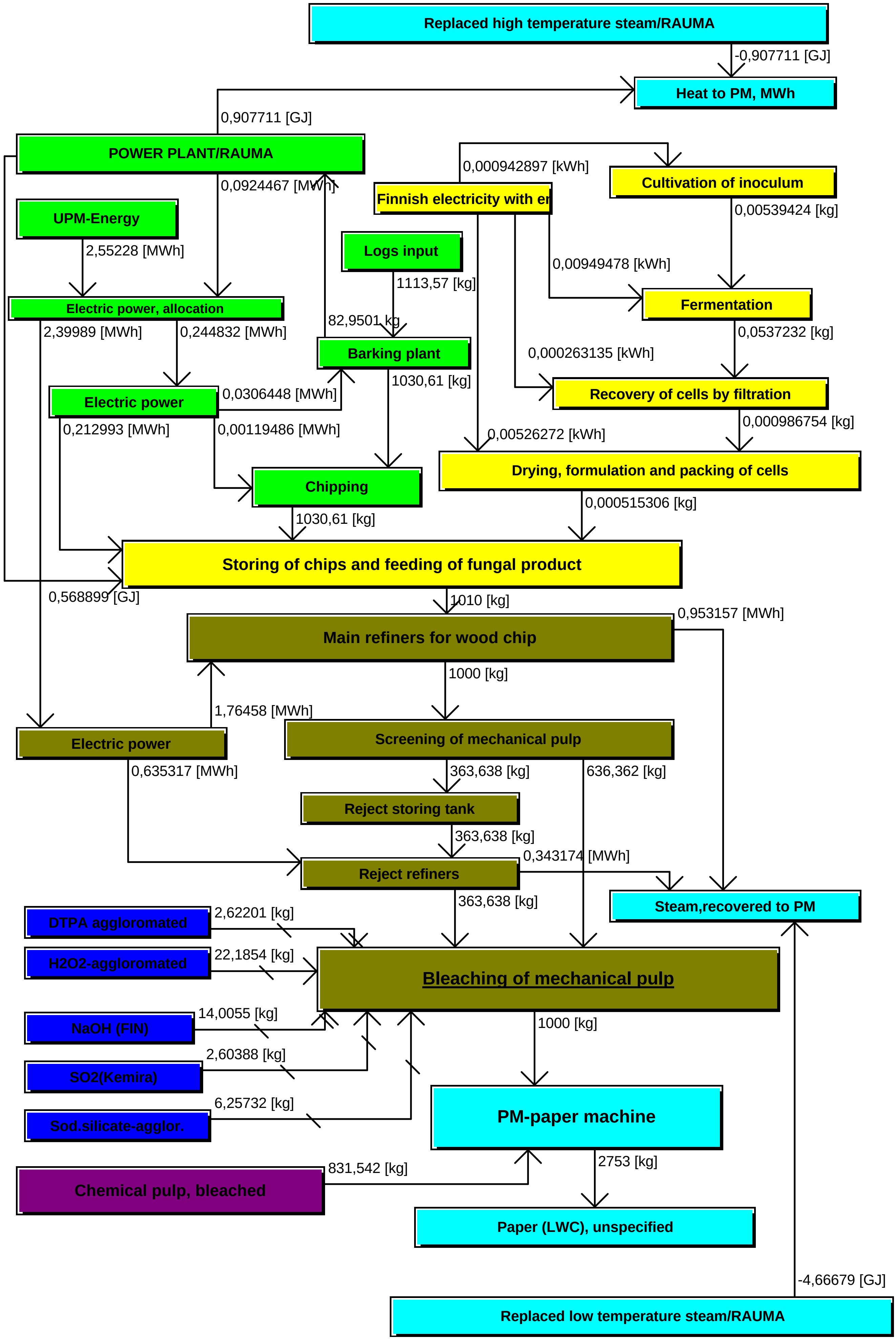

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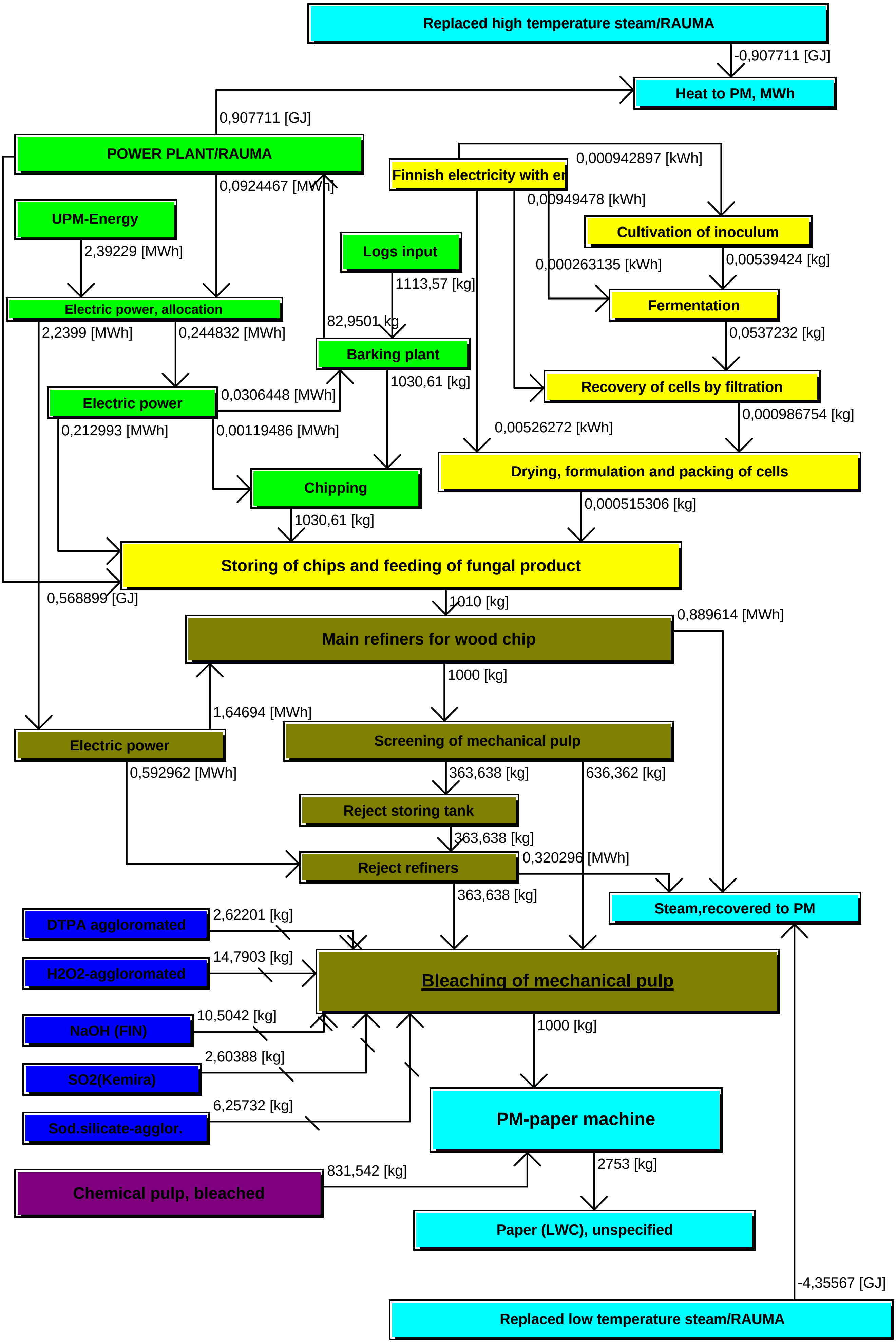

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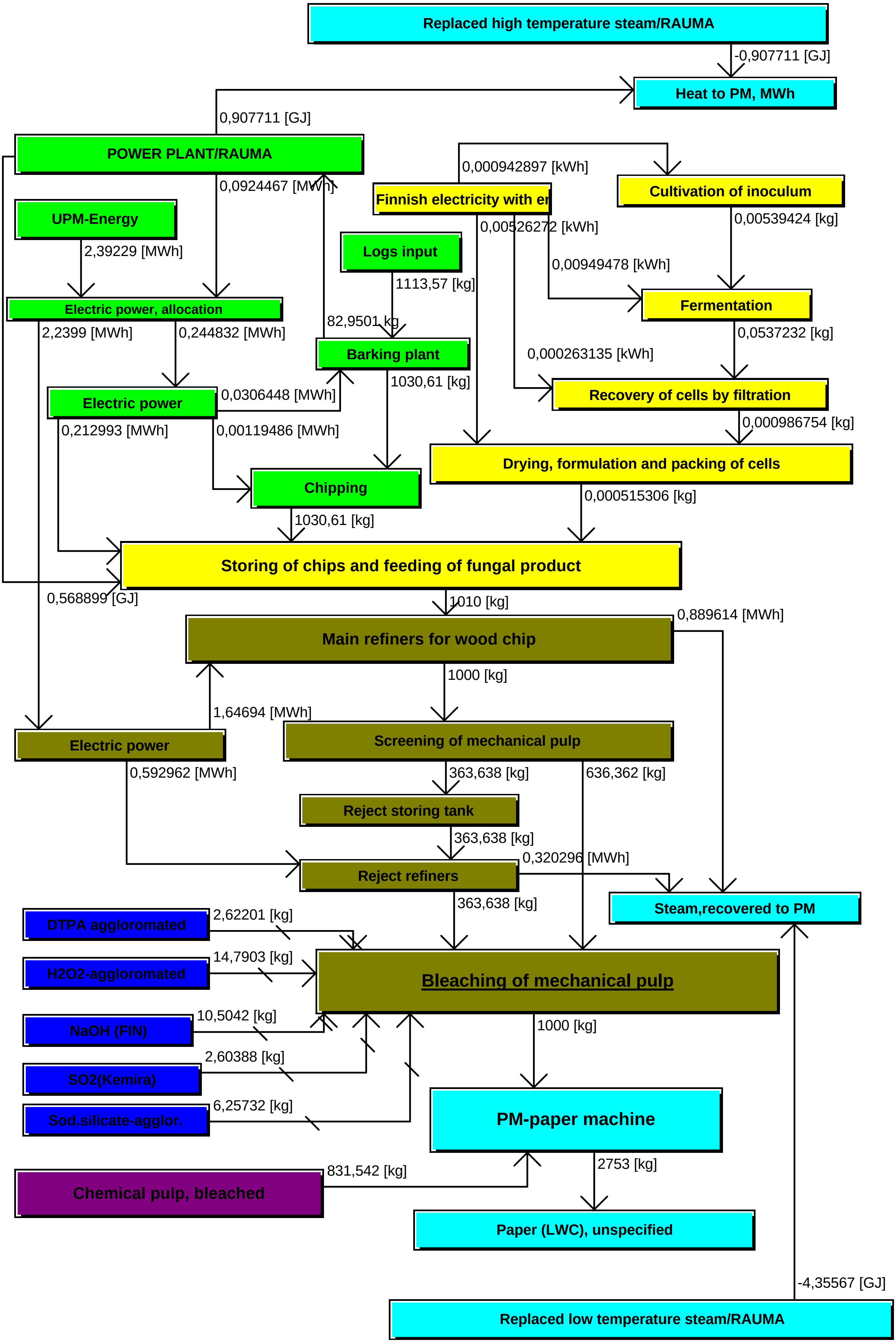
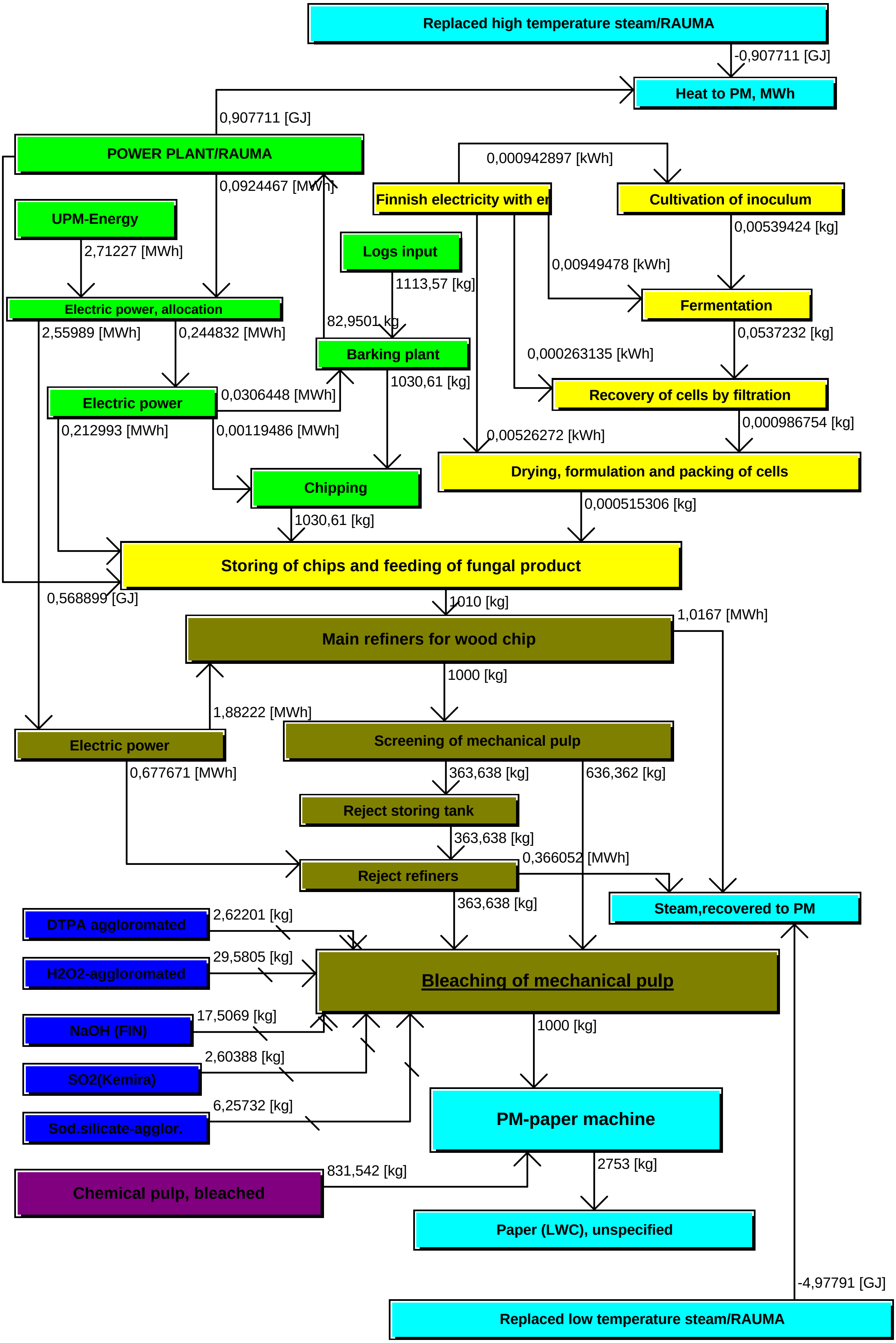


REAL 2005, electricity -20 %, H2O2 +400%, NaOH +250%



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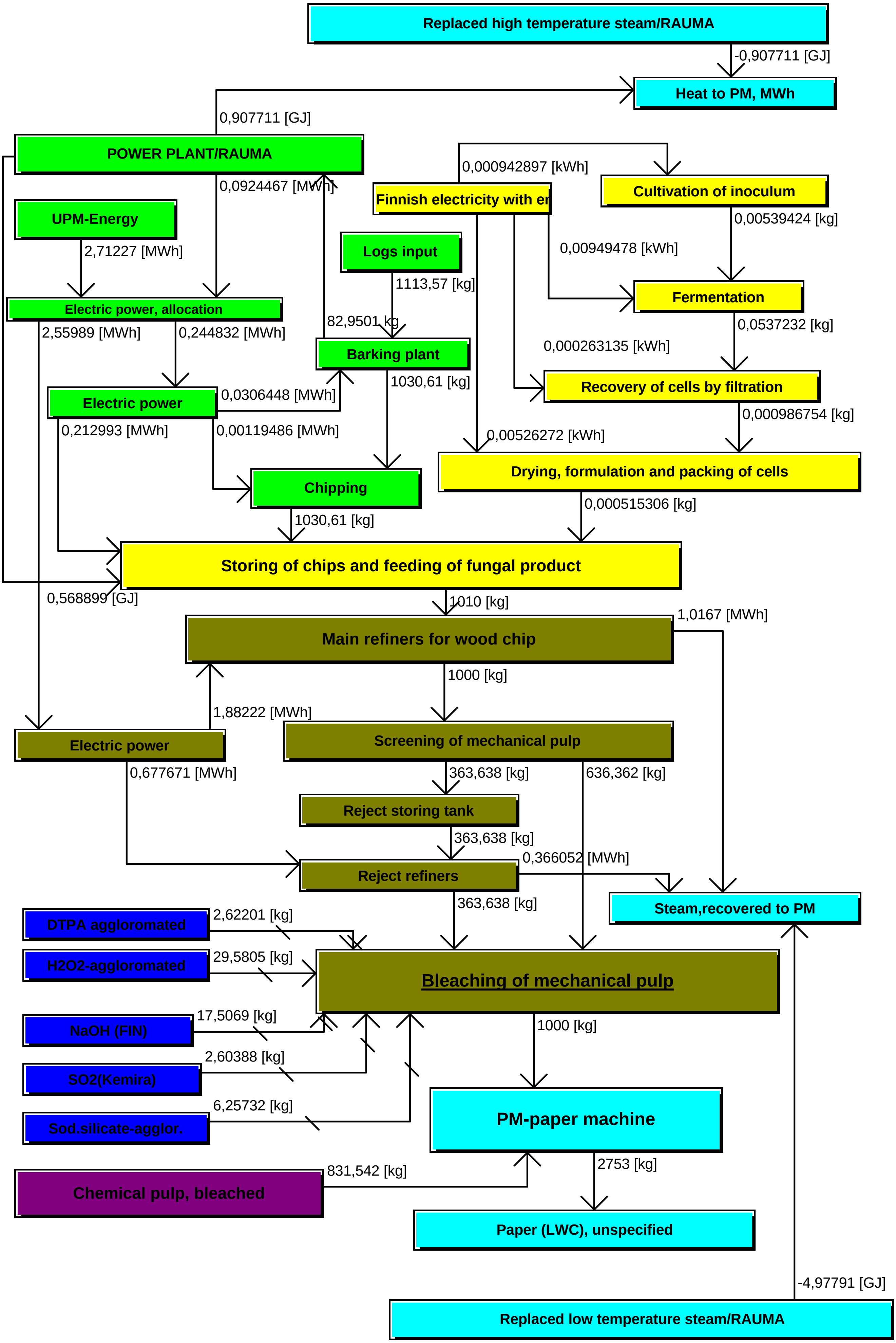
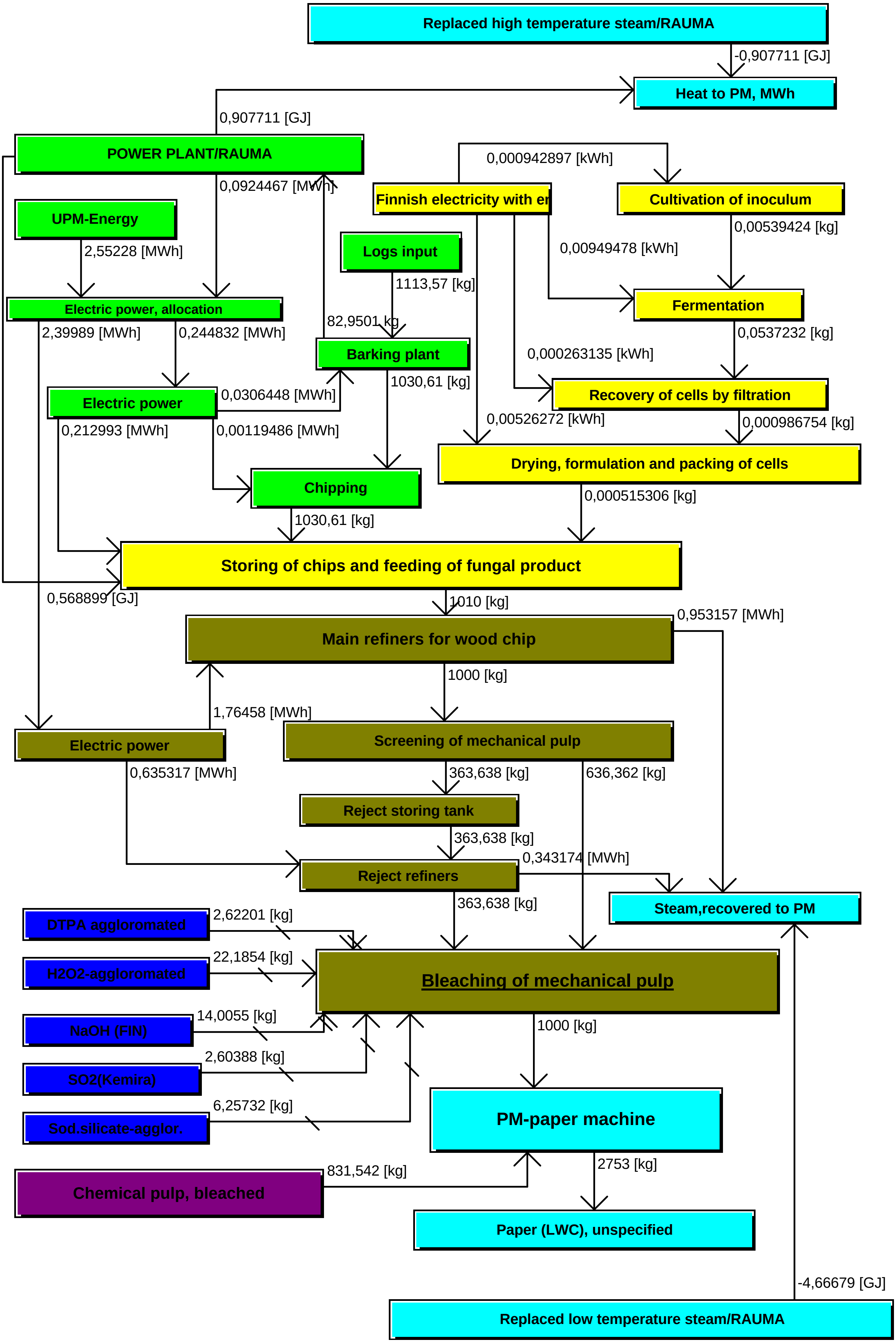


TMP4 - REAL 2020 electricity -25 %, H2O2 +300%, NaOH +200%



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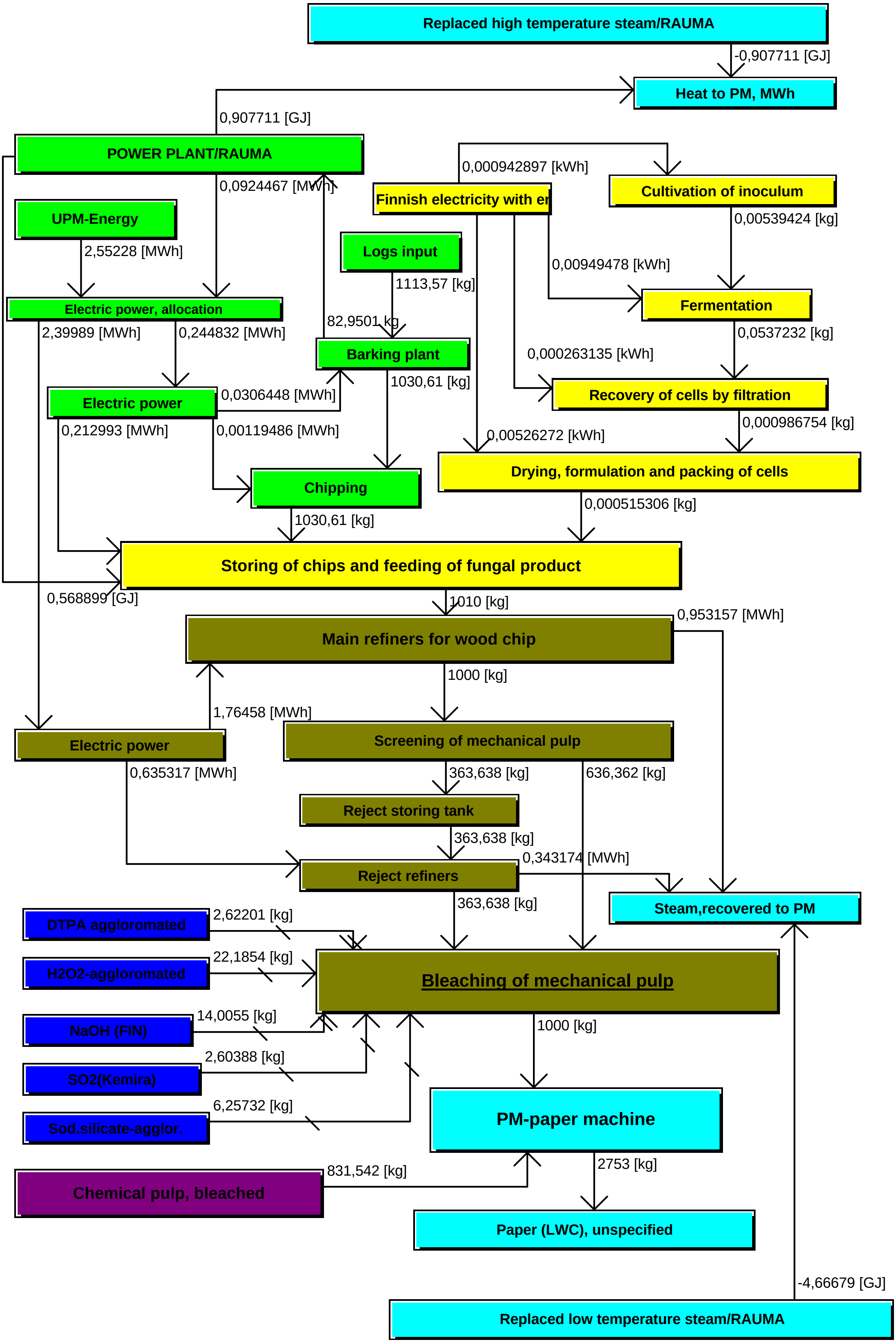

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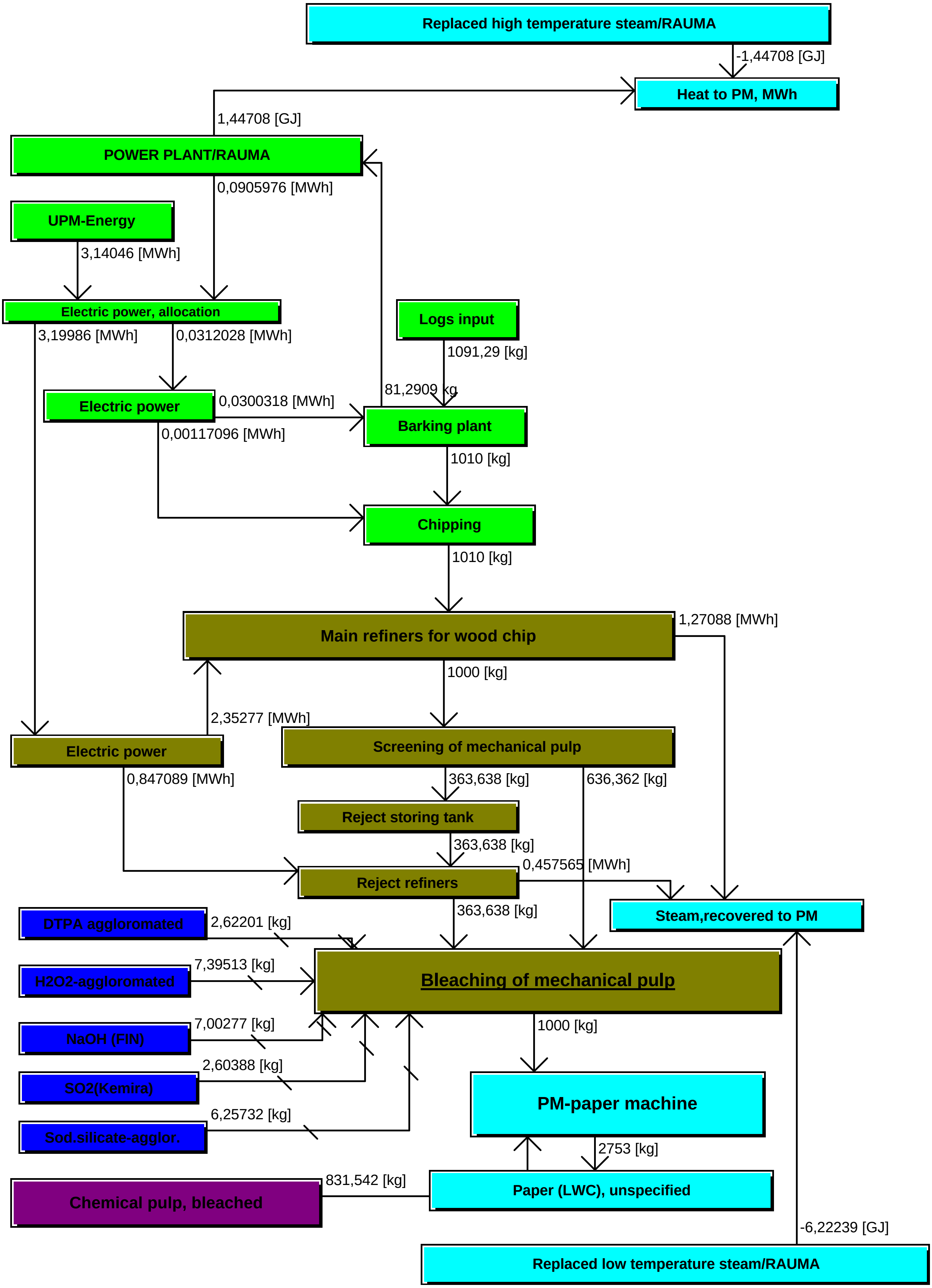

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Title

Biotechnical methods for improvement of energy economy in mechanical pulping

Abstract

Forest industry is a notable user of electric power in Finland. The main reason for this is mechanical pulping, which is very energy intensive. Energy savings in mechanical pulping will also affect indirectly emissions of greenhouse gases (GHG). The aims of the study were to a) study the potential for energy savings and reduction of GHGs by implementation of biotechnical methods in mechanical pulping, b) estimate their cost-efficiency and c) assess the environmental impacts of their adoption into TMP production using the LCA methodology. Two different biotechnical methods were considered, namely fungal pretreatment of chips (biopulping) and enzyme-aided refining, both of which have shown marked potential for energy savings in mechanical pulping. Biopulping has been studied intensively, but without experience in mill scale. Enzyme-aided refining was developed during 1990s in collaborative projects and the method has been succesfully verified in mill scale trials.

Cost-efficiency, adoption and effects on emissions of GHGs of the biotehnical methods as compared with other competing technologies were estimated by the EFOM model. Two different scenarios extending to 2030 were used. In the ´optimistic´scenario the new cleaner biotechnologies develop rapidly and they are adopted effectively into use, whereas in the ´realistic´ scenario new technologies reducing greenhouse gas emissions penetrate rather slowly into the energy and industrial systems.

The results showed that enzyme-aided refining was very competitive as compared with alternative methods and it has a potential of being largely applied in mechanical pulping. Biopulping, which is technically more difficult to control and also more expensive to invest and operate, could be largely adopted according to the optimistic scenario in 2020. It is shown by the LCA study that implementation of the biotechnical methods would reduce total emissions of GHGs. Acidifying emissions from production of bleaching chemicals would, however, increase due a need of extra bleaching for biopulped chips, but the portion of acidifying emissions from the total emissions were assumed to be low. Effects on wastewater loadings arising from the application of biotechnology were not assessed in this study due to lack of relevant data.

Keywords
pulping industry, mechanical pulping, energy economy, energy conservation, pretreatment, enzymes, fungi, environmental impacts, emissions, life-cycle assessment

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