FRAUNHOFER-INSTITUT FÜR MIKROSTUKTUR WERKSTOFFEN UND SYSTEMEN IMWS

LCA ÄÄNEKOSKI

Life Cycle Assessment of fibres from bioproduct mill compared to fibres from average European and Latin America pulp mills

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Content

Preface

The following report is a life cycle assessment (LCA) of pulp production process chains where the Elemental Chlorine Free (ECF) pulp production of Äänekoski bioproduct mill, the pulp production of average European Total Chlorine Free (TCF) pulp mills, as well as the pulp production of average pulp mills in Europe and Latin America are assessed.

This study was commissioned by METSÄ FIBRE OY, Finland, on 23 March 2022. The main contractor to carry out the study is Fraunhofer IMWS. The report was prepared on 05 October 2022.

The study was conducted according to the requirements of the International Standard DIN EN ISO 14044.

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List of Abbrevations

AbwV	Abwasserverordnung
ADMT	Air-dried metric ton
AOX	Adsorbable organically bound halogens
APOS	Allocation at Point Of Substitution
BAT	Best Available Technology
BAT-AEL	Best Available Technologie – Associated Emission Levels
BFR	Bundesinstitut für Risikobewertung
BOM	Bill of Material
BR-MG	state of Minas Gerais, in Brazil
BV	Biodiversity Value
BVI	Biodiversity Value Increment
CA-QC	Canada-Quebec
CED	Cumulated energy demand
CEPI	Confederation of European Paper Industries
CER	Certified Emission Reduction Units
CHP	Combined heat and power plant
CO_2	Carbon Dioxide
COD	Chemical oxygen demand
DCP	1,3-Dichlor-2-propanol
DTPA	Diethylene triamine pentaacetic acid
ECF	Elemental Chlorine Free
EDTA	Eethylenediaminetetraacetic acid
EPD	Environmental Product Declaration
EU	European Union
Eurofins	Eurofins Scientific SE
EMPA	Swiss Federal Laboratories for Mechanical Science and Technology
FAU	Forest Analysis Unit
FU	Functional Unit
GWP	Global Warming Potential
GL	Giftigkeit in Leuchtbakterien (toxocitie of luminescence bacteria)
HW	Hard Wood
ILCD	International Life Cycle Data System
IUCN	International Union for Conservation of Nature
IPCC	Intergovernmental Panel on Climate Change
KCL	Oy Keskuslaboratorio – Centrallaboratorium Ab.
LANCA	LANd use indicator value CAlculation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LQI	Land Quality Index
MCPD	3-monochloropropane-1,2-diol or 3-chloropropane-1,2-diol
MOAH	Mineral oil hydrocarbons
MOSH	Mineral oil saturated hydrocarbons
n.d.	not detected
NOX	Nitrogen oxide
OX	Organically bound halogens
PEF	Product Environmental Footprint
PEFC	Programme for the Endorsement of Forest Certification Schemes

PEFCR	Product Environmental Footprint Category Rules
PCR	Product Category Rules
PM	Particulate Matter
PO_4^{3-}	Phosphate
POCP	Photochemical Ozone Creation Potential
PRTR	Pollutant Release and Transfer Register
RER	Region Europe
RL	Robustness Level
RoW	Rest of World (means global)
SETAC	Society of Environmental Toxicology and Chemistry
SDGs	Sustainable Development Goals
SLCA	Social Life Cycle Assessment
sob	solid over bark
SW	Soft Wood
TCF	Total Chlorine Free
TRACI	Tool For Reduction and Assessment of Chemicals and other Environmental Impacts
UNEP	United Nations Environmental Programme
WMO	World Metereological Organisation
WWF	World Wildlife Fund

Units and Dimensions used

µm	micrometre, 10^{-6} metre
L	litre
m²	square metre
m³	cubic metre, 1.000 litre
mg	milligram
g	gram
kg	kilogram
t	tonne, 1.000 kilograms
kJ	kilojoule, 1.000 joules
kt	kilotonne, 1.000 tonnes
MJ	megajoule, 1. 000 kilojoule
W	watt
MWh	megawatt hours, 1.000 kilowatt hours
a	year

Note on decimal separator:
The symbol used as the decimal separator throughout this document is a comma. This is in line with the recommendations of (ISO 80000-1 2013) for international documents.

Introduction

This report on the research project "Life Cycle Assessment of fibres from bioproduct mill compared to fibres from average European and Latin America pulp mills" provides the overall view of the results and findings obtained in the project in which a Life Cycle Assessment (LCA) was conducted.

In addition to detailed information on the goal and scope, advanced LCA method estimating the biodiversity Increment of wood feedstocks are reported.

To support the interpretation of the assessment made, independent laboratory tests were carried out for relevant key Figures on the environmental impact. Effluent water was analysed of emissions and as well the impurities in final tissue products were measured to highlight the impact on toxicity. Additional toxicity tests with luminescence bacteria were carried out, at wastewater and tissue samples. The toxicity tests were performed to evaluate if impurities, such as AOX, have an impact on toxicity.
The given key numbers are a surplus material to this LCA and can be found in chapter “additional information”.

1 Goal and scope of the study

1.1 Goal of the study

The following points were defined as objectives of the LCA:

1.1.1 Intended application

The main use of the study results is to inform the client about the environmental impact of the production of sulphate pulp from the aspects of raw material preparation and the technological processes used for wood fibre bleaching.

Evaluations of modern pulping technology compared to existing average pulp mills are expected to provide insights into pulping technology development.

Insights found in this study will be given as objective information to decision-making persons with an interest in further development of the pulp and paper industry, such as employees in ministries and authorities. Information should also be brought to decision-making persons in branches with direct relations to consumers of pulp and paper products, as interested public.

1.1.2 Reasons for carrying out the study

To provide information about the actual environmental performance at the site at Äänekoski, the interaction of Best Available Technology (BAT) and sustainable forest management will be investigated in form of a LCA, to investigate environmental impacts.

In public discussion, ECF bleaching is often seen as more harmful than TCF bleaching, a further reason to carry out this holistic environmental impact assessment is the analysis and comparison of both bleaching methods.

To encourage further pulp industry sites to mitigate environmental impacts, this study looks at the technological average of European and Latin American ECF pulp mills, and average European TCF pulp mill compared to the relatively newly ommissioned ECF Äänekoski bioproduct mill.

1.1.3 Intended audience

This study is being carried out to present insights into the environmental impact of the Äänekoski bioproduct mill to the interested public on one side and further to stakeholders.

The study is also aimed at scientific institutions, professionals in environmental organisations and public authorities, those responsible in the tissue industry and related sectors, as well as the wholesale trade in everyday goods.

1.1.4 Comparative assertions

The initiator of the study wishes to make the results of this comparative study publicly available and has therefore commissioned a critical review in accordance with DIN EN ISO 14040:2006 and 14044:2006.

1.2 Scope of the study

In defining the scope of the study, the following issues were considered and described:

1.2.1 Product systems to be studied, time and region

In this study sulphate kraft pulp production with different bleaching technology and different wood raw material has been studied. For sulphate kraft pulp production two bleaching processes have become industrially established. The Elemental Chlorine Free (ECF) process is free of pure chlorine, or chlorine gas, and uses alternative chemicals for bleaching, such as chlorine dioxide. The Totally Chlorine Free (TCF) sulphate process relies on oxygen compounds such as hydrogen peroxide and ozone. Due to the high reactivity, or selectivity towards lignin, of chlorine dioxide, ECF processes allow the optimization of process steps in bleaching, compared to TCF processes, with comparable paper technical properties (Schacht, 2000).

In bioproduct mill Äänekoski the modern ECF bleaching uses optimal configurated best available technology (BAT) and has only 3 bleaching stages. TCF bleaching sequence is as well according to EU BAT, but usually has more bleaching stages (4 - 5 stages), which can lead to higher environmental footprint. In addition to the optimised bleaching sequence, the heat recovery boiler at Äänekoski is also of high efficiency in comparison to the recovery boilers in average pulp mills. For recycling of chemical agents in the pulping process, the bioproduct mill runs a sulphuric acid plant reducing the amount of fresh sulphuric acid (Valmet, 2022).

This study investigates the integrated impacts of the highly efficient subsystems of the bioproduct mill Äänekoski in comparison to average pulp mills. The investigated subsystems in bioproduct mill are as follows:

- Highly efficient heat recovery boiler
- Highly efficient ECF bleaching (higher yield with less Fibre loss)
- Highly efficient recycling of chemicals

The following configurations, from raw material supply and technology to Fibre extraction and bleaching, were considered in the study:

- Sulphate pulp, bioproduct mill Äänekoski (ECF) northern Europe
  - feedstock from northern Europe based forest (wood from thinning)
  - highly efficient technology of bioproduct mill

- Sulphate pulp, average European pulp mill (TCF)
  - feedstock from northern Europe based forest
  - average technological standard of TCF pulp mill

- Sulphate pulp, average European pulp mill (ECF)
  - feedstock from northern Europe based forest
  - average technological standard of ECF pulp mill

- Sulphate pulp, average Latin America including Caribbean, Central and South America, pulp mill (ECF)
  - feedstock from Latin American based forest
  - average technological standard of ECF pulp mill

To assess the use of raw materials from forest systems, a biodiversity analysis was prepared.

Time period of 12 months is chosen to assess the system of forest management, the delivery of wood, and the pulp production over all seasons of one year.

The datasets of forest management and average pulp technology representing decades, to show representative averages.

The dataset for average pulp mills represents pulp mill data from 2015 and the production year of 2017 (ecoinvent, 2021).

Data for forest management stem from 2010 until 2012 and are extrapolated by literature to show averages. The data of wood harvesting are estimated for the year 2011 (ecoinvent, 2021).

The data collected on emissions to air and water are taken from the environmental monitoring system for key emissions at bioproduct mill Äänekoski, that is active in the timeframe 2017 to 2021. Data from 2021 used in this study, related to the chosen reference year of production at the bioproduct mill. Additional data collected on emissions to surface water and end products are from sample series and externally conducted measurements from 2022.

Regarding the use of different years of production, see 1.2.8 Assumptions regarding the long-time lasting investments in pulp mills.

The geographical regions under study are Europe and Latin America, to assess the regional specific forest systems that are used as feedstocks in regionally located pulp production.

1.2.2 Function of the product systems

The functions of the product systems are sulphate pulp extraction and pulp bleaching. In case of normal grades of bleaching, the main product sulphate pulp is identical between the ECF and TCF processes. Significant differences will be found in higher strengths of fibre from bleaching using chlorinated bleaching, whereas a high bleaching grade is slightly more robust in reaching unchlorinated bleaching (Schacht, 2000). Because the higher strength of pulp Fibres and, on other hand, the robustness of bleaching only in specific paper applications were taken to account, the pulp from ECF and TCF can be seen of identic quality.

The processes of TCF and ECF bleaching show specific differences. The TCF process enables the drastic reduction of halogenated organic compounds (AOX) in process water and product. The ECF process enables a very efficient operating sequence due to a reduced number of process steps, while staying significant below legal limits for AOX.

The yield of by-products from the sulphate pulp process is not significantly influenced by the bleaching sequence, because the mass and energy streams of by-products are most related to Fibre digestion in a process step before bleaching.
Because the Äänekoski bioproduct mill has an optimised operation process and innovative energy recovery system, the yield of surplus electricity as by-product is significantly higher than from average ECF sulphate pulp mills (Table 01).

1 Air Dry Metric Tonne of pulp	bioproduct mill	TCF EUR	ECF EUR	ECF RLA
E thermal [MWh]	**0,258**	**0**	**0,314**	**0,711**
E electric [MWh]	**0,574**	**0**	**0,254**	**0,224**

Table 01: By-products related to 1 ADMT bleached pulp, data from ecoinvent 3.8 and bioproduct mill data from Metsä.

1.2.3 Functional Unit

The function used in this study for the comparison of the different raw material bleaching systems is the production of

- 1 ADMT (Air Dry Metric Tonne) bleached Sulphate pulp, from virgin fibre for production of tissue.

The Functional Unit was chosen for the following reasons:

- The material quantity Air Dry Metric Tonne allows comparisons by mass, on basis of equal amounts of 10% Equilibrium humidity in pulp, under normal climate condition. This ensures, that pulp containing no rests of process water.

1.2.4 System boundaries

Inside the system boundary of this study, we cover forest management (specific to geographical region of the investigated pulp mill), transport of wooden raw material to pulp mill, production and transport of chemical agents for pulping and bleaching. The study ends at the gate of the pulp mill.
The scope of this cradle-to-gate study includes neither the use of paper as a secondary raw material nor the intercontinental transport of pulp, for the objective comparison of pulping technologies.

In detail the system boundaries (Figure 1) include:

- regional forestry and transport __________________ [raw material]
- Chemicals, region specific produced and transported [ancillary input]
- Energy mix, region specific ______________________ [energy input]
- Surface water _________________________________ [elementary flow]
- Emission to air ________________________________ [elementary flow]
- Emission to water ______________________________ [elementary flow]
- Inert waste, sludge _____________________________ [waste]
- Electricity and heat _____________________________ [by-products]
- the foreground system (pulp mill) contains:
    - wood handling
    - pulping
    - pulp bleaching
    - energy production on-site
    - recovery cycles of chemicals
    - internal waste-water treatment
    - drying pulp to air-dry

As Figure 01 shows, the system uses surface water as cooling water and process water [elementary flows], supplied chemicals [ancillary input], and energy from the regional electricity mix for starting the process [energy input], regular processing is driven by renewable energy from within the system [process energy].
The treatment of process and cooling water, which is taken from nature and fed back in, is within the system boundaries and accounted for. Also is within the system the (partial) recovery of bleaching chemicals [intermediate products], and the processing of energy [energy output].
The system outputs the following energy and material streams: Bioenergy in the form of electricity and heat [energy output], material residues from fibre pulping as sludge for fertiliser [elementary flow] and inert waste [waste], dust [waste], treated process water (within emissions to water), emissions to air, and pulp.

Outside the system boundary and not investigated in this study are possible by-products of a pulp mill or the even broader possible by-products of a bioproduct mill.

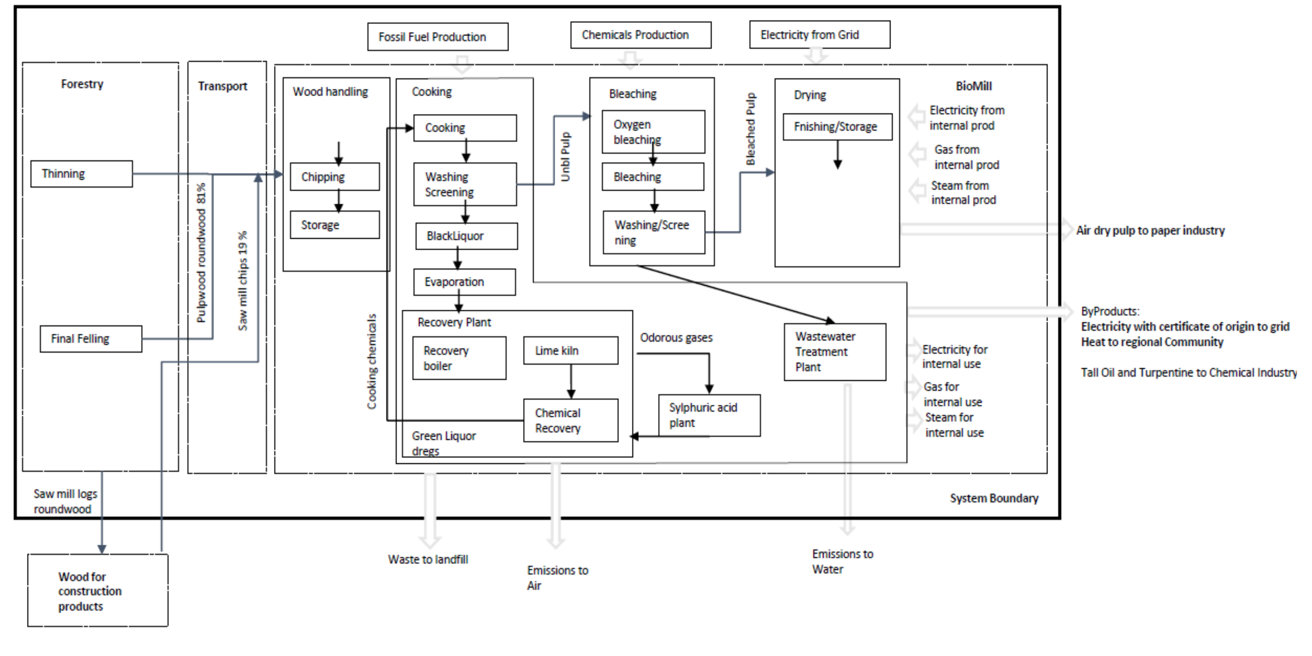


Figure 01: System boundary.

The bleaching technologies were modeled according to the state of the art for ECF and TCF on the level of whole pulp mills. By this, the physical inventory of pulp mills is modeled in a rough granularity that aggregates the process steps of wood handling, pulping, bleaching, water treatment, the recovery of chemicals and energy, and drying. The input and output of each of the modeled pulp mills differs in relation to the modeled bleaching technology because different bleaching methods use different chemical agents and also, in one bleaching method, the ratio of bleaching agents is specific to the pulp mill and used feedstock (model 04). The ratio between softwood/hardwood in feedstock is set in models 01, 02, and 03 at 64 / 36 and model 04 uses only hardwood, stemming from eucalyptus.

1.2.5 The cut-off criteria

The decisions on including inputs and outputs are made supported by cut-off criteria, regarding the mass and environmental significance.

The mass-based cut-off criteria are 0,5 mass% of cumulative mass of product, because the inputs from the techno-sphere, like bleaching agents, can have significant impacts on the environment.
Environmental significance-related cut-off-criteria were chosen in the case of emissions from internal production, and biofuels were used as process energy. Because the emission profile of recovery boilers in pulp mills was not available, the emission calculation does not contain specific emission values for the use of black liquor, sludge and tall oil pitch in any of the compared models. The emissions from recovery boilers and uses of tall-oil pitch are given by key emission factors measured by the pulp industry in all compared models (Agency, 2019)
The system boundary of this investigation ends at the gate of the pulp mill.

1.2.6 The allocation procedures

In the sections of the life cycle of a process or product system, allocations of material and energy flows may become necessary, for example to carry out fair partitioning of burdens from the processes of extraction and production. In the standard text (DIN ISO 14044), this means: "Allocation refers to the division of the input or output flows of a process or a product system between the product system under investigation and one or more other product systems."

At the Äänekoski bioproduct mill, due to the efficient process control in the use of material and energy flows, a significant surplus amount of energy (heat and electricity) is produced during pulp production as by-product. The referenced technology represents the average pulp mills in Europe and Latin America that generate lower amounts of surplus energy as by-product during pulp production. By this, the surplus produced electricity and industrial heat from pulp production will be allocated as by-product.

[redacted]

Figure 02: Based on the mass of used feedstock wood [mass % wood] the partition of wood between pulp and energy produced is shown, marked in orange colour.

The allocation of wood raw material to the main- and by-products is done related to the mass of the wood. Figure 02 shows the partition of wood material into main product ADMT pulp ([redacted] mass % wood), and the wood mass used for heat production in the recovery boiler ([redacted] mass % wood) to
win the energy needed for pulp mill operation, within the by-products "Heat sold out" (from [redacted] mass % wood) and "Electricity sold out" (from [redacted] mass% Wood), as Figure 02 shows.

[redacted]

Figure 03: Based on the mass of used feedstock wood [mass % wood] the allocation between pulp "ADMT out" and the by-products "Heat out" and "Electricity out" is shown, marked in orange colour, printed bold. As second allocation method the heat and electricity energy are weighted by a quality index (Percentage of exergy), marked in green colour, printed bold.

Related to the shares of wood mass used for heat and for electricity, the quality of exergy (Wall, 1977) was used to give a second rule for allocation to exergy quality of the by-products. The exergy for wood as biomass is hereby set to 95, because potential heat energy in wood mainly stems from sun light so, for electricity in this system, the exergy is set to maximum 95. For heat energy, the exergy quality is set to 30 as it is usable for industrial heating (see Table 02).

	Form of energy	Quality index (Percentage of exergy
Extra superior	Potential energy[1]	100
	Kinetic energy[2]	100
	Electrical energy	100
Superior	Nuclear energy[3]	Almost 100
	Sunlight	93
	Chemical energy[4]	95
	Hot steam	60
	District heating	30
Inferior	Waste heat	5
Valueless	Heat radiation from the earth	0

[1] e.g. highly situated water resources
[2] e.g. waterfalls
[3] e.g. the energy in nuclear fuel
[4] e.g. oil, coal, gas or peat

Table 02: The quality of different forms of exergy, following (Wall, 1977).

In addition to the allocation according to mass and exergy, a third allocation method, the economic allocation, was defined to obtain robust results for the informative value of the modeling in a sensitivity analysis.
In economic allocation 1,00 €/kg was defined for the main product pulp, and the economic value of 0,40 €/kWh was defined for the by-product electricity, and 0,10 €/kWh for the by-product heat.

The allocation model Allocation at Point Of Substitution (APOS) is used in secondary data (ecoinvent, 2021) to reflect influences from cascadic organised production processes like the production and delivery of chemical agents for pulping. In such cascadic organised production processes, the state of the art of by-products or useful waste materials is technologically embedded. The point of substitution describes the point where upgrade by-products or waste materials take place, and where the environmental burdens from the initiating production process are taken to account.
APOS model can be seen as a conservative approach because, instead of cut-off, the environmental burdens from the initial production process that burden by-products are more realistically distributed to the processes under investigation.

1.2.7 The methods for impact assessment and the impact categories

The selection of environmental impact categories for the environmental assessment in the present study is based on European Union Environmental Footprint methods (Kommission, 2021), (Zampori L., Suggestions for updating the Product Environmental Footprint (PEF) method, 2019). Impact categories showing different robustness factors under the focus of reliability of assessment.

This is based on the high sensitivity and complexity of matter and the actual state of science. Robustness I is meaning as recommended and satisfactorily high. Robustness II means recommended but needs improvement, and Robustness III means a recommended impact indicator but with results to be used cautiously with the current given methods for this study.

The up-to-date environmental footprint Version 3.0 is used in this assessment.

The following environmental impact categories and impact indicators, described in the associated characterization models (Zampori L., Suggestions for updating the Product Environmental Footprint (PEF) method, 2019), are considered in this study:

The impact category **Climate Change** is expressed in kg CO_2 equivalents and expresses the radiative forcing of all relevant greenhouse gases such as methane, laughing gas and others that are released in the analysed artificial processes. The actual known numbers for radiative forcing in the Earth's atmosphere related to relevant time horizons 25, 100 and infinite years stem from periodical reports by the Intergovernmental Panel on Climate Change (IPCC). In this study, the 100-year time horizon is expressed as CO_2 equivalent per functional unit. Robustness factor I means the most reliable analysis.

In this study, the Impact category **Ozone Depletion Potential** is expressed in kg CFC-11-equivalents of ozone layer-depleting molecules like nitrous oxide and hydrocarbons, which are strongly related to summertime circulations in the southern hemisphere of the Earth, observed by the World Meteorological Organization (WMO). These molecules rise into the Stratosphere and are exposed to high UV energy, reacting catalytically to the decomposition of ozone molecules. Robustness factor I means the most reliable analysis.

Particulate Matter is fine dust described in the aerodynamic diameters of $PM_{0.2}$, $PM_{2.5}$ and PM_{10}, to reflect the complex mixture of organic and inorganic substances in fine dust. The distinction between primary and secondary PM provides information about the formation under natural conditions or induced by artificial activities. They are robust, measurable with particle counters and can be found indoors and outdoors with different retention times in the atmosphere. The characterisation model to describe the relation between PM and disease incidences was developed by the Society of Environmental Toxicology and Chemistry (SETAC) as a member of UN Environmental Programme (UNEP). The disease incidence is the unit in this indicator for environmental impact related to diseases caused by PM concentrations (disease incidences/kg $PM_{2.5}$) because the impact of $PM_{2.5}$ on human health was well understood. Robustness factor I means the most reliable analysis.

Acidification is mainly caused by air emissions of nitrogen and sulphur compounds. The method of Accumulated Exceedance (AE) (Seppälä, 2005) characterises critical loads, brought by acidifying substances on terrestrial areas and the main freshwater ecosystems. The acidification potential is expressed in mol H+-equivalent, and the unit for Accumulated Exceedance is brought into relation with the database for critical loads of geographical regions like Europe. The atmospheric transport and distribution of acidifying pollutants are determined by the actual EMEP Eulerian atmospheric dispersion model and used as basis for updating the AE method (Posch, 2008). Robustness factor II describes the recommendation of the impact indicator and indicates the need for improvement of this impact indicator to reach a satisfactory level.

Eutrophication of land areas and fresh and salt waters is significantly induced by N and P inputs. Eutrophication of land areas is expressed in Accumulated Exceedance (AE), while nutrient inputs to water bodies are indicated as mass-based equivalents of P and N. Robustness factor II describes the recommendation of the impact indicator and indicates the need for improvement of this impact indicator to reach a satisfactory level.

Land use as an impact category uses the four most significant parameters of soil quality: Biotic production [kg], Erosion Resistance [kg Soil], Mechanical Filtration [m^3 Water], and Recharge Groundwater [m^3 Groundwater] to describe functions of land in its different expressions. The Soil Quality Index (SQI) (Valeria De Laurentiis, 2019) is actual method to aggregate the parameters of soil quality mathematical linear, for mapping the soil quality on regional landscapes and derive soil quality description with dimensionless unit in points (pt). The reference model used in EF 3.0 is LANd use indicator value CAlculation (LANCA®) within the LANCA characterisation factors (Ulrike Bos, 2016). The unit is dimensionless points (pt). The robustness factor III describes the recommendation of the impact description, but the results should be interpreted cautiously in this analysis.

Emissions of **Ionising radiation** are indicated in unit kBq^{U235} -equivalent. The model of Human Health Effects developed by (Dreicer, 1995) is used to reference the effects of different known sources for ionising radiation in relation to health effects from Uran 235. Emitting sources of ionising radiation to water is focused (due to cooling water cycles in nuclear power plants), whereas emissions to higher stacks of the atmosphere are neglected. Robustness factor II describes the recommendation of the impact indicator and indicates the need for improvement of this impact indicator to reach satisfactory level.

Photochemical ozone formation reflects the potential of increasing tropospheric ozone (also known as “summer smog”) by atmospheric chemistry to emissions of precursor substances NO_x or NMVOC. The indicator is expressed in mass of Non-Methane Volatile Organic Compound -equivalent (g NMVOC-eq). Robustness factor II describes the recommendation of the impact indicator and indicates the need for improvement of this impact indicator to reach satisfactory level.

The two Impact Categories **Human Toxicity** – carcinogenic and Human Toxicity – non-carcinogenic are both expressed in Comparative Toxic Unit for Human Health (CTUh). This impact category uses as reference model the USEtox2.1-model updated by (Saouter, 2017) as a scientific consensus model, in its development fostered by UNEP-SETAC and recommended by the European Commission (EC) to be used as assessment method for toxicities in EF 3.0. Robustness factor III describes the recommendation of the impact indicator, but the results should be interpreted cautiously in this analysis.

Ecotoxicity is under ongoing study with regards to the toxic effects of organic substances on living organisms in the water column. For the assessment of inorganic and metallic substances, characterisation factors agreed with the emitting industry are used. Ecotoxicity is expressed in Comparative Toxic Unit for ecosystems (CTUe). Robustness factor III describes the recommendation of the impact indicator in EF 3.0, but the results should be interpreted cautiously in this analysis.

The use of mineral and metallic resources, as well as energy resources, is shown as **Abiotic Resource Depletion** (ADP). Mineral and metallic resources are shown as Sb-equivalent per kg extraction, and energetic resources as MJ-equivalent. Robustness factor III describes the recommendation of the impact indicator, but the results should be interpreted cautiously in this analysis.

For the investigation of the impacts of forestry on **biodiversity** in the forest and plantation areas from which the raw material wood for pulp production is sourced, the methods architecture to estimate the Biodiversity Increment (BVI) according to (Lindner, Fehrenbach, Winter, Bloemer, & Knuepffer, Valuing Biodiversity in Life Cycle Impact Assessment, 2019) was used. The method architecture describes a hemeroby based approach, using fuzzy thinking to bring activities of land use in relation to biodiversity value.
"In summary, the model proposes assessing biodiversity by subdividing it into individual parameters, defining their relationships, and calculating their respective biodiversity contributions." The method derives a quality of influencing biodiversity, that can be brought via area*time into accountability for LCA in form of BVI/FU. BVI is not implemented in EF 3.0, and because of this without a robustness factor.

Water use assesses potential water deprivation for humans and/or ecosytems in relation to activities under study. It is assumed, that shrinking water availability will cause deprivation in the region under study. The original reference model Available Water Remaining per area (AWARE) calculates the water Availability Minus the Demand (AMD) of humans and ecosystems for region-specific watersheds using three parameters [m^3], [m^2] and, [month] as description. Normalising with world average AMD gives value results that indicate surface-time equivalent to generate unused water, which means the time needed to end deprivation for the following uses of water in the region under study. AMD is set in relation to the geographical region (including the temporal volatility of water supply over relevant time horizons, e.g. season) and the type of use (agriculture or industry) in order to indicate potential overexploitation of regional water resources by specific AWARE factors. It must be noted that, for EF 3.0, only the adoption in country scale is recommended, using default CF averaged over space and time, for reasons of applicability. Under assessment is only blue water consumption where consumption is defined as the difference between the withdrawal and release of blue water. Green water, rainwater, seawater and fossil ground water are not characterised in AWARE factors. The expressed unit is m^3 world equivalent. Robustness factor III describes the recommendation of the impact indicator, but the results should be interpreted cautiously in this analysis.

Impact categories within their impact indicators and units, the underlying characterisation model and, robustness level listed in Table 03.

EF 3.0 Impact category	Impact category	Unit of impact indicator	Characterization model	Robust-ness level
Climate change	Radiative forcing as global warming potential (GWP100a)	kg CO_2- equivalent	IPCC reference model of 100 years (based on IPCC 2013).	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11- equivalent	Ozone depletion potential at steady state as in (WMO 2014 + integrations)	I
Particulate matter	Effects on human health	desease incidence	Fine dust model (Fantke et al., 2016 in UNEP 2016)	I
Acidification	Accumulated Exceedance (AE)	mol H+- equivalent	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	II
Eutrophication, land (terrestrial)	Accumulated Exceedance (AE)	mol N-equivalent	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	II
Eutrophication, inland water (fresh water)	Nutrient fraction entering the freshwater end compartment. (P)	kg P-equivalent	EUTREND-model (Struijs et al., 2009), implemented in ReCiPe	II
Euthrophication, sea (marine)	Nutrient fraction entering the seawater end compartment. (N)	kg N-equivalent	EUTREND-model (Struijs et al., 2009), implemented in ReCiPe	II
ionizing radiation, human health	Efficiency of human exposure to U^{235}	kBq U^{235} - equivalent	model of human health effects developed by Dreicer et al. 1995 (Frischknecht et al., 2000)	II
Photochemical formation of ozone, human health	Increase in the concentration of tropospheric ozone	kg NMVOC equivalent	LOTOS-EUROSmodel (Van Zelm et al., 2008), implemented in ReCiPe 2008	II
Ecotoxicity, fresh water	Toxicity comparison unit for ecosystems (CTUe)	CTUe	USEtox-model 2.1 (Fankte et al., 2017) adopted like in Saouter et al., 2018	III
Human toxicity, carcinogenic	Toxicity comparison unit for humans (CTU_h)	CTUh	USEtox-model 2.1 (Fankte et al., 2017) adopted as in Saouter et al., 2018	III
Human toxicity, non-carcinogenic	Toxicity comparison unit for humans (CTU_h)	CTUh	USEtox-model 2.1 (Fankte et al., 2017) adopted as in Saouter et al., 2018	III
Land use	Soil Quality Index (SQI)	Dimensionless (pt)	Soil quality index aggregates the four significant soil qualities (Biotic production, Erosion resistance, Mechanical filtration, and Recharge groundwater) based on LANCA model (DeLaurentiis et al., 2019) and LANCA characterisation factor version 2.5 (Horn and Maer, 2018)	III
	Biotic production	kg biotic production		
	Erosion resistance	kg Soil		
	Mechanical filtration	m^3 Water		
	Groundwater regeneration	m^3 Ground water		
Resource utilization, minerals and metals	Abiotic ressource depletion (ADP)	kg Sb-equivalent	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002	III
Resource utilization, fossil	Abiotic ressource depletion – fossile (ADP)	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002	III
Water use	Water deprivation potential of users (water consumption weighted by deprivation).	m^3 World equivalent	Remaining available water (AWARE-model) (Boulay rt al., 2018; UNEP 2016)	III
Not part of EF 3.0, but used in study	**Impact description**	**Unit of impact**	**Characterisation model**	
Biodiversity	Biodiversity Value Increment	BVI/FU	(Lindner, Fehrenbach, Winter, Bloemer, & Knuepffer, Valuing Biodiversity in Life Cycle Impact Assessment, 2019)	n.n.

Table 03: List of used Impact categories, units, literature sources and indication of robustness. In addition to impact categories of EF 3.0 here also the Biodiversity Increment is listed, for additional investigation in this study.

Recommendations given by UBA (Schmitz, 1999) are coherent with the impact indicators listed here and in principle the same impact categories.

Differences between the EF3.0 and the UBA set of impact categories can be found in water eutrophication, where UBA combines sea and freshwater eutrophication in one.

The selected categories use scientific methods and find widespread application in life cycle assessments.
The scientific methods use models, some of which rely on assumptions, to analyse the complex interrelationships of environmental impacts. By analysing overall interrelationships that take to account several categories (multi-criteria), plausibility checks become possible and thus the analysis of complex environmental impacts is methodologically validated.
However, it must be kept in mind that an impact assessment does not provide any directly applicable predictions of environmental impacts, such as concrete threshold value exceedances, or actual hazards from the use of the production systems under consideration.

1.2.8 The data types and sources

The main requirement of data is the valid representation of a whole year of production from all used systems within the system boundary, which describes the minimum length of time over which data should be collected.

The production year should be determined in a period without irregularities, as for instance pandemic situations, in the economic sector.

Data for raw material of wood and data for pulp processing should be stemming from same geographical region.

As bleaching technology is marginally represented in the aggregated secondary dataset that will be usable for modelling average pulp production, the secondary dataset will represent the major used bleaching method (what today is ECF) of the average bleaching technology.

Primary data of input, output and emissions should show no significant variances, if the data stems from a period without irregularities in the economic sector.

If primary data on emissions is not available, the emission of average secondary data from state of the art should be used for study.

Completeness seems to be given, when all elementary inputs, outputs, and emissions for processes within the system boundaries are given as primary or secondary data.

Consistency will be achieved by handling all primary and secondary data under same principles, meaning allocation procedures, impact categories, and the system boundary.

Reproducibility is achieved, within the complete information to data, methodologies, and results in this study.

Primary data related to processing at Äänekoski bioproduct mill have been given by the client of the study. Data related to the practice of forest management originate from Metsä Cooperative in the form of personal interviews with a representative from Metsä Forest and statistical data from Luke, Finland. All secondary data related to background, forest management, chemical agents and pulp processing by the averaged pulp mills stem from the ecoinvent 3.8 database.

As secondary data in ecoinvent database is reviewed information from industry sectors, a high reliability is achieved.

Emission data from recovery boiler are in all models included in form of key emission factors from paper industry, because of mismatch of the emission of a black liquor boiler and wood chips combustion and because of a lack of appropriate approximation. The emissions of the recovery boiler are included in the measurements of key emission from pulp mills, and given in primary data for bioproduct mill Äänekoski to see listed at 2.1 Collection of data, and also in secondary data from ecoinvent 3.8 database for the average mills, that are investigated in this study.

1.2.9 Assumptions

It is assumed that long-term investments like a pulp mill and data from different decades are usable in the foreground system.
A study analysing the contribution of technology innovation to the pulp and paper sector and energy consumption and GHG emission savings until 2050 points out approaches for incremental upgrades of pulp mills (Moya, 2018). High-temperature recovery boilers (within the need for high-energy subsystems for combined power and heat production) and continuous digesters are two relevant BATs that offer the greatest opportunities for energy savings, coupled with an investment cost of EUR 860/tonne of pulp per year for high-temperature recovery boilers, and EUR 2190/tonne of pulp per year for continuous digesters. If all features are incorporated in high-temperature and high-pressure boiler design, the total power production of a pulp mill can increase by 16%.
ECF and TCF technologies are stable in use, without disruptive innovation or shifting the partition of one from both bleaching technologies in recent decades. In ecoinvent 3.8, neither ECF and the TCF are further distinguished, because of a comparable low number of actual existing TCF mills, it is assumed that the average mill datasets from ecoinvent 3.8 can be seen as ECF mills.

Data for material and energy flows, also emissions to environment, is in all four compared models for background systems chosen from secondary data base ecoinvent 3.8.
The infrastructure of the pulp mill is in all models that study the average mill set as the same unit, as it is given by the secondary data source of average pulp mills.

The secondary source for raw material wood is chosen in geographical relation to the pulp mill. As a form of forest management, the sustainability forest management is chosen in each model.
As reported (Group, Metsä Group sustainability Report 2021, 2022), Metsä practices the cascadic use of forests: timber for construction and trees with low diameter not usable for construction for pulping. To represent this in this study of secondary dataset of forest management in Sweden, the share of energy wood from thinning during the phase of growth in forest management is used for the feedstock of Äänekoski bioproduct mill, because this energy wood is stemming from thinning during the phase of growth.
The use of a secondary dataset for feedstock can be counted as a conservative assumption for the bioproduct mill at Äänekoski and, from interviews with the forest management in Metsä Group, the advanced level of forest management was reported to the practitioner of the LCA. This type of information´s will be separately studied in the biodiversity assessment (see 1.2.9).

It is assumed that emissions from black liquor burning are reflected by the key emission factors provided by the pulp industry in the secondary datasets (ecoinvent, 2021) of emissions from recovery boiler. At Äänekoski bioproduct mill the key emission factors SO_2, NO_x, PM and CO_2 were given for use in modelling.

The year of data collection for the ground-laying model of an average TCF sulphate pulp mill is dated 2007 by the authors in ecoinvent 2.2. (Hischier, 2007). For this reason, the Inventory was updated manually by implementing the datasets from ecoinvent 3.8 in the ground-laying model of a TCF sulphate pulp.
The year of data collection for averaged ECF sulphate pulp mill processing data is 2015, and a minimum of 20 pulp mills in northern Europe and Latin America were taken to account to display the average for both regions. The validity of secondary data of pulp mill processing is stated from 2017 to 2020.

The datasets are for pulp mills with active links to raw materials, so the most actual secondary data for forest management and chemical agents are used, as it is for the background data of transport and electricity in all four compared models.

1.2.10 Value choices and optional content

For the optional study of biodiversity using the hemeroby approach, published statistical data from Finnish forestry were prepared and cross-checked by interviews with experts from sustainability management in Metsäliitto Cooperative. A plausibility check of information obtained from interviews was done using forest account statistics from the Natural Resources Institute Finland, Luke.
For the Latin America-based average pulp mills, it was possible to link the geographical relation to the forest system via public relation literature (Bracell Ltd., 2021).

Following DIN EN ISO 14044 the evaluation optional uses three elements:

1. normalisation
2. order
3. weighting (not applicable in comparing studies DIN EN ISO 14040/44)

The element order is examined in this study. *Table 04* is showing two criteria: ecological thread, and distance to target. Both criteria are individual assessed in a ranking of 5 steps A to E, named as follows: A (very large); B (large), C (middle), D (small), and E (very small). Definition of criteria ecological thread and distance to target bases on Annex II of UBA given method (Schmitz, 1999).

The UBA method contains a further proposal for ordering by normalisation basis on the emission values of national economies. This ordering method is not applicable in the context of this study, as the production systems compared here, such as Brazilian cellulose production, supply very different markets in a global context.

impact category	ecological thread	distance to target	robustness level	ecological priority
climate change	A (very large)	A (very large)	I	Very large
ozone Depletion Potential	A (very large)	D (small)	I	Large
euthrophication (terrestrial)	B (large)	B (large)	II	Large
acidification	B (large)	B (large)	II	Large
potochemical ozone formation	D (small)	B (large)	II	Large
euthrophication (aquatic)	B (large)	C (middle)	II	Large
resource depletion (fossile)	C (middle)	B (large)	III	Large

Table 04: Grey scale to show “ecological priority”, based on definition of criteria “ecological thread”, and “distance to target”.

The assessment of each of the impact categories is done by equilibrated summed up to “ecological priority” of each of the criteria, recommended by UBA: Climate Change (very large priority); Eutrophication terrestrial (large priority); Acidification (large priority); Photochemical ozone formation (large priority); Eutrophication aquatic (large priority); Ozone Depletion Potential (middle priority). The qualitative description ecological priority will be used to bring normalized characterisation factors in a hierarchic order.

1.2.11 The constraints/limitations

Primary data was only available for the processing in the Äänekoski bioproduct mill. This mill displays the BAT and so for the three averaged types of pulp mill-systems secondary data from ecoinvent (ecoinvent, 2021) was used:

For the forest management of the boreal coniferous forests of Finland that are the source of raw material for pulp processes at the Äänekoski bioproduct mill, primary information is accessible for a biodiversity analysis (see 1.2.9). Unfortunately, no primary information for Western Europe and Latin America-based forest systems in local relation to pulp mills was available, so the assessment of biodiversity for the raw material of Western Europe based average pulp mills, and Latin American pulp mills uses secondary data.
All compared four systems use secondary data for the background system, which means ground laying data describing harvest efficiency of feedstock wood from forest, energy from the grid, and transport.
The compared four systems also using secondary data for forest management, chemical agents for pulping and bleaching, and for pulp mill construction.

Primary data available are only for the foreground systems of processing the material and energy flows at Äänekoski bioproduct mill, based on the statistical average production year 2021, in confidential annex.
Secondary data (ecoinvent, 2021) with stated validity for the period 1 January 2017 to 31 December 2020 are used for the referenced comparison systems, which represent the technical average in the European region and also the Latin American region of production (AISBL, 2017).

The transport of Latin American-produced pulp for further processing in Europe is constrained by the cradle-to-gate scope of study and is thus not counted.

The technological possible incremental innovation of average European and Latin American pulp mills is not taken to account in this assessment, because, unfortunately up to now, such innovations are not publicly available.

The limitation of different timeframes in the data of pulp mill processing between the bioproduct mill under study, which started in 2017, and the averaged pulp mills in Europe and Latin America with data counted from 2015, is not seen as a criterion for exclusion, because of the long operating time of pulp mills (on average 30 years), and in some cases far longer.

1.2.12 The data quality requirements

The primary data must give annual production that can be classified as average data for one year of production. Data collected during the operation of the plant must be statistically reliable and a representation of technology level, geographical region of pulp production and relation to time.
Secondary data must originate from a database version and period of time validity in order to ensure the standardisation of the background data. In this study, it is ecoinvent3.8 with included Environmental Footprint (EF) environmental impact factors version EF 3.0 for System model Allocation at the point of substitution, with validity till End of 2024.

If processes are available in previously issued versions of ecoinvent, the processes should be updated to secondary datasets of ecoinvent 3.8.

1.2.13 Uncertainties in data and parameters

Secondary data used in the study are subject to normal uncertainties, which can hardly be examined in a satisfactory way with mathematical - statistical methods regarding to error deviations because of regular done assumptions in average data. Therefore, a threshold for significance was set. The threshold for significance was set to at least 10% deviation between the results that are to compare in this LCA.

Publicly available data regarding the bioproduct mill Äänekoski (Metsä Group, 2022) and the forest management for eucalyptus in Brazil, region Bahia (Bracell Ltd., 2021) was used.

1.2.14 Type of critical review

The critical review aims to check the consistency of this study within the international standards for Life Cycle Assessment.

The critical review by a panel of interested parties is structured in two phases: reading and iterative reflection. The review is done by three external experts with backgrounds and relevant foci in Life Cycle assessment, following DIN CEN ISO TS 14071 / DIN SPEC 35803.

Access to all relevant information, data and models is given to the critical reviewer team.

1.2.15 Type and format of the report required for the study

The third-party report will be based on this study documentation containing confidential information. As a reference document available to any third party to whom the communication is made, the confidential information will be excluded, and the report will be structured as recommended in DIN EN ISO 14044.
To allow the reader to comprehend the inherent complexities and interdependencies, an LCA focus report will be derived from this study. By this, the interpretation of results should be usable in a manner consistent with the goals of the study.

2 Production systems under study

This study deals with the production of pulp from predominantly hardwood and softwood, bleached in the Elemental Chlorine Free (ECF) and Totally Chlorine Free (TCF) processes.

Four models were developed to enable the comparative analysis. The four models were considered in the "cradle to gate" system boundaries to map the comparison of environmental impacts from pulp production with TCF versus ECF bleaching methods in European state-of-the-art pulp mills and at bioproduct mill Äänekoski. Regarding differing feedstock, a Latin American average of pulp production with ECF bleaching on basis of eucalyptus is also considered.

The four models are as follows:

- model 01, Sulphate pulp (ECF), bioproduct mill Äänekoski
  Region Norther Europe, Finland
- model 02, Sulphate pulp (TCF), average EUR pulp mills
  Region Europe
- model 03, Sulphate pulp (ECF), average EUR pulp mills
  Region Europe
- model 04, Sulphate pulp (ECF), average RLA pulp mills
  Region Latin America, within Caribbean, Middle- and South America

The composition of hardwood and softwood in models 1 to 3 was considered in the production methods in equal mass ratios, to be comparable to the bioproduct mill where a typical production ratio for kraft pulp from virgin fibre consists of short Fibres, hardwood: 36 weight% and long fibres from softwood in 64 weight%. The datasets for both types of feedstock hard- and softwood describing forest systems in region Northern Europe.

Only model 4 contains 100 weight % hardwood from one species, eucalyptus, because the Latin America- based pulp mills uses no mixed ratios of wood type in feedstock.

The models examined are described below. The models using secondary data sets for processing chemical, energy from grid and feedstock wood. This secondary data sets including transport and raw material provision also as treatment of waste, allocated by APOS. The used secondary datasets are listed in Table 4.
In foreground system of all models used Bill of Material are described in Chapter 3.2. For model 01 primary data for the foreground system is available and in use (see chapter 3.1.5), that is provided by the client of this study. The data of foreground systems in all other models stemming from database ecoinvent (see Table 06).

2.1 model 01, bioproduct mill Äänekoski (ECF)

bioproduct mill Äänekoski processes hardwood and softwood from the geographical region around Äänekoski bioproduct mill, using a high proportion of wood from thinning. The main product is bleached pulp, although the Äänekoski bioproduct mill is fundamentally set up in such a way that other biobased products can be manufactured. Furthermore, the production facility is equipped with an effective recovery system for processing chemicals and energy, so that heat and electrical energy are generated as by-products on top to the own energy needed for pulp production.

The allocation of environmental impacts between pulp as the main product and the energetic by-products is related to the input mass of the raw material wood, see the methodology presented in chapter 1.2.4. Figure 04 shows the material and energy flow diagram for the Äänekoski bioproduct mill, as example for modern pulp mills.

2.2 model 02, average pulp mill Europe (TCF)

The model is based on the secondary data sets of the ecoinvent database, whereby the allocation of the energetic by-products is based on the APOS method (Allocation at Point Of Substitution).
The processed proportions of hardwood and softwood originate from surrounding regions, since in addition to pulp mills in Northern Europe, mills in Central Europe are also shown in the secondary data for pulp mills, wood from Germany is also used (*see Table 06*).

Due to the declining use of the TCF bleaching process in economic practice, a older secondary data set of ecoinvent 2.2 was used, via update to secondary data of ecoinvent 3.8. The updating procedure is described in chapter 3.1.6.

2.3 model 03, average pulp mill Europe (ECF)

The model is based on the secondary data sets of the ecoinvent database, see Table 04, whereby the allocation of the energetic by-products is based on the APOS method (Allocation at Point Of Substitution).
The processed proportions of hardwood and softwood originate from surrounding regions of represented pulp mills and by this wood from Region of Europe is used (see Table 06).

2.4 model 04 average Latin America based (ECF)

The model is based on the secondary data sets of the ecoinvent database, see Table 04, whereby the allocation of the energetic by-products is based on the APOS method (Allocation at Point Of Substitution).
The average pulp mill in the Latin America region processes a singular wood raw material eucalyptus, while all other models process a mixture of hardwood and softwood. The eucalyptus wood material used in the model comes from the

Brazil Minas Gerais (BR-MG) region. Since secondary data sets on eucalyptus cultivation are not available for all regions in Latin America, the BR-MG region of origin was chosen because its located in Eco Region of a pulp mill (Bracell Ltd., 2021) that is declared to be operating sustainably.

2.5 Flow chart of model 01

The flow chart shows the process steps of pulp production from virgin Fibres in a representative way for modern pulp mills.

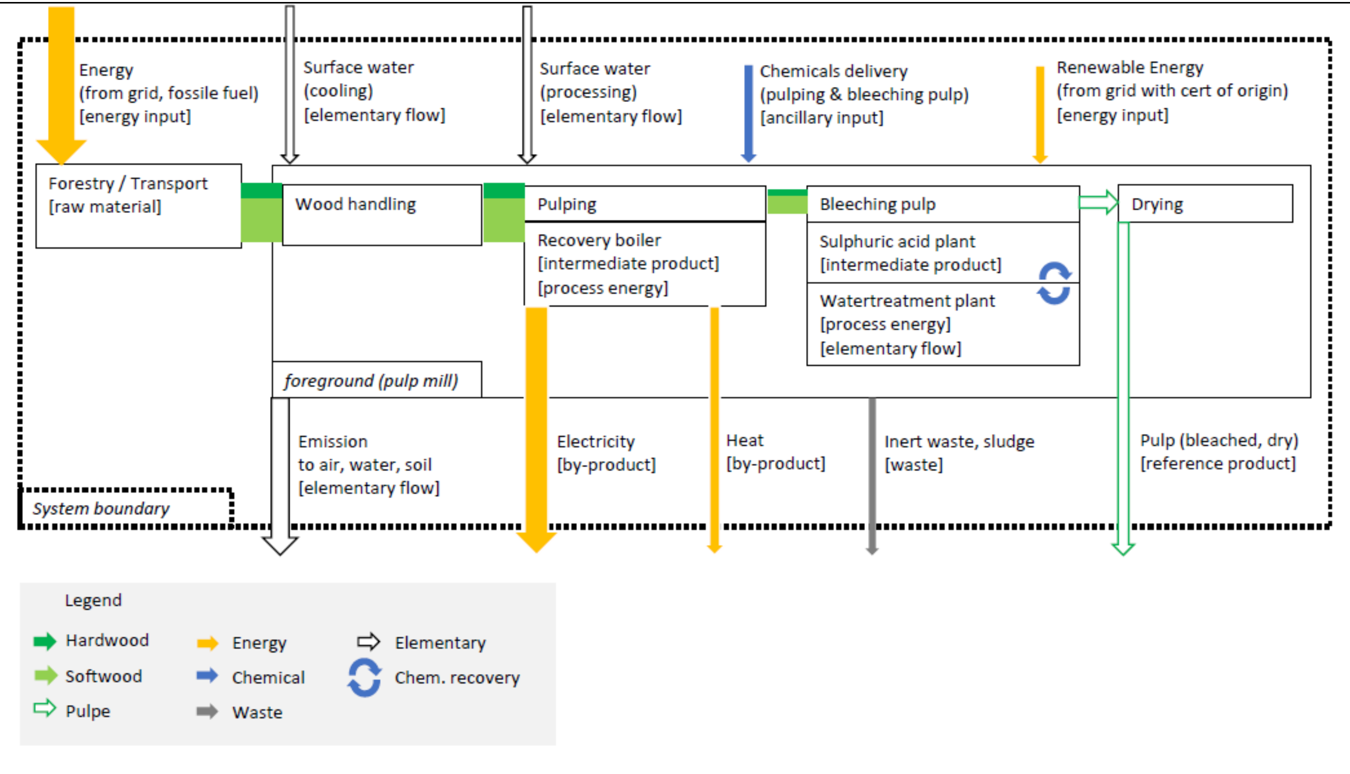


Figure 04: System boundary within material and energy flow.

The flow chart in Figure 04 marks out the mass and energy flow in Äänekoski bioproduct mill. The diameter of arrows illustrates the proportion of masses and energy flows. As elementary flow the process water of 18 m³/t inflow to Äänekoski bioproduct mill and is outlet after cleaning as wastewater. Cooling water is used also as elementary flow from surface water and be let out from the mill in not treated form.

2.6 Scenarios included

Representative baseline scenarios were balanced for the four models investigated order to map pulp production in the four specific systems. These base scenarios are defined in the descriptions of the models (see previous chapters).
Beyond the basic scenarios, sensitivity analyses were carried out to test the relevance of data sets and assumptions to the results. Parameters were

deliberately changed, in part fictitiously, in order gaining insights into the expected effects of changed parameters.

The following sensitivities were investigated:

- Sensitivity of the allocation methods in model 01
- Sensitivity of the AOX emissions in model 01

3 Life Cycle Inventory

To enable a transparent and comprehensible investigation, the data sources and methods of data collection are named and described.

3.1 Collection of data

At Äänekoski bioproduct mill, primary data on material and energy flows and emissions to environment were collected from the start of plant processing in 2017 when Äänekoski bioproduct mill started. Its first full year of production was 2018. The energy- and material flows and emissions were selected from 2021, as it was a representative year at Äänekoski bioproduct mill in terms of the foreground system. Directly related to the production year, the environmental emissions from the Äänekoski bioproduct mill measurement system were collected in 2021 following key emission factors:

- to air: dusts [Particulate Matter]; NOx [t]; SO2 [t]
- surface water: N [t]; P [t]; TSS [t]; AOX [t]; COD [t]
- to own landfill: non-hazardous waste [t]

Table 05 shows emissions from ECF bleaching in Best Available Technology (BAT) compared to regular averaged measurements in Äänekoski bioproduct mill over the year 2021 and values of a single measurement in May 2022.

Parameter	Bleached pulp BAT- AEL	Äänekoski Bioproductmill average 2021	Äänekoski wastewater measurement Fresenius May 2022
Waste water flow m³/t	25 – 50	18.4	16.3
Total suspended solids kg/t	0.3–1.5	0.27	Not measured in 2022
COD_{Cr} kg/t	7–20	6.5	4.9
Total phosphorus kg/t	0.01–0.03	0.005	0.002
Total nitrogen kg/t	0.05–0.25	0.05	0.05
AOX kg/t	0–0.2	0.11	0.087

Table 05: Emission values from ECF average technology in comparison with Äänekoski mill showing values significant below the emissions from ECF average pulp mills for the reference year 2021.

The data for average pulp production in European and Latin American pulp representing the average of input and output flows and emissions for state-of-the-art pulp mills. So at least 30% of the pulp mills of each world region under investigation should be covered, within data from a whole year of production.

The data for raw material production (wood) for use in European and Latin American pulp should represent the average input and output flows and emissions for wood production. The geographical frame of wood production should allow a plausible relation with the pulp mill. Wood production should reflect a yearly production rate in forests under investigation.

For studying biodiversity in forests used for pulp production, detailed primary data on forestry are required. Such operational data on forestry must be requested from regional forestry management directly related to location of pulp mills, to ensure reliable data quality.
The level of detail, required for biodiversity studies, should enable a complete description of forest biomes in regions under study.

In background systems, secondary data from databases in System model Allocation at the point of substitution (APOS) (ecoinvent, 2021) were taken to represent forest feedstock, transport and chemical supply. For the representation of comparable systems, the elemental and material and energy fluxes of the average European and Latin American pulp mills were taken from literature as secondary data, averaged over longer timelines (ecoinvent 3.8), also APOS allocated by products of electricity and thermal energy.

In the foreground system of Äänekoski bioproduct mill the allocation is done by mass based allocation of wood-material, and is described in 1.2.4 allocation procedures.

	Input	01 ECF Äänekoski	02 TCF EUR average	03 ECF EUR average	04 ECF BR average
1	**Forest HW (Hard Wood)** data from 2015, with validity statet for upcoming years, 2017-2020, ecoinvent 3.8	Hardwood forestry, birch, sustainable forest management, [SE]	Hardwood forestry, birch, sustainable forest management, [SE]	Hardwood forestry, birch, sustainable forest management, [SE]	
2				Market for wood chips, dry, measured as dry mass [RER]	
3					Hardwood forestry, eucalyptus ssp., sustainable forest management [BR-MG]
4	**Forest SW (Soft Wood)** data from 2015, with validity statet for upcoming years, 2017-2020, ecoinvent 3.8	Softwood forestry, pine, sustainable forest management, [SE]	Softwood forestry, pine, sustainable forest management, [SE]	Softwood forestry, pine, sustainable forest management, [SE]	
5			Softwood forestry, pine, sustainable forest management, [DE]		
6			Softwood forestry, spruce, sustainable forest management, [SE]	Softwood forestry, spruce, sustainable forest management, [SE]	
7				Market for residual softwood, wet [RER]	
8	**Mixed Wood** data from 2015, with validity statet for upcoming years, 2017-2020, ecoinvent 3.8			Market for wood chips, dry, measured as dry mass [RER]	
	Input	**01 ECF Äänekoski**	**02 TCF EUR average**	**03 ECF EUR average**	**04 ECF BR average**

	Input	01 ECF Äänekoski	02 TCF EUR average	03 ECF EUR average	04 ECF BR average
9	**Transport of Wood** background data, ecoinvent 3.8	Market for transport freight, lorry, >32 metricton EURO5 [RER]	Market for transport freight, lorry, 16-32 metricton EURO5 [RER]	Market for transport freight, lorry, >32 metricton EURO5 [RER]	Market for transport freight, lorry, >32 metricton EURO5 [BR]
10		Market group for transport, freight train [RER]	Market group for transport, freight train [DE]	Market group for transport, freight train [RER]	Market group for transport, freight train [RoW]
11				Market for transport, freight, sea, bulk carrier for dry goods [GLO]	Market for transport, freight, sea, bulk carrier for dry goods [GLO]
12				Market for transport freight, inland waterways, barge [RER]	Market for transport freight, inland waterways, barge [RoW]
13	**Chemicals** background data, ecoinvent 3.8	Market for methanol from biomass [CH]		Market for methanol from biomass [CH]	
14		Market for sulfuric acid [RER]	sulfuric acid production [RER]	Market for sulfuric acid [RER]	Market for sulfuric acid [RoW]
15		Market for sodium hydroxide, without water in 50% solution state [GLO]	Market for sodium hydroxide, without water in 50% solution state [GLO]	Market for sodium hydroxide, without water in 50% solution state [GLO	Market for sodium hydroxide, without water in 50% solution state [GLO]
16		Market for quicklime, milled, loose [CH]	Quicklime production, milled, loose [CH]	Market for quicklime, milled, loose [CH]	Market for quicklime, milled, loose [RoW]
17				Market for calcium carbonate, precipitated [RER]	Market for calcium carbonate, precipitated [RoW]
18		Ethylene glycol production [RER]			
19		Market for sodium chlorate powder [RER]		Market for sodium chlorate powder [RER]	Market for sodium chlorate powder [RoW]
20		Carbon dioxide production, liquid [RER]	Carbon dioxide production, liquid [RER]		
21		Market for oxygen, liquid [RER]	Market for oxygen, liquid [RER]	Market for oxygen, liquid [RER]	Market for oxygen, liquid [RoW]
22		Market for malusil [GLO]	Malusil production [RER]	Market for malusil [GLO]	Market for malusil [GLO]
23		Market for magnesium sulfate [GLO]	Magnesium sulfate production [RER]	Market for magnesium sulfate [GLO]	Market for magnesium sulfate [GLO]
24		Market for hydrogen peroxide without water in 50% solution state [RER]	Hydrogen peroxide productionin 50% solution state [RER]	Market for hydrogen peroxide without water in 50% solution state [RER]	Market for hydrogen peroxide without water in 50% solution state [RoW]
25		Market for trichloroacetic acid [RER]			
26			Ozone production, liquid [RER]		Market for Ozone, liquid [RoW]
27			EDTA production [RER]	Market for EDTA [GLO]	
28			Market for sulfur dioxide, liquid [RER]	Market for sulfur dioxide, liquid [RER]	
29			Inorganic nitrogen fertilizer, as N to generic market for organic fertilizer an N [GLO]		

		01 ECF Äänekoski	02 TCF EUR average	03 ECF EUR average	04 ECF BR average
30				Market for sodium sulfate anhydride [RER]	Market for sodium sulfate anhydride [RoW]
31				Market for sodium formate [RER]	
32				Market for sand [CH]	
33				Market for chemical, organic [GLO]	Market for chemical, organic [GLO]
34					Market for chemical, inorganic [GLO]
35					Market for Sulfur [GLO]
36					Market for sodium hypochlorite, without water in 15% solution state [RoW]
37					Market for magnesium oxide [GLO]
38					Market for hydrogen peroxide without water in 50% solution state [RoW]
39					Market for hydrochloric acid, without water in 30% solution state [RoW]
40					Market for chlorine dioxide [RoW]
41					Market for aluminium sulfate powder [RoW]
42	**Transport Chemicals** ecoinvent 3.8	Within the market dataset in chemicals		Within the market dataset in chemicals	Within the market dataset in chemicals
43	**Electricity** background data, ecoinvent 3.8	Electricity, high voltage, renewable energy products [CH]	Market for electricict, medium voltage [SE]	Market group for electricity, high voltage [RER]	Market group for electricity, high voltage [RLA]
44			Market for electricict, medium voltage [RER]		
45	**Fuels (fossile)** background data, ecoinvent 3.8		Heavy fuel oil production, petroleum refiniery operation [Europe without switzerland]	Marked group for heavy fuel oil [RER	Market for heavy fuel oil [CO]
46					Market for heavy fuel oil [BR]
47					Market for diesel [PE]
48					Market for diesel [BR]
49					Market for diesel [CO]
50				Market group for light fuel oil [RER]	Market for light fuel oil [PE]
51					Market for light fuel oil [BR]
		01 ECF Äänekoski	**02 TCF EUR average**	**03 ECF EUR average**	**04 ECF BR average**

		01 ECF Äänekoski	02 TCF EUR average	03 ECF EUR average	04 ECF BR average
52			Hard coal mine operation and hard coal preparation [Europe, without Russia and Turkey]		
53			Natural gas production, high pressure, vehicle grade [RoW]	Market for natural gas production, high pressure [CH]	Market for natural gas production, high pressure [BR]
54	**Pulp mill infrastructure** background data, ecoinvent 3.8	Pulp factory construction [RER]	Pulp factory construction [RER]	Pulp factory construction [RER]	Market for pulp factory [RoW]
55	**Pulping process** different sources	Sulfate pulp production , from hardwood, bleached [RER] (ecoinvent 3.8) updated with primary data (metsä production year 2021)	ecoinvent 2.2 updated by change of input-data ecoinvent 3.8	Sulfate pulp production, from hardwood, bleached [RER] ecoinvent 3.8	Sulfate pulp production, from eucalyptus, bleached [RLA] ecoinvent 3.8
		Sulfate pulp production , from softwood, bleached [RER] (ecoinvent 3.8) updated with primary data (metsä production year 2021)		Sulfate pulp production, from softwood, bleached [RER] ecoinvent 3.8	
	Input	**01 ECF Äänekoski**	**02 TCF EUR average**	**03 ECF EUR average**	**04 ECF BR average**

Table 06: Datasets from ecoinvent 3.8, that are implemented in the four models under study.

In chapter 2.2.2 Bill Of Materials can be found the physical values for the used datasets in all four models. The BOM uses same names of substances and flows as in Table 04 the name of the Datasets.

3.1.1 Wood provision from forestry for bioproduct mill Äänekoski

Following listed dataset represents the wood provision for bioproduct mill Äänekoski in data quality of ecoinvent 3.8 and was thereby chosen for this study.

The dataset softwood forestry, pine, Sweden and Dataset softwood forestry, spruce, Sweden is taken from a secondary dataset (ecoinvent, 2021).

The dataset hardwood forestry, birch, Sweden is taken from a secondary dataset (ecoinvent, 2021).

In key factors needed for assessment of biodiversity, this dataset shows correlation with the results of interviews and research regarding forest management in Metsäliitto Cooperative in Finland.

3.1.2 Wood provision from forestry for average european TCF sulphate pulp mill

Following listed dataset represents the wood provision for European pulp Industry in data quality of ecoinvent 3.8 (ecoinvent, 2021) and was thereby chosen for this study.

- The sort of wood and region of origin is taken over from ecoinvent 2.2 dataset for TCF pulp mill.
- The dataset softwood forestry, pine, Germany is from ecoinvent 3.8.
- The dataset softwood forestry, pine, Sweden and Dataset softwood forestry, spruce, Sweden is taken from a secondary dataset ecoinvent 3.8.
- The dataset hardwood forestry, birch, Sweden is from ecoinvent 3.8.

3.1.3 Wood provision from forestry for average european ECF sulphate pulp mill

Following listed dataset represents the wood provision for European pulp industry in data quality of ecoinvent 3.8 (ecoinvent, 2021) and was thereby chosen for this study.

- Dataset softwood forestry, pine, Sweden and Dataset softwood forestry, spruce, Sweden are token from secondary data set ecoinvent 3.8.
- The data set hardwood forestry, birch, Sweden are from ecoinvent 3.8.
- The data set residual softwood, wet, Europe are from ecoinvent 3.8
- The data set market for wood chips, dry, Europe are from ecoinvent 3.8.

3.1.4 Wood provision from forestry for average latin american ECF sulphate pulp mill

This dataset represents the eucalyptus production in Latin America in data quality of ecoinvent 3.8 (ecoinvent, 2021) and was thereby chosen for this study.

- The dataset hardwood forestry, eucalyptus ssp., Latin America is taken from secondary dataset ecoinvent 3.8.

3.1.5 ECF sulphate pulp from bioproduct mill Äänekoski

The production of sulphate pulp at the Äänekoski bioproduct mill is represented based on primary data from Metsä Group as foreground data. As this primary data only gives the amount and values of used raw material, transport, energy, chemicals, water and emissions from processing, they are coupled with the existing dataset

- ECF sulphate pulp obtained from Northern European softwood and hardwood, taken from secondary dataset (ecoinvent 3.8, 2021).

This dataset is in detail adopted to the recipe of the bioproduct mill Äänekoski for production of sulphate pulp. The data sources for the background system, such as for externally supplied energy from renewable resources (certificates of origin for electricity from renewables produced in bio product mill are devaluated by the bioproduct mill) and chemicals for pulping and bleaching from European market, also taken from the ecoinvent 3.8 database (see Table 06).

Model type APOS is used to reflect the complex industrial processes like the production and delivery of chemical agents in pulping. The primary data given by Äänekoski bioproduct mill are in Appendix A. An excerpt of the primary data is shown in Table 07, whereby the data from reference year 2021 is used in model.

Input (Äänekoski)	2018	2019	2020	**2021**
HW logs [fresh m³ sob]	[redacted]	[redacted]	[redacted]	[redacted]
SW logs [fresh m³ sob]	[redacted]	[redacted]	[redacted]	[redacted]
SW chips [fresh m³]	[redacted]	[redacted]	[redacted]	[redacted]
Out (Äänekoski)	2018	2019	2020	**2021**
Pulp [ADMT]	[redacted]	[redacted]	[redacted]	[redacted]
Surplus [MWh el]	[redacted]	[redacted]	[redacted]	[redacted]
Surplus [MWh th]	[redacted]	[redacted]	[redacted]	[redacted]

Table 07: Input of Biomass and output of pulp and by products electricity and heat, over the years from start production to reference year 2021 of bioproduct mill Äänekoski.

Specific to Äänekoski bioproduct mill is the use of alternative wood sources, as there are: sawmill from wood handling for construction industry, and thin diameter trees that are not usable for construction, because of the cascadic use of wood (Group, 2022). In Metsä Group, timber and logs are used for products in construction (beams, etc.). To reflect this cascadic use of wood, and to count for main use of wood from thinning activities for pulp making in bioproduct mill Äänekoski, in this study the share energy wood from forest management Sweden is used as secondary data (ecoinvent, 2021), because of wood from thinning activities is used as so called energy wood.

- Dataset softwood forestry, pine, Sweden and Dataset softwood forestry, spruce, Sweden are token from secondary data set (ecoinvent, 2021).

- The data set hardwood forestry, birch, Sweden are from (ecoinvent, 2021).

A detailed Bill of Material for production year 2021 is in the annex under disclosure.

3.1.6 TCF sulphate pulp from average European pulpmill

TCF sulphate pulp production in Region Europe is based on

- TCF Sulphate pulp production, from softwood, bleached, Europe (ecoinvent 2.2)

and has been updated to current secondary data from the ecoinvent 3.8 database (see Table 06).

The update was in cooperation with IFU-institute Hamburg, provider of the Umberto NXT software for LCA. The Dataset was opened and all ecoinvent 2.2 based datasets are substituted by ecoinvent 3.8 dataset. Mass- and energy flows where hold on same values and the type of emissions where not changed. Since the ecoinvent 3.8 gives no single dataset for:

  - disposal, treatment of green liquor,
  - disposal, hazardous waste,
  - disposal, limestone residual,
  - disposal, municipal waste and,
  - disposal, wood ash in a pulp mill,

this datasets was not updated, and all from ecoinvent 2.2 given emissions from pulp mill operating are let in values from original dataset from Econinvent 2.2. All substituted datasets are listed in Table 06.

As the dataset description shows, in TCF mills energy sufficiency is reached with negligible surplus only in heat energy (Hischier, 2007). For this reason, no by-products from TCF dataset are given. This model is carried out without by-products.

3.1.7 ECF sulphate pulp from average European pulp mill

ECF Sulphate pulp at an average European pulp mill is based on (ecoinvent, 2021)

- Sulphate pulp production, from softwood, bleached, Europe ecoinvent 3.8.
- Sulphate pulp production, from hardwood, bleached, Europe ecoinvent 3.8.

model type APOS is used to reflect the complex industrial processes like the production and delivery of chemical agents in pulping, in the study.

3.1.8 ECF sulphate pulp from average Latin American pulp mill

ECF sulphate pulp production in Region Latin America is based on (ecoinvent, 2021)

- Sulphate pulp production, from hardwood, bleached, Latin America, ecoinvent 3.8.

model type APOS is used to also bring by-products from the given dataset into the study.

3.2 Bill of Materials

In confidential appendix are all input and output Tables of all models to find. To give a comprehensible view for comparison of the four models here listed are the bill of materials in Table 08 till 11, please see below.
For model 01 Äänekoski bioproduct mill is a grey-scale code given, to mark out the stages of pulp cooking, and pulp bleaching. Cooking is white letters on black ground, and bleaching stage is marked by black letters on light grey ground. Grey ground signs on, that this input is used in both, cooking and also bleaching.

input model 01	**1kg HW/SW pulp**	
elec, high voltage renewable	[redacted]	kWh
water unspecific source	[redacted]	m³
cleft timber HW	[redacted]	kg
wood chips SW	[redacted]	kg
cleft timber SW	[redacted]	kg
transport train	[redacted]	t*km
transport lorry	[redacted]	t*km
pulp factory	[redacted]	unit
carbon dioxide liquid	[redacted]	kg
ethylene glycol	[redacted]	kg
quick lime milled loose	[redacted]	kg
sulfuric acid	[redacted]	kg
sodium hydroxide	[redacted]	kg
hydrogen peroxide	[redacted]	kg
magnesium sulfate	[redacted]	kg
malusil	[redacted]	kg
methanol from biomass	[redacted]	kg
oxigen liquid	[redacted]	kg
sodium chlorate powder	[redacted]	kg
trichloroacetic acid	[redacted]	kg
cooking		
cooking and bleaching		
bleaching		

Table 08: BOM of model 01, ECF bleaching in Äänekoski bioproduct mill.

Because the model 02 TCF bleaching EUR average pulp mill represents mills in different European countries, two electricity mixes, medium voltage are to find in the BOM. One also can find different sources of feedstock hardwood, in relation to the origin of the represented anonymised pulp mills with TCF bleaching. The place of origin from each of the used datasets can be found in Table 06.

input model 02	**1kg HW/SW pulp**	
electricity, medium voltage [SE]	0,04270000	kWh
electricity, medium voltage [RER]	0,05730000	kWh
heavy fuel oil	0,01030000	kg
hard coal	0,00508000	kg
natural gas, high pressure, vehicle grade	0,01192164	kg
Water, unspecified natural origin [natural resource/in water]	0,02100000	m3
Water, cooling, unspecified natural origin [natural resource/in water]	0,03600000	m3
pulpwood, hardwood, measured as solid wood under bark	0,00082000	m3
pulpwood, hardwood, measured as solid wood under bark	0,00061100	m3
pulpwood, softwood, measured as solid wood under bark	0,00297100	m3
transport, freight train	0,19800000	t*km
transport, freight, lorry 16-32 metric ton, EURO5	0,38700000	t*km
pulp factory	4,36E-11	unit
carbon dioxide, liquid	0,00200000	kg
EDTA, ethylenediaminetetraacetic acid	0,00300000	kg
hydrogen peroxide, without water, in 50% solution state	0,02640000	kg
magnesium sulfate	0,00360000	kg
malusil	0,00200000	kg
organic nitrogen fertiliser, as N	0,00020000	kg
oxygen, liquid	0,03700000	kg
ozone, liquid	0,00300000	kg
quicklime, milled, loose	0,01040000	kg
sodium hydroxide, without water, in 50% solution state	0,04000000	kg
sulfur dioxide, liquid	0,00600000	kg
sulfuric acid	0,02420000	kg

Table 09: BOM of model 02, TCF bleaching in average pulp mills in Europe.

Because the model 03 ECF bleaching EUR average pulp mill represents mills in different European countries, different sources of feedstock hardwood are to find in the BOM, related to the origin of the represented anonymised pulp mills in model. Also different sources of feedstock hardwood are to find, in relation to the origin of the represented anonymised pulp mills with ECF bleaching. The place of origin from each of the used datasets can be found in Table 06.

input model 03, ECF EU average	1kg HW/SW pulp (36/64)	unit
electricity, high voltage [RER]	0,0298139	kWh
heavy fuel oil [RER]	0,0073036	kg
light fuel oil [RER]	0,002507	kg
Water, unspecified natural origin [natural resource/in water]	0,0653586	m3
natural gas, high pressure [CH]	7,089E-05	m3
natural gas, high pressure [EUR without CH]	0,0109802	m3
pulpwood, hardwood, measured as solid wood under bark	0,0019653	m3
pulpwood, softwood, measured as solid wood under bark	0,0014735	m3
residual softwood, wet	8,208E-06	m3
wood chips, dry, measured as dry mass	0,3480691	kg
wood pellet, measured as dry mass	0,0051494	kg
residual softwood, wet	1,324E-05	m3
transport, freight, sea, bulk carrier for dry goods [GLO]	0,1722414	metric ton*km
transport, freight, inland waterways, barge [RER]	0,0355727	metric ton*km
transport, freight, lorry >32 metric ton, EURO5 [RER]	0,2687496	metric ton*km
transport, freight train [RER]	0,3167541	metric ton*km
pulp factory	4,358E-11	unit
sodium chlorate, powder	0,011428	kg
sodium hypochlorite, without water, in 15% solution state	0,0001355	kg
sodium hydroxide, without water, in 50% solution state	0,022892	kg
sodium sulfate, anhydrite	0,0004389	kg
sodium sulfite	2,177E-05	kg
sulfuric acid	0,0254864	kg
sand	9,826E-05	kg
magnesium sulfate	0,0019618	kg
sulfur dioxide, liquid	0,0002666	kg
sulfur	4,244E-05	kg
oxygen, liquid	0,0229746	kg
ozone, liquid	1,959E-05	kg
methanol, from biomass	0,0014907	kg
methanol	6,05E-05	kg
hydrogen peroxide, without water, in 50% solution state	0,0096819	kg
malusil	0,0007161	kg
chemical, organic	0,0020601	kg
chemical, inorganic	3,755E-05	kg
quicklime, milled, loose	0,0036473	kg
EDTA, ethylenediaminetetraacetic acid	0,0003686	kg
calcium carbonate, precipitated	0,0024478	kg
sodium formate	0,0005497	kg
quicklime, milled, loose	0,0049185	kg

Table 10: BOM of model 03, ECF bleaching in average pulp mills in Europe.

Because the model 04 ECF bleaching RLA average pulp mill represents mills in different Latin American countries, different sources of fuels are to find in the BOM, related to the origin of the represented anonymised ECF-pulp mills in model. The place of origin from each of the used datasets can be found in Table 06.

input model 04, ECF RLA average	**1kg HW/SW pulp**	**unit**
electricity, high voltage	0,01023025	kWh
Diesel [PE]	0,00002567	kg
Diesel [BR]	0,00018155	kg
Diesel [CO]	0,00000873	kg
light fuel oil [PE]	0,00020429	kg
light fuel oil [BR]	0,00152539	kg
light fuel oil [CO]	0,00021999	kg
natural gas, high pressure [BR]	0,02527453	kg
heavy fuel oil [PE]	0,00145774	kg
heavy fuel oil [BR]	0,00960931	kg
heavy fuel oil [CO]	0,00250335	kg
Water, unspecified natural origin [natural resource/in water]	0,02580913	m3
sawlog and veneer log, eucalyptus ssp., measured as solid wood under bark [RoW]	0,00309436	m3
transport, freight, inland waterways, barge	0,02487248	t*km
transport, freight, sea, bulk carrier for dry goods	0,02313701	t*km
transport, freight, lorry >32 metric ton, EURO5	0,23463999	t*km
transport, freight train	0,00236400	
pulp factory	4,36E-11	unit
aluminium sulfate, powder	0,00040644	kg
calcium carbonate, precipitated	0,00283013	kg
chemical, organic	0,00059868	kg
chemical, inorganic	0,00020629	kg
chlorine dioxide	0,00938226	kg
hydrogen peroxide, without water, in 50% solution state	0,00528191	kg
hydrochloric acid, without water, in 30% solution state	0,00101828	kg
magnesium oxide	0,00197775	kg
magnesium sulfate	0,00017381	kg
malusil	0,00138785	kg
ozone, liquid	0,00024228	kg
oxygen, liquid	0,01512504	kg
sodium hypochlorite, without water, in 15% solution state	0,00016415	kg
sodium sulfate, anhydrite	0,00015274	kg
sodium hydroxide, without water, in 50% solution state	0,01629080	kg
sodium chlorate, powder	0,00324271	kg
sulfur	0,00000088	kg
sulfuric acid	0,01178752	kg
quicklime, milled, loose	0,00162487	kg

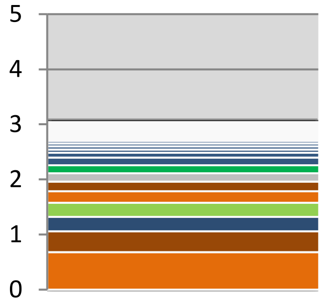
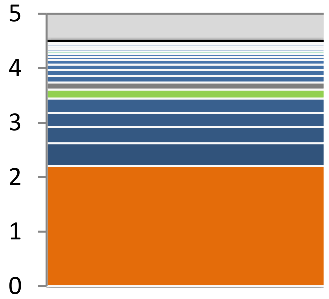
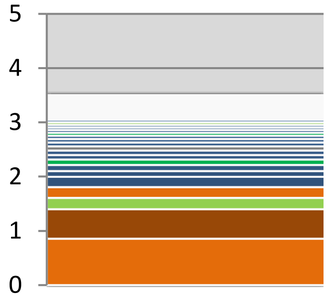
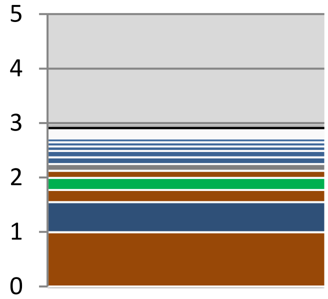
Table 11: BOM of model 04, ECF bleaching in average pulp mills in region Latin America.

4 Life Cycle Impact Assessment

Based on the LCI, the assessed impacts on the environment are converted using environmental impact categories (see Chapter 1.2.5 The methods of impact assessment and the impact categories).

4.1 Graphical presentation of the results

The detailed results from the impact assessment of the four models are compared in stacked bar charts. The stacked bars enable the identification of hotspots by representing each of the LCI elements. Table 12 gives reading guide.

<table>
<tr><td colspan="8">Impact categoriy and [unit]</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">model 01</td><td colspan="2">model 02</td><td colspan="2">model 03</td><td colspan="2">model 04</td></tr>
<tr><td colspan="8">1 ADMT pulp</td></tr>
<tr><td colspan="2">Value of impact [unit]</td><td colspan="2">Value of impact [unit]</td><td colspan="2">Value of impact [unit]</td><td colspan="2">Value of impact [unit]</td></tr>
<tr><td colspan="8">Byproduct E_{el}</td></tr>
<tr><td>Value by product [unit]</td><td>Value of impact [unit]</td><td>Value by product [unit]</td><td>Value of impact [unit]</td><td>Value by product [unit]</td><td>Value of impact [unit]</td><td>Value by product [unit]</td><td>Value of impact [unit]</td></tr>
<tr><td colspan="8">Byproduct E_{th}</td></tr>
<tr><td>Value by product [unit]</td><td>Value of impact [unit]</td><td>Value by product [unit]</td><td>Value of impact [unit]</td><td>Value by product [unit]</td><td>Value of impact [unit]</td><td>Value by product [unit]</td><td>Value of impact [unit]</td></tr>
<tr><td colspan="8">Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})</td></tr>
<tr><td colspan="2">value of impact [unit]</td><td colspan="2">value of impact [unit]</td><td colspan="2">value of impact [unit]</td><td colspan="2">value of impact [unit]</td></tr>
</table>

Colour code for reading the stacked bars to identify LCI elements:

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

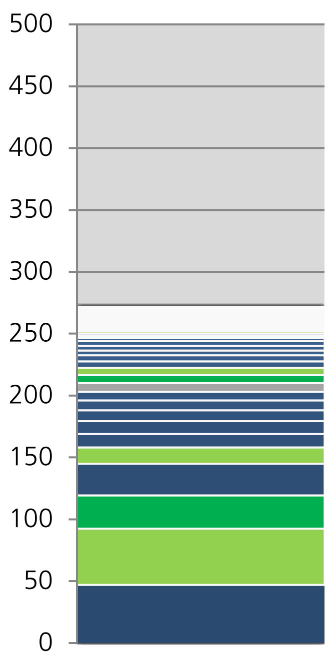
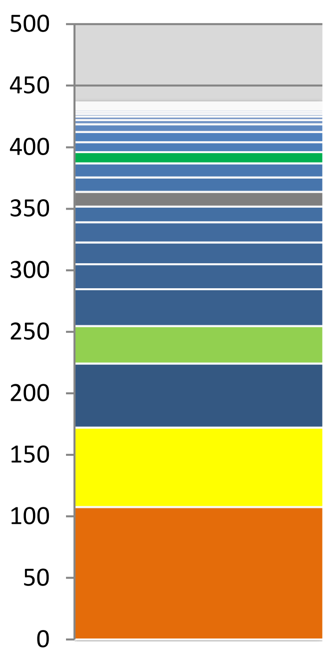
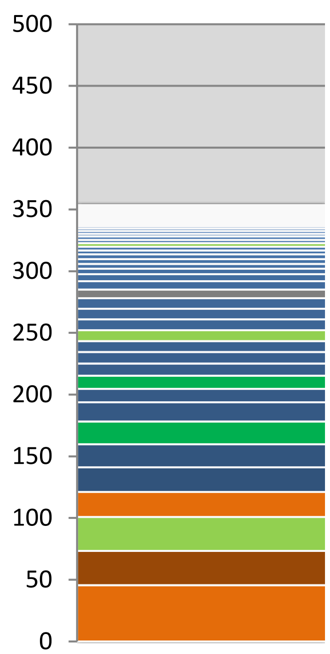
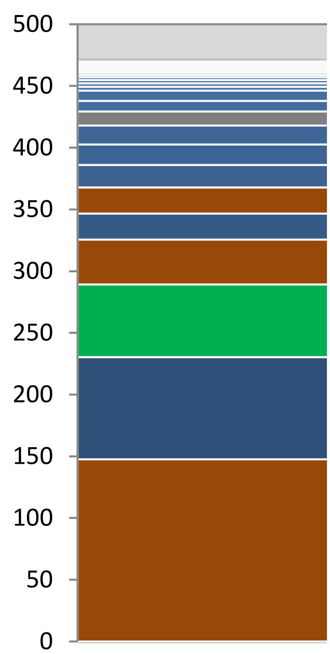
Table 12: as a reading guide, description of graphical representation of results related to Functional Unit of 1 ADMT of bleached pulp.

4.2 Results of baseline scenarios

In the following, the evaluation results of the four models in baseline scenario, with allocation to mass, are presented prior to Robustness Level I till III (see Table 4). The subheadings show the individual impact categories, related to the FU of 1 ADMT of bleached pulp.

4.2.1 Climate change [GWP 100a]

ECF using European Hard- and Softwood showing the lowest GWP 100a in comparison to TCF production and ECF production using eucalyptus.

<table>
<tr><th colspan="8">Climate change (GWP 100a , IPCC 2013) in [kg CO2-Eq] Robustness Level I</th></tr>
<tr>
<td colspan="2">
</td>
<td colspan="2">
</td>
<td colspan="2">
</td>
<td colspan="2">
</td>
</tr>
<tr><td colspan="2">model 01</td><td colspan="2">model 02</td><td colspan="2">model 03</td><td colspan="2">model 04</td></tr>
<tr><td colspan="8">1 ADMT pulp</td></tr>
<tr><td colspan="2">231,375 kg CO_2-Eq</td><td colspan="2">431,996 kg CO_2-Eq</td><td colspan="2">338,411 kg CO_2-Eq</td><td colspan="2">438,31 kg CO_2-Eq</td></tr>
<tr><td colspan="8">By product E_{el}</td></tr>
<tr><td>575 kWh</td><td>15,972 kg CO_2-eq</td><td>0 kWh</td><td>0 kg CO_2-Eq</td><td>252 kWh</td><td>11,094 kg CO_2-Eq</td><td>224 kWh</td><td>12,750 kg CO_2-Eq</td></tr>
<tr><td colspan="8">By product E_{th}</td></tr>
<tr><td>258 kWh</td><td>7,088 kg CO_2-eq</td><td>0 kWh</td><td>0 kg CO_2-Eq</td><td>314,377 kWh</td><td>3,433 kg CO_2-Eq</td><td>711,111 kWh</td><td>10,119 kg CO_2-Eq</td></tr>
<tr><td colspan="8">Sum of impacts (1 ADMT pulp + By product E_{el} + By product E_{th})</td></tr>
<tr><td colspan="2">271,328 kg CO_2-Eq</td><td colspan="2">431,996 kg CO_2-Eq</td><td colspan="2">352,938 kg CO_2-Eq</td><td colspan="2">461,179 kg CO_2-Eq</td></tr>
</table>

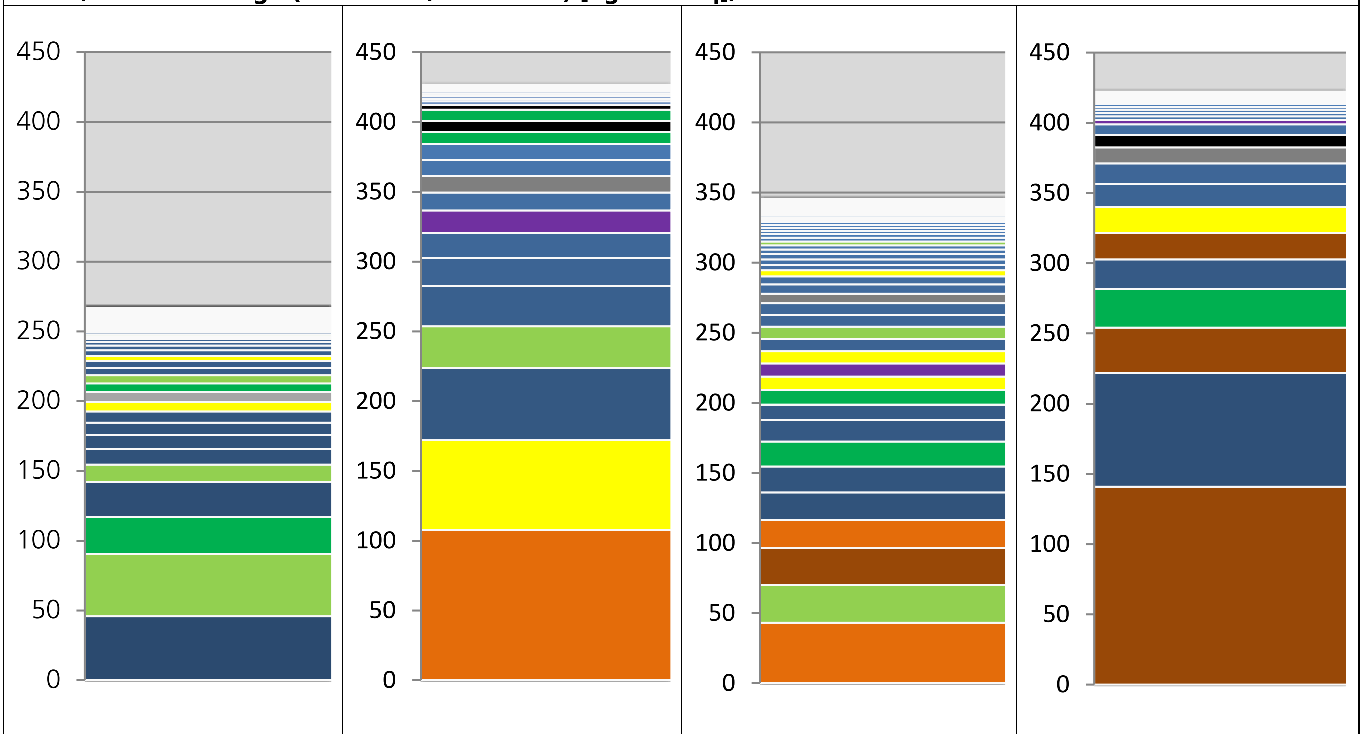
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 13: Climate change of all four models.

4.2.2 Fossil, climate change [GWP100a]

models 02 and 04 showing high fossil GWP from pulp mill processing and purchase of bleaching agents. Induced by the fossil-free processing in Äänekoski model 01 shows no relevant impacts from processing of pulp mill.

Fossil, climate change (GWP 100a, IPCC 2013) [kg CO2-Eq], Robustness Level I



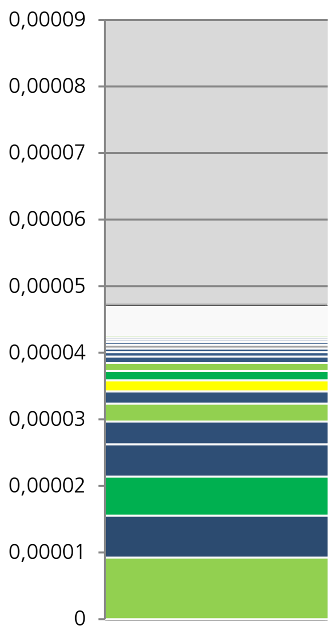
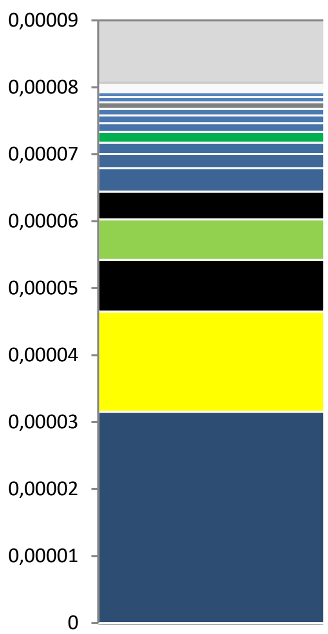
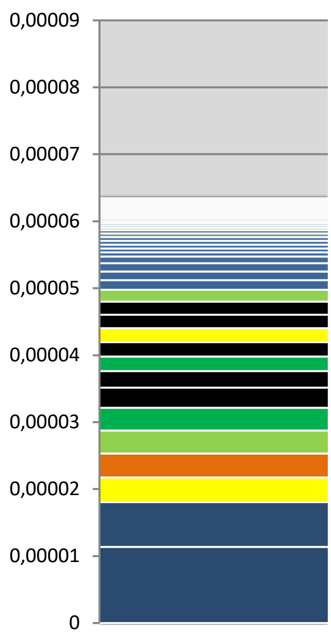
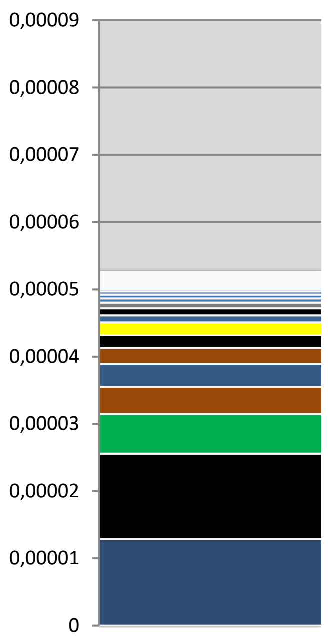
model 01		model 02		model 03		model 04	
1 ADMT pulp							
227,751 kg CO_2-Eq		426,397 kg CO_2-Eq		331,074 kg CO_2-Eq		401,066 kg CO_2-Eq	
Byproduct E_{el}							
575 kWh	30,005 kg CO_2-Eq	0 kWh	0 kg CO_2-Eq	252 kWh	10,845 kg CO_2-Eq	224 kWh	11,637 kg CO_2-Eq
Byproduct E_{th}							
258 kWh	6,965 kg CO_2-Eq	0 kWh	0 kg CO_2-Eq	314,377 kWh	3,357 kg CO_2-Eq	711,111 kWh	9,236 kg CO_2-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
260,256 kg CO_2-Eq		**426,397 kg CO_2-Eq**		**345,276 kg CO_2-Eq**		**421,939 kg CO_2-Eq**	

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 14: Climate change Potential, related to fossil fuels of all four models.

4.2.3 Ozone depletion, ozone depletion potential (ODP)]

The models 01, 03 and 04 using ECF bleaching showing comparable Emissions related to ODP. model 02 using TCF bleaching is showing a trend to comparable high emissions from ODP.

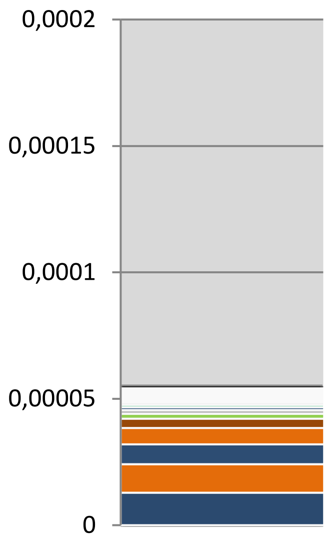
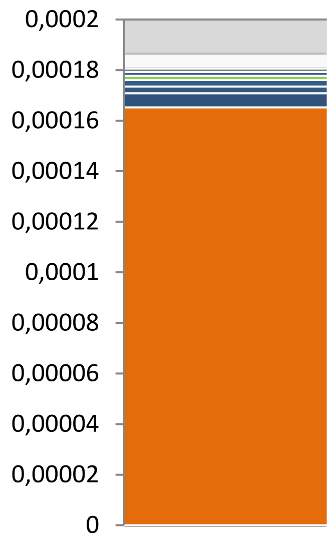
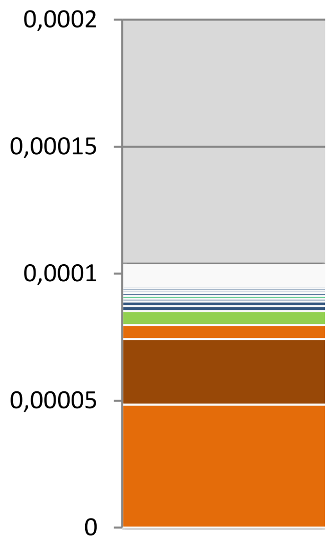
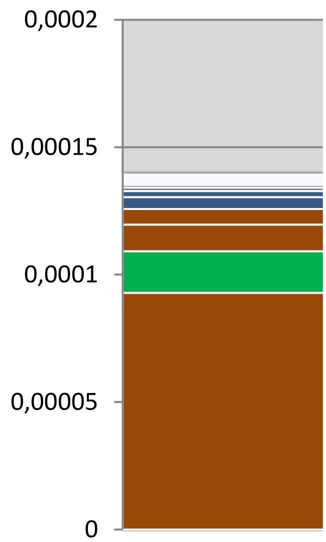
Ozone depletion, ozone depletion potential (ODP), Robustness Level I							
							
model 01		model 02		model 03		model 04	
1 ADMT pulp							
4,27E-05 kg CFC-11-Eq		8,033E-05 kg CFC-11-Eq		6,071E-05 kg CFC-11-Eq		4,989E-05 kg CFC-11-Eq	
Byproduct E_{el}							
575 kWh	2,79E-06 kg CFC-11-Eq	0 kWh	0 kg CFC-11-Eq	252 kWh	2,03E-06 kg CFC-11-Eq	224 kWh	1,47E-06 kg CFC-11-Eq
Byproduct E_{th}							
258 kWh	1,25E-06 kg CFC-11-Eq	0 kWh	0 kg CFC-11-Eq	314,377 kWh	6,3E-07 kg CFC-11-Eq	711,111 kWh	1,16E-06 kg CFC-11-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
0,00004682 kg CFC-11-Eq		**0,0000803 kg CFC-11-Eq**		**0,00006337 kg CFC-11-Eq**		**0,0000525 kg CFC-11-Eq**	

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 15: Ozone Depletion, of all four models.

4.2.4 Particulate Matter formation, impact on human health

The models 01, 03 and 04 using ECF bleaching showing comparable Emissions related to fine dust. model 02 using TCF bleaching is showing comparable high emissions from Particulate Matter.

Particulate Matter formation, impact on human health [disease incidence]							
							
model 01		model 02		model 03		model 04	
1 ADMT pulp							
4,896E-05 disease incidence		1,8553E-04 disease incidence		9,869E-05 disease incidence		1,3210E-04 disease incidence	
Byproduct E_{el}							
575kWh	3,17E-6 disease incidence	0 kWh	0 disease incidence	252 kWh	3,3E-06 disease incidence	224 kWh	3,91E-06 disease incidence
Byproduct E_{th}							
258 kWh	1,42E-6 disease incidence	0 kWh	0 disease incidence	314,377 kWh	1,02E-06 disease incidence	711,111 kWh	3,1E-06 disease incidence
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
0,00005355 disease incidence		**0,00018553 disease incidence**		**0,00010301 disease incidence**		**0,00013911 disease incidence**	

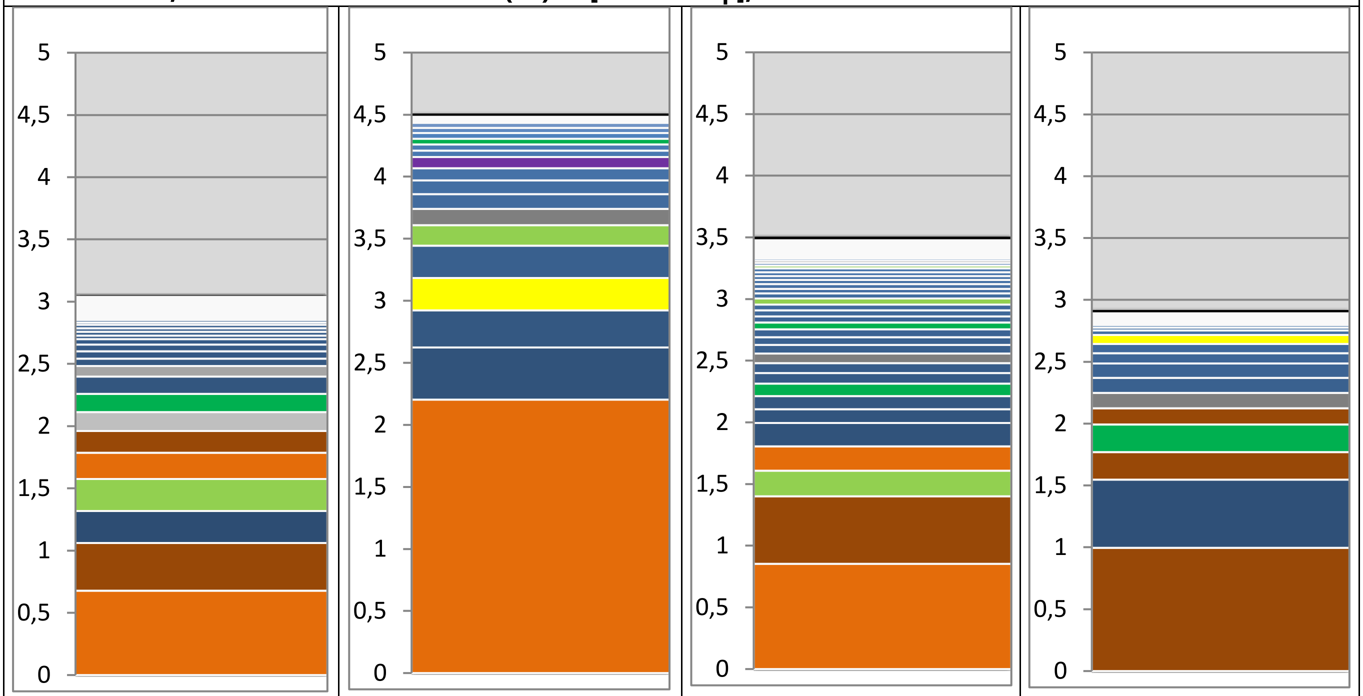
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 16: Fine dust related disease incidence of all four models.

4.2.5 Acidification, accumulated exceedance (ae)

The models 01, 03 and 04 using ECF bleaching showing comparable Emissions related to Acidification. model 02 using TCF bleaching is showing comparable high emissions from Acidification in sensitive terrestrial areas and freshwater ecosystems.

Acidification, accumulated exceedance (ae) in [mol H+-Eq.], Robustness Level II



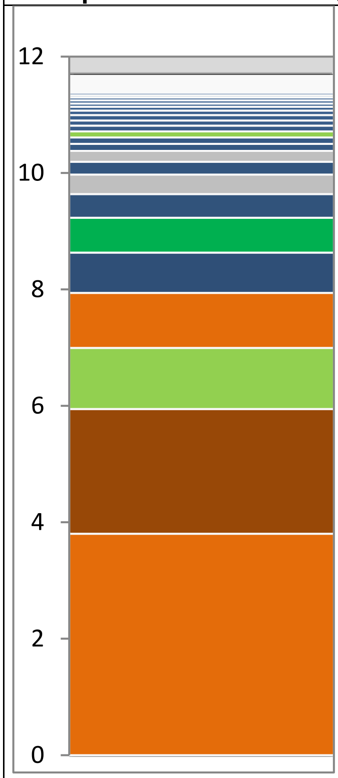
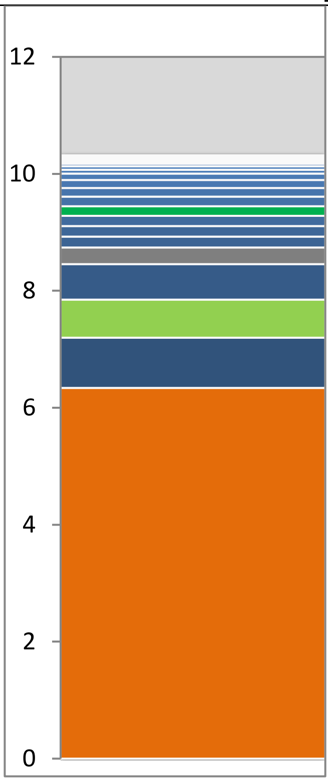
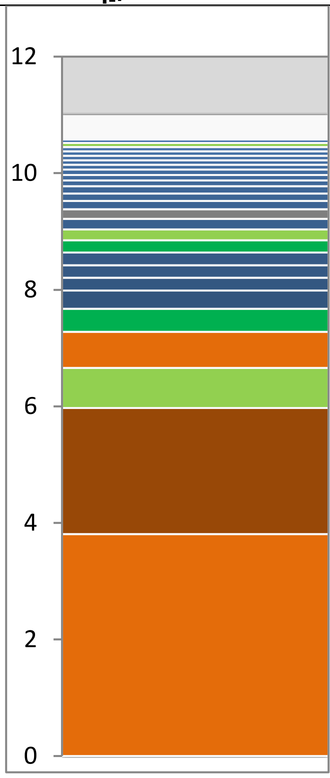
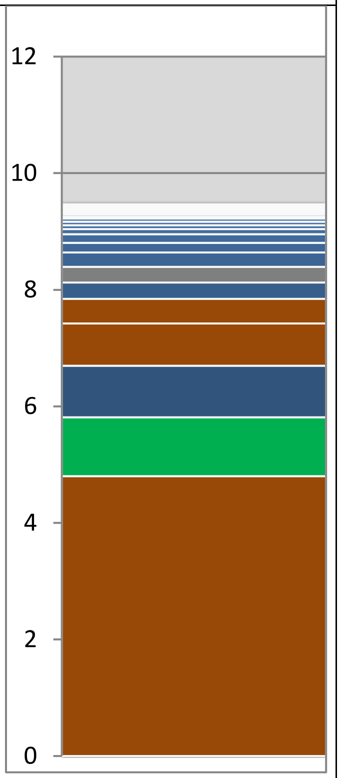
model 01		model 02		model 03		model 04	
1 ADMT pulp							
2,7701 mol H+-Eq		4,4989 mol H+-Eq		3,3494 mol H+-Eq		2,7653 mol H+-Eq	
Byproduct E_{el}							
575 kWh	0,1761 mol H+-Eq	0 kWh	0 mol H+-Eq	252 kWh	0,1093 mol H+-Eq	224 kWh	0,0789 mol H+-Eq
Byproduct E_{th}							
258 kWh	0,0790 mol H+-Eq	0 kWh	0 mol H+-Eq	314,377 kWh	0,0338 mol H+-Eq	711,111 kWh	0,0626 mol H+-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
3,0252 mol H+-Eq		**4,4989 mol H+-Eq**		**3,4925 mol H+-Eq**		**2,9068 mol H+-Eq**	

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 17: Acidification, accumulated exceedance of all four models.

4.2.6 Eutrophication: terrestrial, accumulated exceedance (AE)

The models 02, 03 and 04 showing comparable Emissions related to Acidification. model 01 is showing comparable high impact to eutrophication terrestrial is in model 01 highest in comparison.

Eutrophication: terrestrial, accumulated exceedance [mol N-Eq], Robustness Level II							
							
model 01		model 02		model 03		model 04	
1 ADMT pulp							
10,799 mol N-Eq		10,312 mol N-Eq		10,513 mol N-Eq		8,991 mol N-Eq	
Byproduct E_{el}							
575 kWh	0,700 mol N-Eq	0 kWh	0 mol N-Eq	252 kWh	0,347 mol N-Eq	224 kWh	0,26 mol N-Eq
Byproduct E_{th}							
258 kWh	0,314 mol N-Eq	0 kWh	0 mol N-Eq	314,377 kWh	0,107 mol N-Eq	711,111 kWh	0,207 mol N-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
11,813 mol N-Eq		**10,312 mol N-Eq**		**10,966 mol N-Eq**		**9,458 mol N-Eq**	

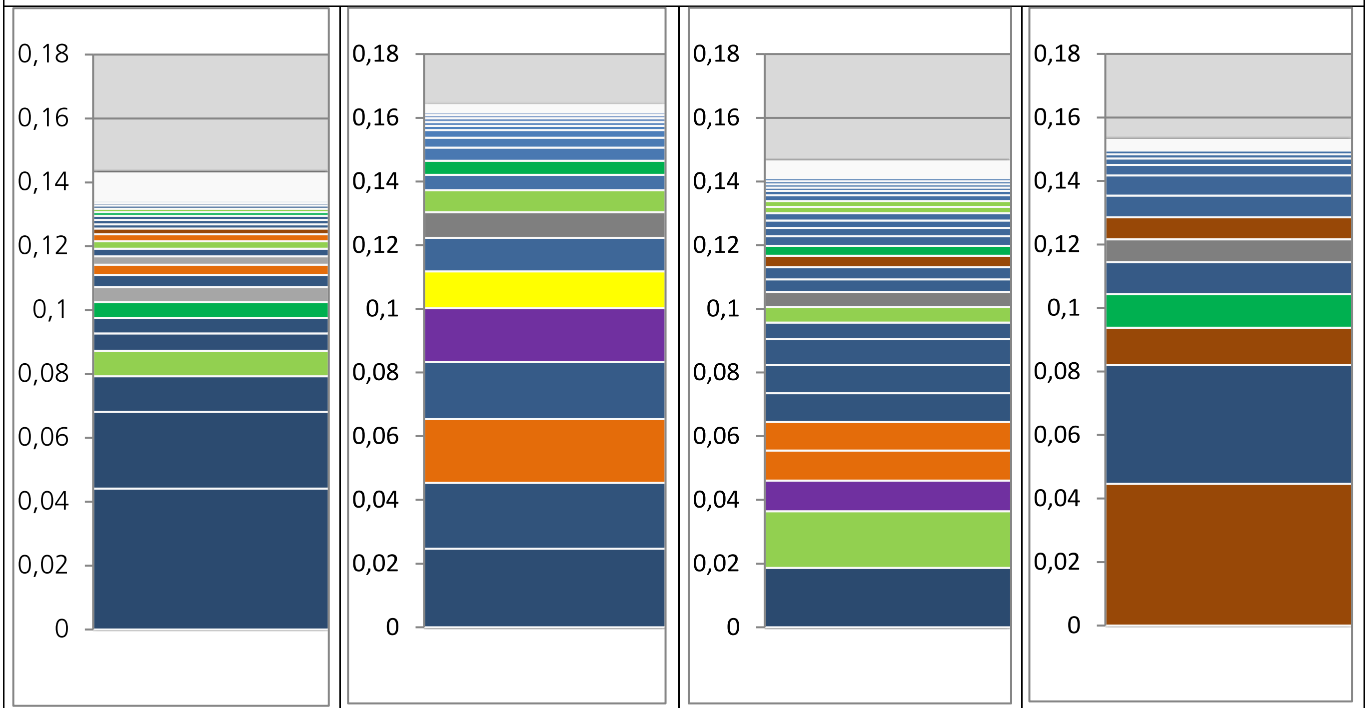
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 18: Eutrophication terrestrial, accumulated exceedance (AE) of all four models.

4.2.7 Eutrophication: freshwater, fraction of nutrition´s reaching freshwater end compartment (P)

The models 01, 03 and 04 showing comparable Emissions related emission of nutrition´s reaching the freshwater end compartment for pulp mills using ECF bleaching.

Eutrophication: freshwater, fraction of nutrition´s reaching freshwater end compartment [kg PO4-Eq], Robustness Level II



model 01		model 02		model 03		model 04	
1 ADMT pulp							
0,131 kg PO4-Eq		0,164 kg PO4-Eq		0,14 kg PO4-Eq		0,145 kg PO4-Eq	
Byproduct E_{el}							
575 kWh	0,008 kg PO4-Eq	0 kWh	0 kg PO4-Eq	252 kWh	0,004 kg PO4-Eq	224 kWh	0,004 kg PO4-Eq
Byproduct E_{th}							
258 kWh	0,004 kg PO4-Eq	0 kWh	0 kg PO4-Eq	314,377 kWh	0,001 kg PO4-Eq	711,111 kWh	0,003 kg PO4-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
0,143 kg PO4-Eq		**0,164 kg PO4-Eq**		**0,145 kg PO4-Eq**		**0,152 kg PO4-Eq**	

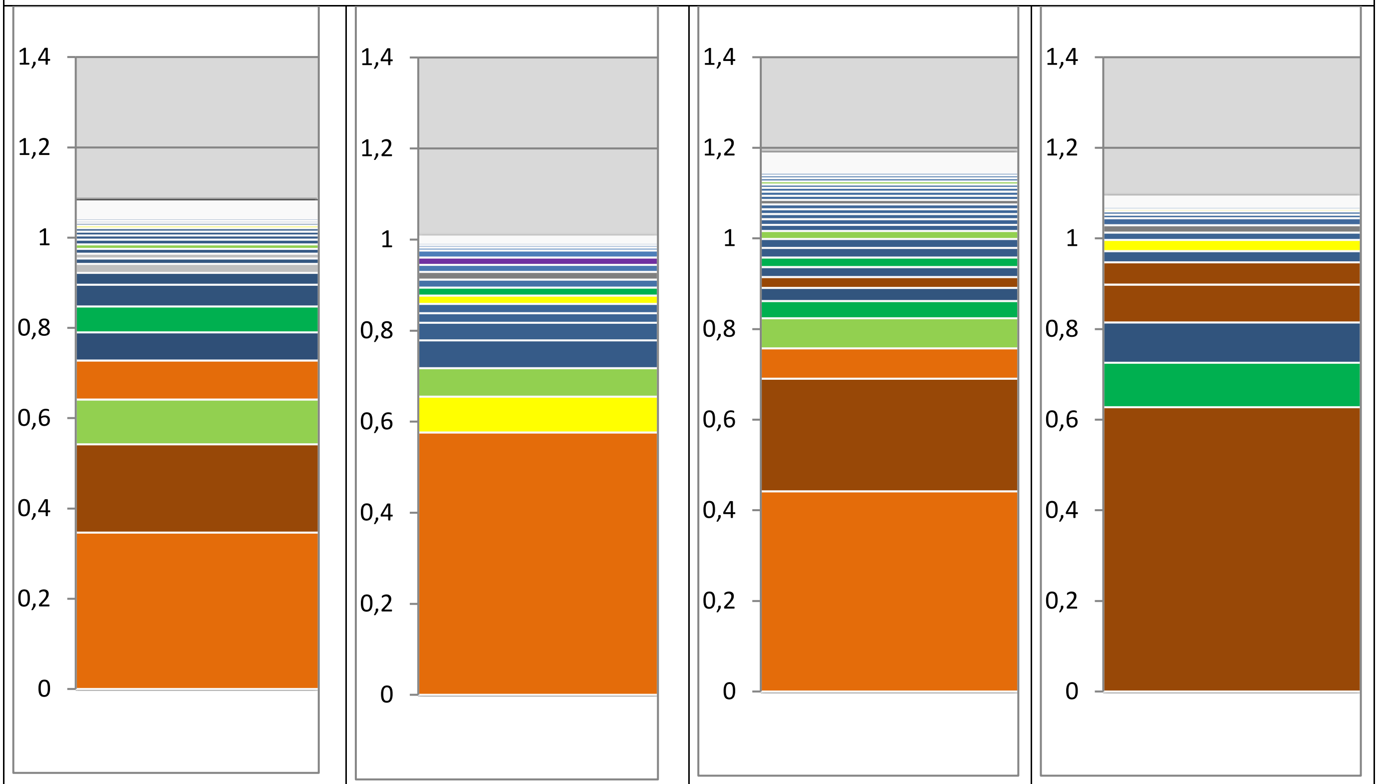
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 19: Eutrophication freshwater, fraction of nutrition´s reaching freshwater end compartment (P) of all four models.

4.2.8 Eutrophication: marine, fraction of nutrition´s reaching freshwater end compartment (N)

The models 01, 02 and 04 showing comparable Emissions related to emission of nutrition´s reaching the freshwater system. model 3 showing a comparable higher emission of nutrition.

Eutrophication: marine, fraction of nutrition´s reaching freshwater end compartmend [kg N-Eq], Robustness Level II



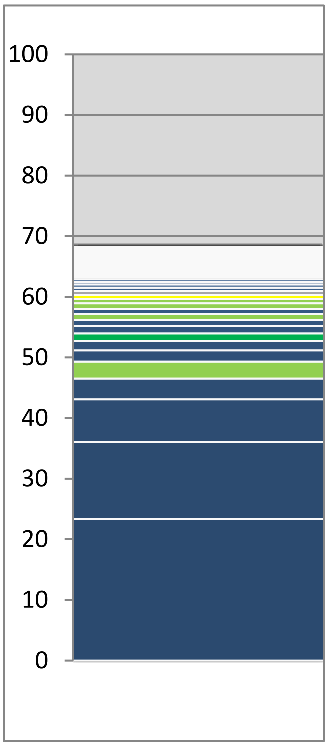
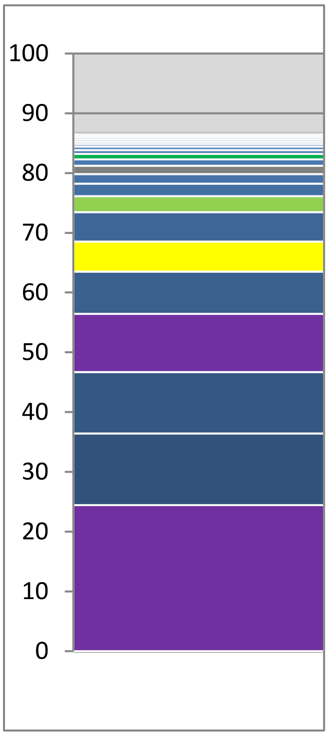
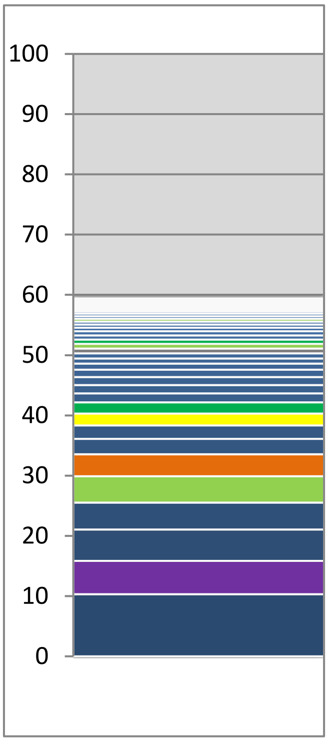
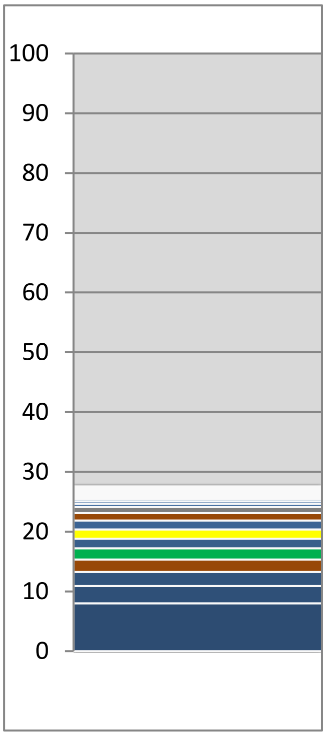
model 01		model 02		model 03		model 04	
1 ADMT pulp							
1,008 kg N-Eq		1,006 kg N-Eq		1,137 kg N-Eq		1,037 kg N-Eq	
Byproduct E_{el}							
575 kWh	0,066 kg N-Eq	0 kWh	0 kg N-Eq	252 kWh	0,038 kg N-Eq	224 kWh	0,03 kg N-Eq
Byproduct E_{th}							
258 kWh	0,030 kg N-Eq	0 kWh	0 kg N-Eq	314,377 kWh	0,012 kg N-Eq	711,111 kWh	0,024 kg N-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
1,104 kg N-Eq		**1,006 kg N-Eq**		**1,187 kg N-Eq**		**1,115 kg N-Eq**	

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 20: Eutrophication freshwater, fraction of nutrition´s reaching freshwater end compartment (N) of all four models.

4.2.9 Ionising radiation: human health, human exposure efficiency relative to u235

The models 02 and 03 showing comparable Emissions related to ionising radiation, model 01 shows comparable high emission related to ionising radiation, whereas model 04 shows comparable lowest impact in this category.

<table>
<tr><td colspan="8">Ionising radiation: human health, human exposure efficiency relative to u235 [kBq U235], Robustness Level II</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td colspan="2">model 01</td><td colspan="2">model 02</td><td colspan="2">model 03</td><td colspan="2">model 04</td></tr>
<tr><td colspan="8">1 ADMT pulp</td></tr>
<tr><td colspan="2">61,724 kBq U235-Eq</td><td colspan="2">86,366 kBq U235-Eq</td><td colspan="2">56,843 kBq U235-Eq</td><td colspan="2">26,141 kBq U235-Eq</td></tr>
<tr><td colspan="8">Byproduct E_{el}</td></tr>
<tr><td>575 kWh</td><td>4,018 kBq U235-Eq</td><td>0 kWh</td><td>0 kBq U235-Eq</td><td>252 kWh</td><td>1,88 kBq U235-Eq</td><td>224 kWh</td><td>0,750 kBq U235-Eq</td></tr>
<tr><td colspan="8">Byproduct E_{th}</td></tr>
<tr><td>278 kWh</td><td>1,803 kBq U235-Eq</td><td>0 kWh</td><td>0 kBq U235-Eq</td><td>314,377 kWh</td><td>0,583 kBq U235-Eq</td><td>711,111 kWh</td><td>0,596 kBq U235-Eq</td></tr>
<tr><td colspan="8">Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})</td></tr>
<tr><td colspan="2">67,546 kBq U235-Eq</td><td colspan="2">86,366 kBq U235-Eq</td><td colspan="2">59,306 kBq U235-Eq</td><td colspan="2">27,487 kBq U235-Eq</td></tr>
</table>

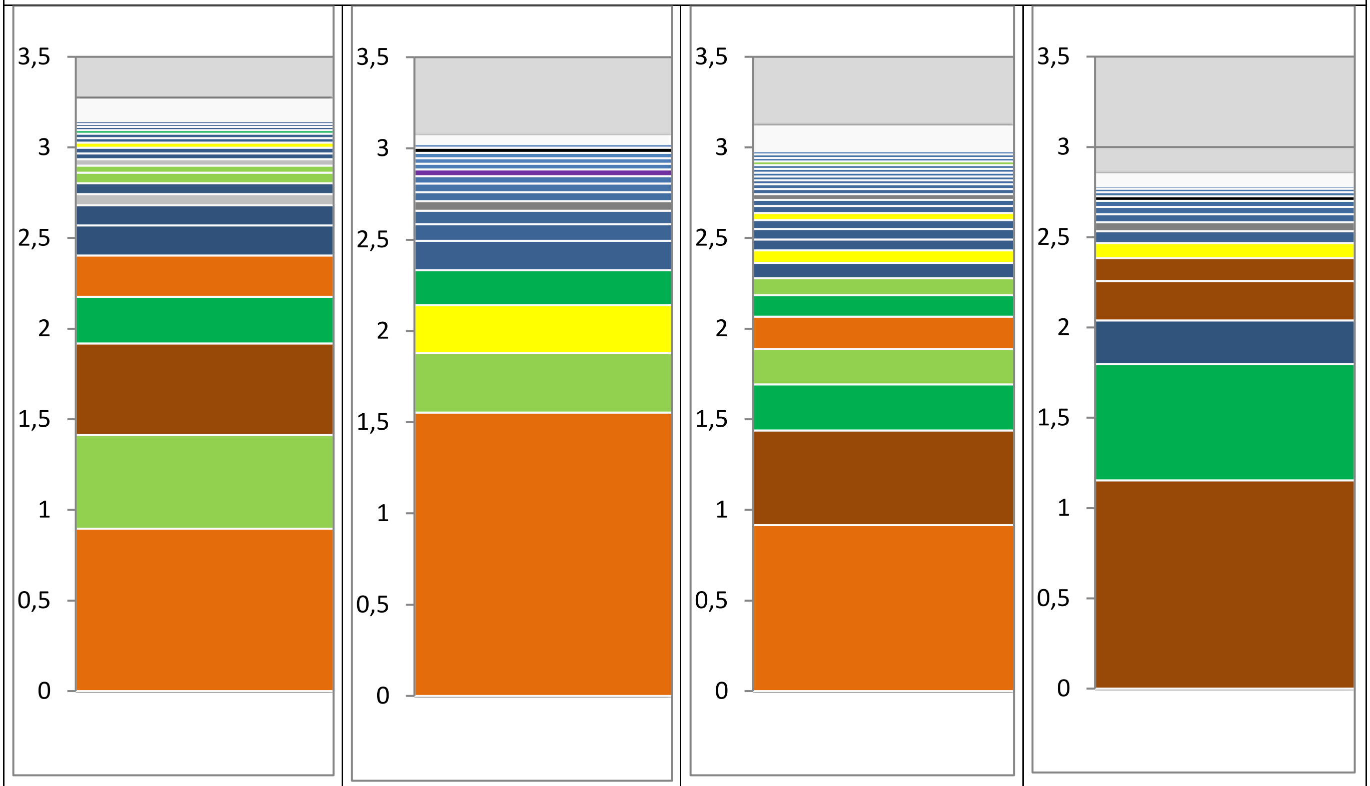
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 21: Ionising radiation, of all four models.

4.2.10 Photochemical ozone formation: human health, tropospheric ozone concentration increase

All four models showing a relative low deviation in impact category photochemical ozone formation.

Photochemical ozone formation: human health, tropospheric ozone concentration increase [NMOC-Eq], Robustness Level II



model 01		model 02		model 03		model 04	
1 ADMT pulp							
3,109 kg NMVOC-Eq		3,065 kg NMVOC-Eq		2,983 kg NMVOC-Eq		2,704 kg NMVOC-Eq	
Byproduct E_{el}							
575 kWh	0,203 kg NMVOC-Eq	0 kWh	0 kg NMVOC-Eq	252 kWh	0,099 kg NMVOC-Eq	224 kWh	0,079 kg NMVOC-Eq
Byproduct E_{th}							
258 kWh	0,091 kg NMVOC-Eq	0 kWh	0 kg NMVOC-Eq	314,377 kWh	0,031 kg NMVOC-Eq	711,111 kWh	0,063 kg NMVOC-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
3,403 kg NMVOC-Eq		**3,065 kg NMVOC-Eq**		**3,113 kg NMVOC-Eq**		**2,846 kg NMVOC-Eq**	

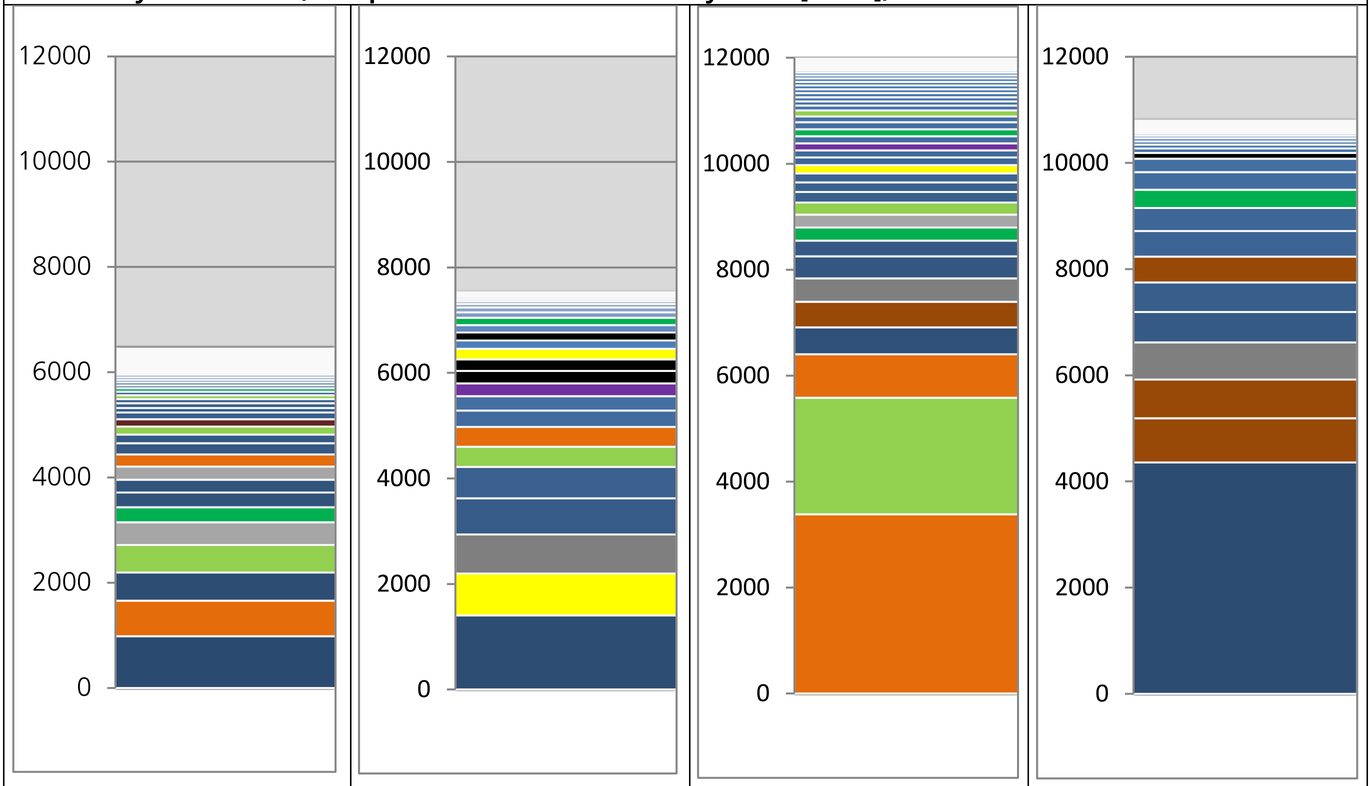
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 22: Photochemical ozone formation of all four models.

4.2.11 Ecotoxicity: freshwater, comparative toxic unit for ecosystems (CTUe)

The average ECF processes showing relative to TCF gained values of ecotoxicity to freshwater in comparative toxic units for ecosystems. model 01 shows lowest ecotoxicity to freshwater of all models.

Ecotoxicity: freshwater, comparative toxic unit for ecosystems [CTUe], Robustness Level III



model 01		model 02		model 03		model 04	
1 ADMT pulp							
5.931,232 CTUe		7.517,156 CTUe		11.676,943 CTUe		10.273,039 CTUe	
Byproduct E_{el}							
575 kWh	348,976 CTUe	0 kWh	0 CTUe	252 kWh	372,265 CTUe	224 kWh	285, 917 CTUe
Byproduct E_{th}							
258 kWh	156,636 CTUe	0 kWh	0 CTUe	314,377 kWh	115,225 CTUe	711,111 kWh	226,918 CTUe
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
6.436,845 CTUe		**7.517,156 CTUe**		**12.363,585 CTUe**		**10.785,874 CTUe**	

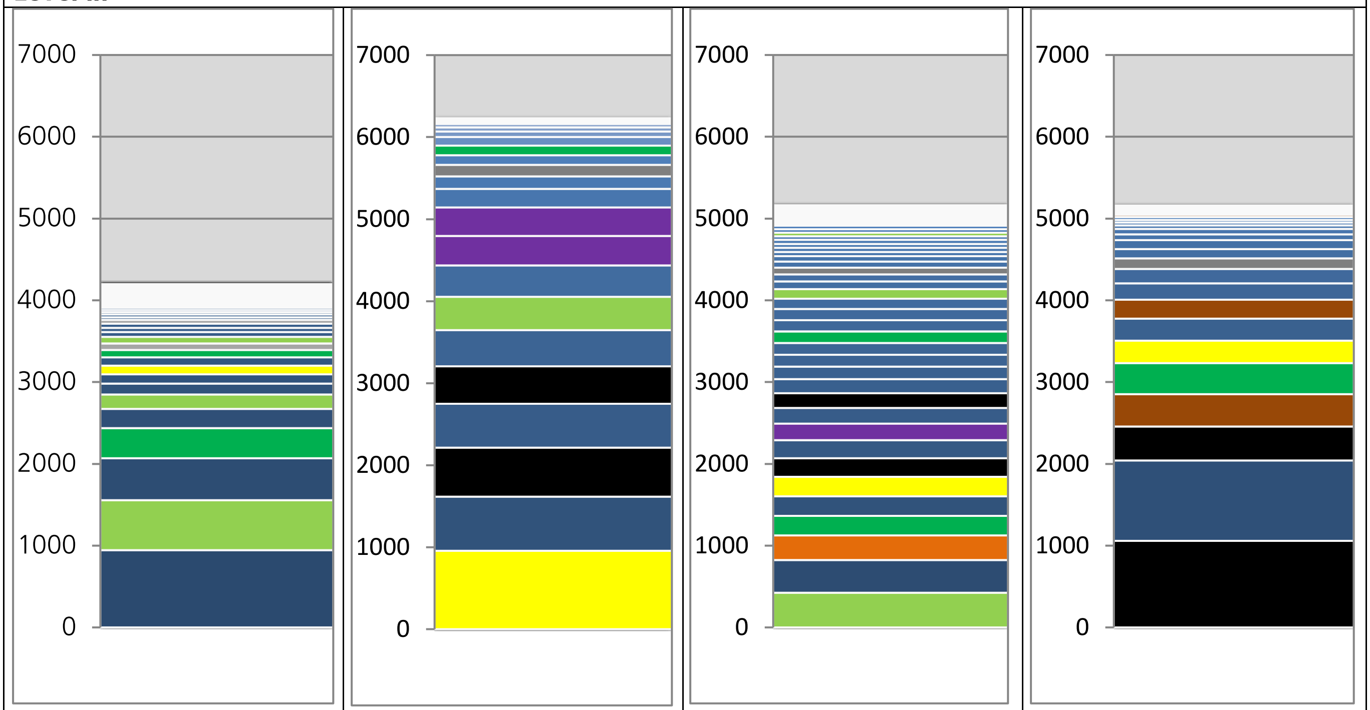
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 23: Ecotoxicity: freshwater, comparative toxic unit for ecosystems of all four models.

4.2.12 Resource utilisation-fossil, Abiotic Depletion Potential (ADP): fossil fuels

All four models showing a relative low deviation in impact category abiotic depletion potential for fossil fuels, with a trend to reduced impact in model 01.

Resource utilisation-fossil, Abiotic Depeltion Potential (ADP: fossil fuels [MJ, net caloric value], Robustness Level III



<table>
<tr><td colspan="2">model 01</td><td colspan="2">model 02</td><td colspan="2">model 03</td><td colspan="2">model 04</td></tr>
<tr><td colspan="8">1 ADMT pulp</td></tr>
<tr><td colspan="2">3.835,189 MJ, net caloric value</td><td colspan="2">6.224,465 MJ, net caloric value</td><td colspan="2">4.940,835 MJ, net caloric value</td><td colspan="2">4.897,119 MJ, net caloric value</td></tr>
<tr><td colspan="8">Byproduct E_{el}</td></tr>
<tr><td>575 kWh</td><td>246,451 MJ, net caloric value</td><td>0 kWh</td><td>0 MJ, net caloric value</td><td>252 kWh</td><td>163 MJ, net caloric value</td><td>224 kWh</td><td>142,429 MJ, net caloric value</td></tr>
<tr><td colspan="8">Byproduct E_{th}</td></tr>
<tr><td>258 kWh</td><td>110,618 MJ, net caloric value</td><td>0 kWh</td><td>0 MJ, net caloric value</td><td>314,377 kWh</td><td>50,453 MJ, net caloric value</td><td>711,111 kWh</td><td>113,039 MJ, net caloric value</td></tr>
<tr><td colspan="8">Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})</td></tr>
<tr><td colspan="2">4.192,258 MJ</td><td colspan="2">6.224,465 MJ</td><td colspan="2">4.991,451 MJ</td><td colspan="2">5.152,587 MJ</td></tr>
</table>

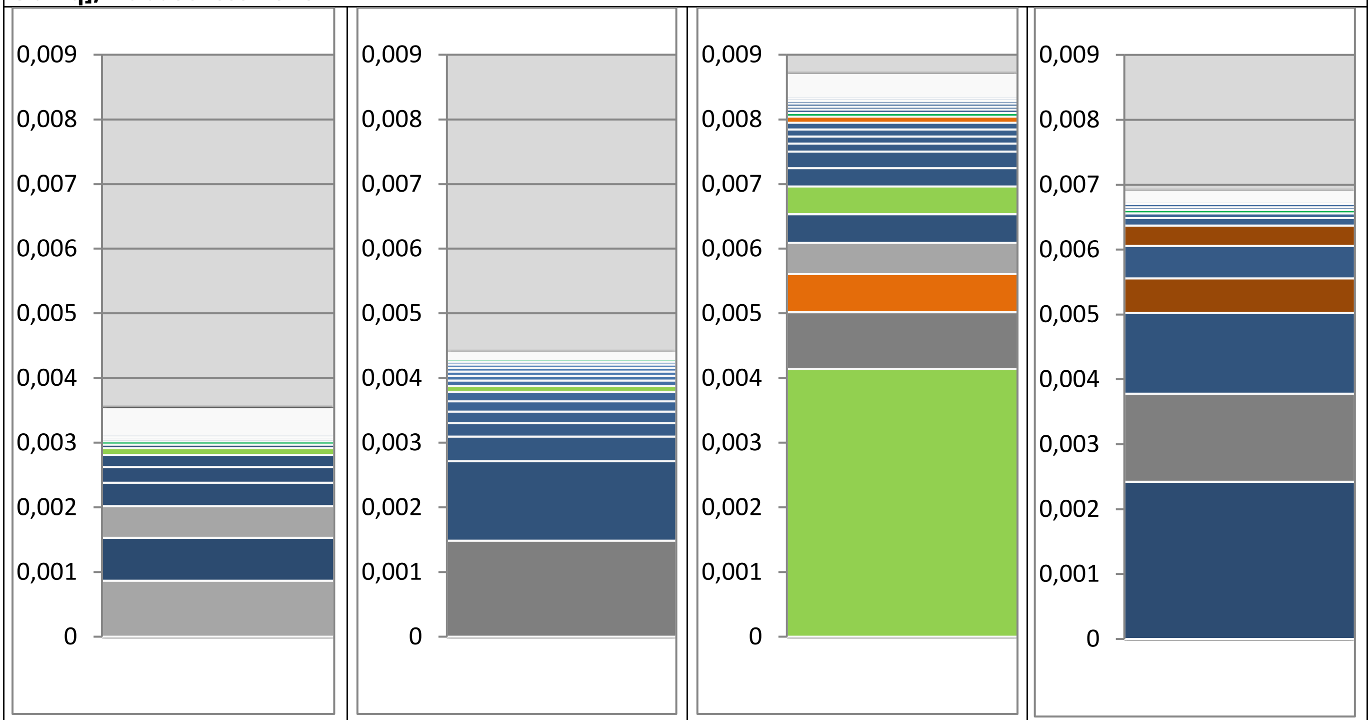
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 24: Resource utilisation-fossil: Abiotic Depletion Potential (ADP): fossil fuels of all four models.

4.2.13 Material resources, metal/minerals, abiotic depletion potential (ADP): elements (ultimate reserves)

The models 03 and 04 representing average ECF processes showing comparable higher impacts in category abiotic depletion potential for elements.

Material resources, metal/minerals, abiotic depletion potential (ADP): elements (ultimative reserves) [kg Sb-Eq], Robustness Level III



model 01		model 02		model 03		model 04	
1 ADMT pulp							
0,0033378 kg Sb-Eq		0,00438267 kg Sb-Eq		0,008 kg Sb-Eq		0,006 kg Sb-Eq	
Byproduct E_{el}							
575 kWh	0,00013182 kg Sb-Eq	0 kWh	0 kg Sb-Eq	252 kWh	0,00033732 kg Sb-Eq	224 kWh	0,00042653 kg Sb-Eq
Byproduct E_{th}							
258 kWh	0,00005917 kg Sb-Eq	0 kWh	0 kg Sb-Eq	314,377 kWh	0,00017346 kg Sb-Eq	711,111 kWh	0,00033852 kg Sb-Eq
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
0,00352879 kg Sb-eq		**0,00438267 kg Sb-eq**		**0,0085 kg Sb-eq**		**0,0068 kg Sb-eq**	

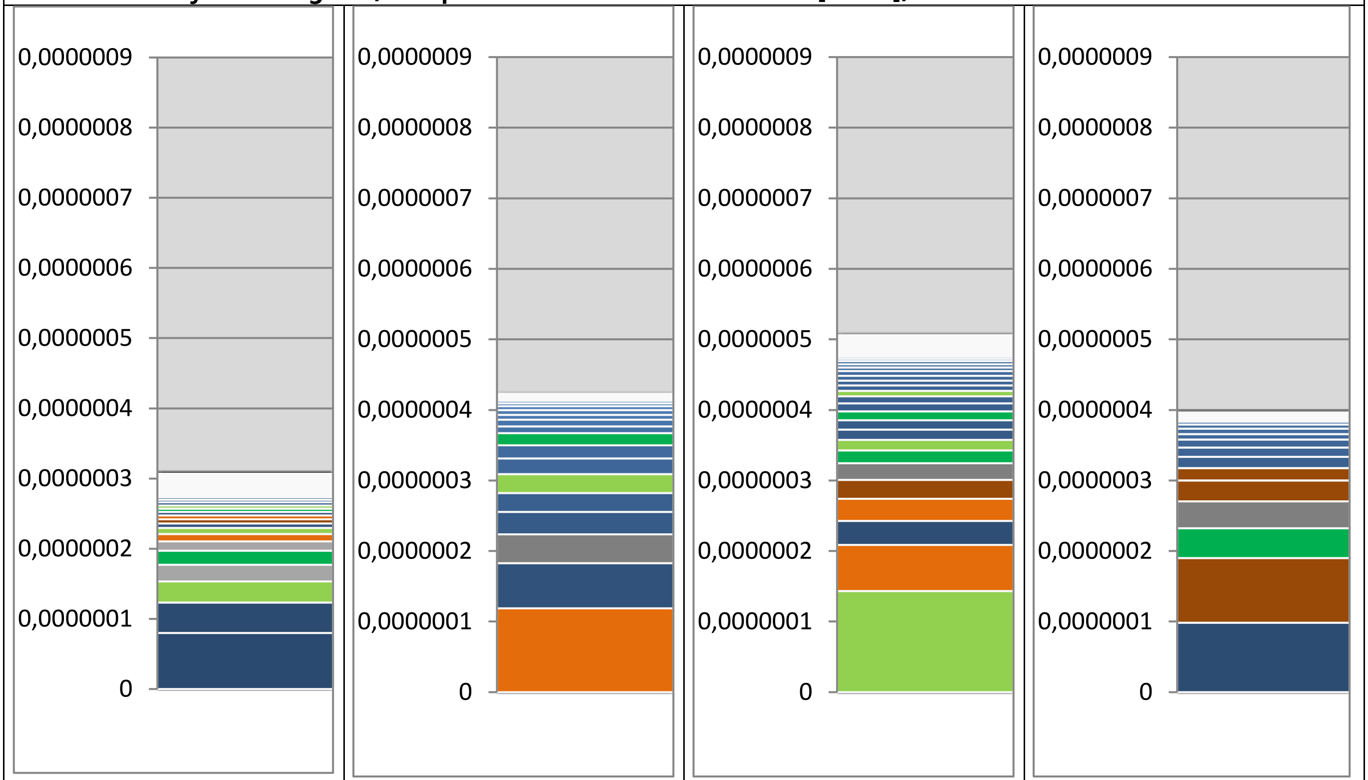
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 25: Material resources depletion, of all four models.

4.2.14 Human toxicity: carcinogenic, comparative toxic unit for human (CTUh)

All four models showing a relative low deviation in impact category human toxicity, non-carcnogenic, with tendece to hogher impact from average ECF processes (model 03).

Human toxicity: carcinogenic, comparative toxic unit for human [CTUh], Robustness Level III



model 01		model 02		model 03		model 04	
1 ADMT pulp							
2,8E-07 CTUh		4,2E-07 CTUh		4,8E-07 CTUh		3,4E-7 CTUh	
Byproduct E_{el}							
575 kWh	2,0E-08 CTUh	0 kWh	0 CTUh	252 kWh	2,1E-08 CTUh	224 kWh	3,0E-08 CTUh
Byproduct E_{th}							
258 kWh	7,3E-09 CTUh	0 kWh	0 CTUh	314,377 kWh	3,1E-09 CTUh	711,111 kWh	2,01E-08 CTUh
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
3,07E-07 CTUh		**4,2E-07 CTUh**		**5,04E-07 CTUh**		**3,902E-07 CTUh**	

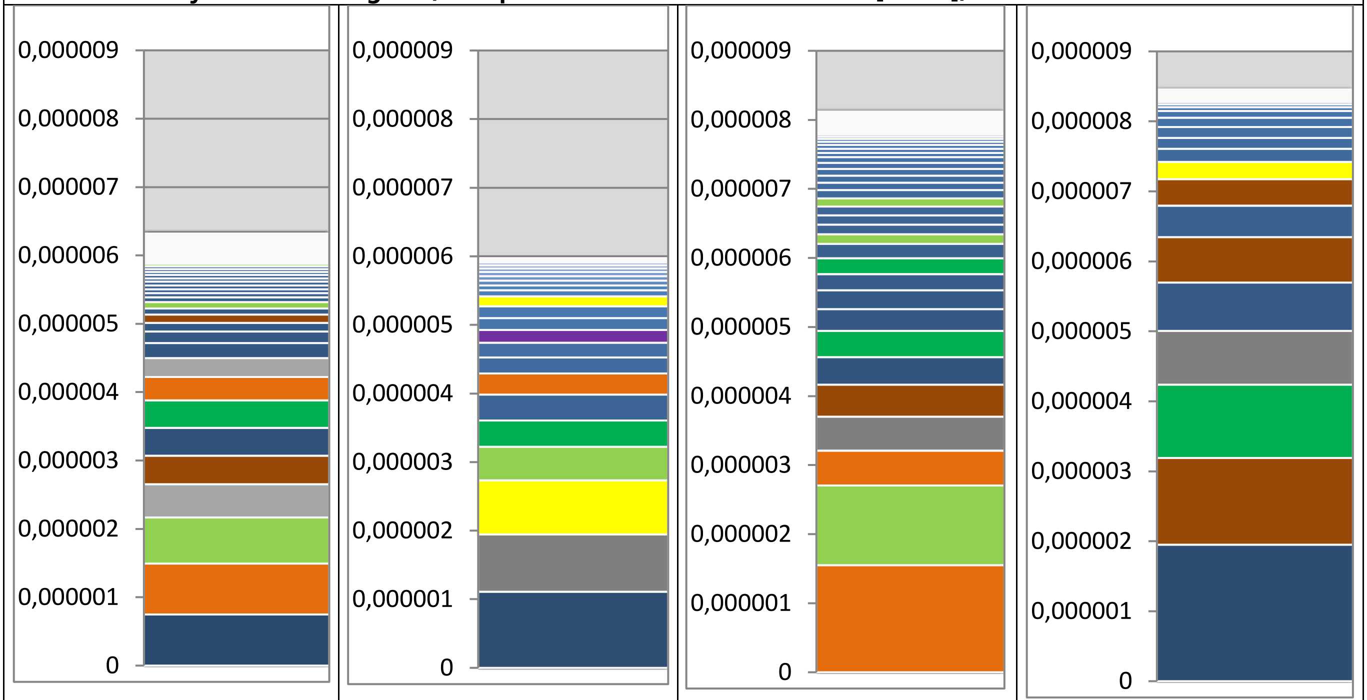
Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 26: Human toxicity, carcinogenic, of all four models.

4.2.15 Human toxicity: non-carcinogenic, comparative toxic unit for human (CTUh)

All four models showing a relative low deviation in impact category human toxicity, non-carcnogenic, with trend to higher impact from average ECF processes (model 03 and 04).

Human toxicity: non-carcinogenic, comparative toxic unit for human [CTUh], Robustness Level III



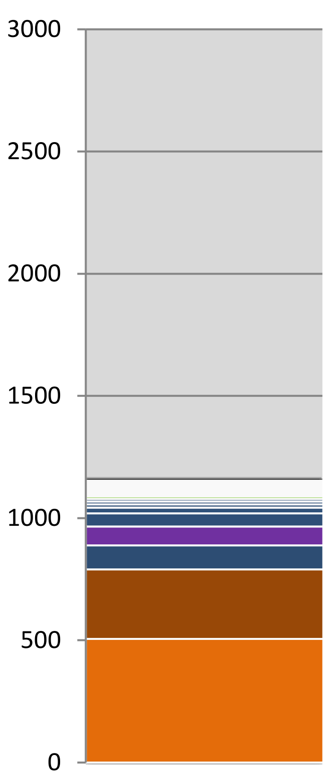
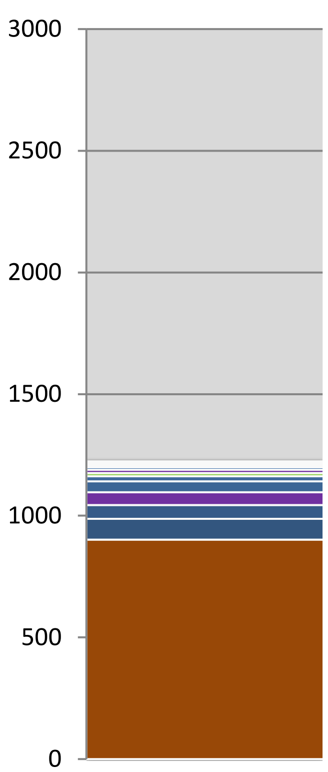
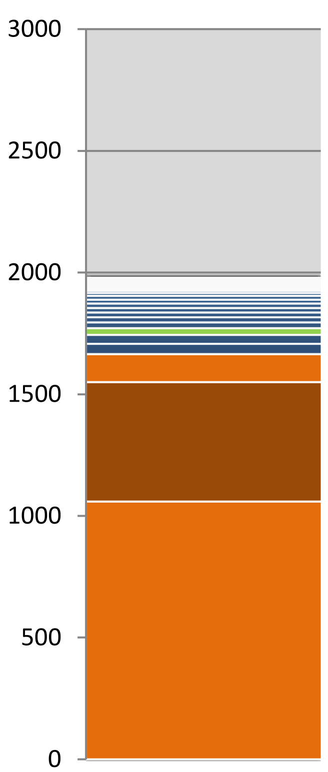
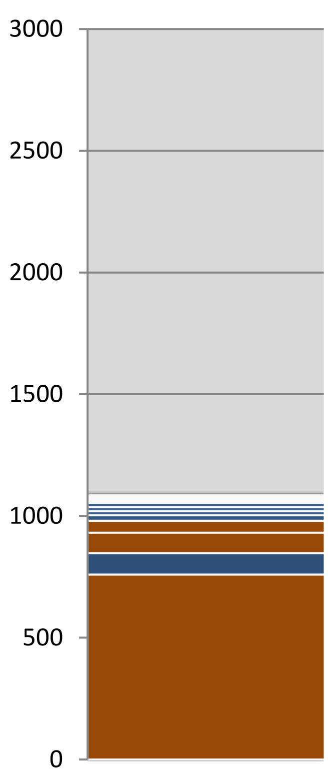
model 01		model 02		model 03		model 04	
1 ADMT pulp							
5,98E-06 CTUh		0,00000597 CTUh		0,0000078 CTUh		0,00000806 CTUh	
Byproduct E_{el}							
575 kWh	3,5E-07 CTUh	0 kWh	0 CTUh	252 kWh	0,00000024 CTUh	224 kWh	0,00000022 CTUh
Byproduct E_{th}							
278 kWh	6,0E-8 CTUh	0 kWh	0 CTUh	314,377 kWh	0,00000007 CTUh	711,111 kWh	0,00000017 CTUh
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
6,39E-06 CTUh		**6,39E-06 CTUh**		**8,11E-06 CTUh**		**8,45E-06 CTUh**	

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 27: Human toxicity, non-carcinogenic, of all four models.

4.2.16 Water use, water user deprivation potential (deprivation-weighted water consumption)

The model 01, 02 and 04 showing equal amount of water use.

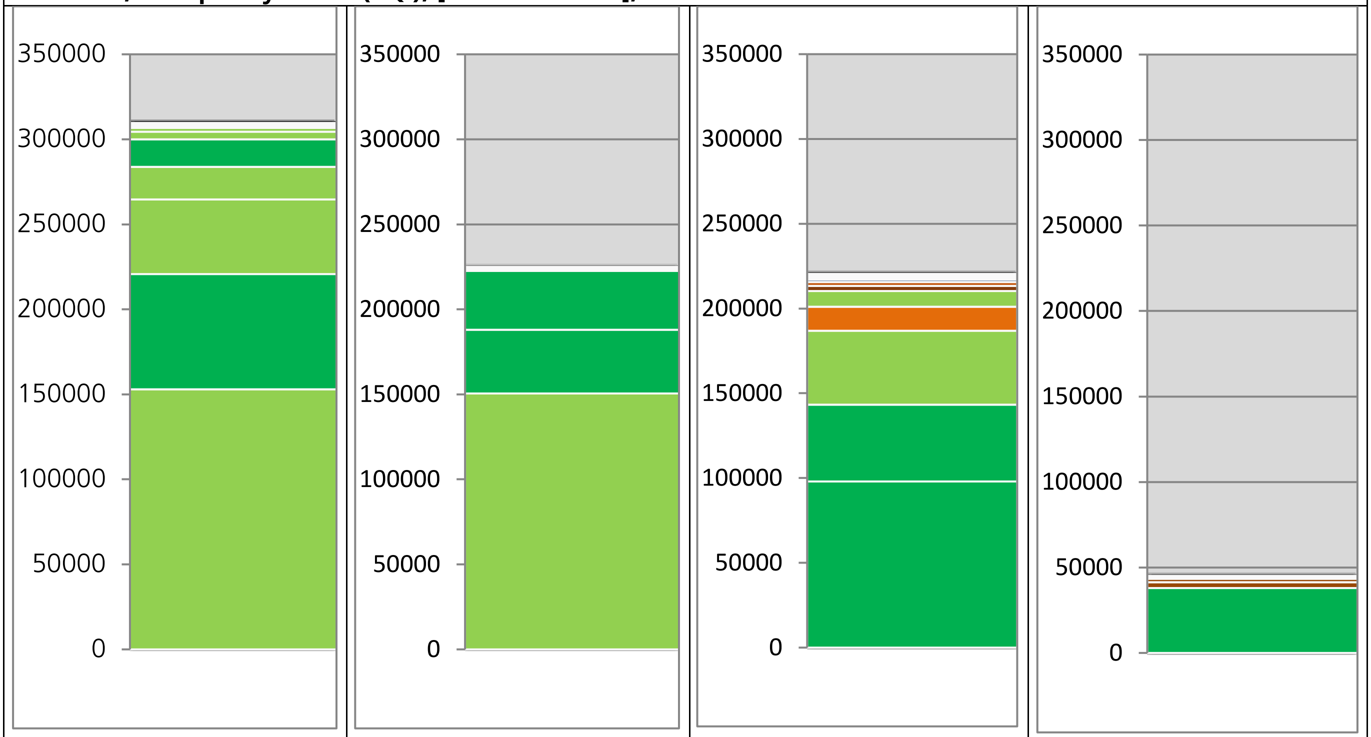
<table>
<tr><td colspan="8">Water use, water user deprivation potential (deprivation-weighted water consumtion), [m³ world-Eq. deprived], Robustness Level III</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">model 01</td><td colspan="2">model 02</td><td colspan="2">model 03</td><td colspan="2">model 04</td></tr>
<tr><td colspan="8">1 ADMT pulp</td></tr>
<tr><td colspan="2">1.160,255 m³ world-Eq. deprived</td><td colspan="2">1.221,224 m³ world-Eq. deprived</td><td colspan="2">1.893,259 m³ world-Eq. deprived</td><td colspan="2">933,554 m³ world-Eq. deprived</td></tr>
<tr><td colspan="8">Byproduct E_{el}</td></tr>
<tr><td>575 kWh</td><td>163,929 m³ world-Eq. deprived</td><td>0 kWh</td><td>0 m³ world-Eq. deprived</td><td>252 kWh</td><td>63,963 m³ world-Eq. deprived</td><td>224 kWh</td><td>83,329 m³ world-Eq. deprived</td></tr>
<tr><td colspan="8">Byproduct E_{th}</td></tr>
<tr><td>258 kWh</td><td>13,66 m³ world-Eq. deprived</td><td>0 kWh</td><td>0 m³ world-Eq. deprived</td><td>314,377 kWh</td><td>19,798 m³ world-Eq. deprived</td><td>711,111 kWh</td><td>66,134 m³ world-Eq. deprived</td></tr>
<tr><td colspan="8">Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})</td></tr>
<tr><td colspan="2">1.337,844 m³ world eq. deprived</td><td colspan="2">1.221,224 m³ world eq. deprived</td><td colspan="2">1.977,02m³ world eq. deprived</td><td colspan="2">1.083,017 m³ world eq. deprived</td></tr>
</table>

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 28: Land use, soil quality index, of all four models.

4.2.17 Land use, soil quality index

model 01 showing in comparison to model 04 a significant increase points of soil quality index.

Land use, soil quality index (SQI), [dimensionless], Robustness Level III							
							
model 01		model 02		model 03		model 04	
1 ADMT pulp							
282.027,432 dimensionless		224.540,198 dimensionless		210.688,828 dimensionless		42.373,338 dimensionless	
Byproduct E_{el}							
575 kWh	18.720,202 dimensionless	0 kWh	0	252 kWh	7.124,014 dimensionless	224 kWh	1.257,373 dimensionless
Byproduct E_{th}							
258 kWh	8.402,467 dimensionless	0 kWh	0	314,377 kWh	2.205,056 dimensionless	711,111 kWh	997,915 dimensionless
Sum of impacts (1 ADMT pulp + Byproduct E_{el} + Byproduct E_{th})							
309.150,100 dimensionless		**224.540,198 dimensionless**		**220.017,90 dimensionless**		**44.628,626 dimensionless**	

Forest Hardwood	Forest Softwood	Pulpmill Hardwood	Pulpmill Softwood	Pulpmill Infrastructure	Chemicals	Transport	Fossil fuel	Electricity from grid

Table 29: Land use, soil quality index, of all four models.

4.2.18 Evaluation of Biodiversity in wood feedstock of bioproduct mill Äänekoski

The ecoregion PA0608 “Scandinavian and Russian Taiga” was chosen to evaluate the forest system, which is the feedstock for the bioproduct mill at Äänekoski.
Most of the needed data is derived from an interview with a forest manager at Metsä Group. Supplementary information comes from publicly available statistical data from Natural Resources Institute Finland.

The ecoregion NT0103 “Rain Forest Region Bahia” was chosen to evaluate the forest system, which is the feedstock for the average pulp mill in Region Latin America. The needed data regarding the forest management activities aretaken over from sustainability report of a pulp producer in this region (Bracell Ltd., 2021).

The Ecoregion PA0445 “Western Europe Broadleaf Forests” is chosen to evaluate the TCF and ECF average pulp mills in Europe, because a significant part of wood feedstock for average mills is stemming from Region of Europe.

Lindner et al. (2019) and Lindner et al. (Lindner, 2020) describe the step-by-step determination of the quality level. A rough distinction is first made between land use types: forestry, pasture, arable, and mining. Within each land use type, the land use-specific biodiversity value (BV_{LU}) is determined (see below for details). The BV_{LU} indicates the proportion of the biodiversity potential that is reached within the quality range of the respective land use type. The standardised biodiversity value (BV_{loc}) is calculated from the BV_{LU} in two further transformation steps. The BV_{loc} indicates the level to which the local biodiversity potential (within a specific Ecoregion) is achieved (more on Ecoregions see below).
By weighting with the Ecoregion Factor (EF), the BV_{loc} is transformed into the global biodiversity value BV_{glo}. The BV_{glo} indicates to what extent the global biodiversity potential is achieved at the location of the process in question. The BV_{glo} corresponds to the quality as defined in the Land Use Framework. The quality level in the reference state is defined as $BV_{loc} = 1$, i.e. at global level the reference quality level differs from one ecoregion to another and corresponds to the EF. The quality difference (characterisation factor) is then $CF = \Delta Q = EF\ (1 - BV_{norm})$. Derived value of ΔQ determines the biodiversity value over use-time and area of the landscape under investigation. To determine the damage done to biodiversity by a land-use process, the characterisation factor is multiplied by the inventory variables area and time (summarised as area-time in m^2a).

Formula 1

$$Impact = (Q_{ref} - Q_0)*(t_{end} - t_0)*A = \Delta Q * \Delta t * A$$

Q_0 quality of area element in use (Assumption: $Q(t) = constant = Q_0$)
A value of area element (constant)

For the biodiversity value, the unit "Biodiversity Value Increment" (BVI) is introduced. It expresses that (a) the value of biodiversity is quantified, and that (b) this value is located on a continuous scale. (Lindner, Fehrenbach, Winter, Bloemer, & Knuepffer, Valuing Biodiversity in Life Cycle Impact Assessment, 2019). This allows a relation between the impact to biodiversity stemming from land use for delivery of wood related to produced end-products, in this case the FU of 1 t ADMT pulp in form of BVI/t.

The calculation is based on assumption, that yield of pulp from hardwood as eucalyptus, birch, and beech is equal. Significant variations has to be aware in occupied surface area for eucalyptus cultivation and in the very short crop rotation.
As one can see in Table 30 there is a significant difference in the harvest rotation of the tree species considered, eucalyptus (7 years), birch (60 years), and beech (140 years). Also differing in the harvested wood per area is stated.

Type of wood	Eucalyptus	Birch	Beech
Eco region code	NT 0103	PA 0608	PA 0445
Ecor region Factor (EF)	0,345	0,285	0,127
Needed amount of wood [m³]	5.000.000	5.000.000	5.000.000
Needed surface [ha]	20.000	10.000	10.000
Year/rotation [a]	7	60	140
Pulp [ADMT]	[redacted]	[redacted]	[redacted]

Table 30: investigation of biodiversity Index is held on comparison of Euycalyptus on Region Mina Gerais and Birch in boreal forest in northern Europe.

In Tables 31, 32 and 33 the calculation of the Biodiversity Values for the Forest management feedstock bioproduct mill Äänekoski, management feedstsock average European pulp mills, and the forest management for Eucalyptus feedstock for Latin American based pulp mills (Table 28) is documented.

Management of the forest system used as feedstock at Äänekoski shows a local Biodiversity Value [BVI_{loc}] of 0,9830 what is near to 1 as the highest value for local biodiversity value.

Short description, following (Lindner, 2020)	**Value**	**BV**
16 criteria are aggregated to Biodiversity Value land use forest	0,3959	BV_{lu}
The range of value of different biodiversity values from diverse types of landuse are brought to in a common interval of values. So the possible specific niveaus of hemerobie for specific types of land use came to comparability	0,8514	BV_{norm}
BV_{lu} is brought to Biodiversity Value local by integrating Biodiversity Value norm max (1) and Biodiversity Value norm min (0,75) as description of Hemerobie Level 1 till 5.	0,9830	BV_{loc}
Scandinavian and Russian Taiga (Eco Region)	0,2850	EF
BV_{loc} is multiplied with Ecoregion Factor (0,285) of chosen ecoregion "PA0608 Scandinavian and Russian Taiga" and give Biodiversity Value global.	0,2801	BV_{glo}
Quality difference, resulting from forest management	**0,0424**	**ΔQ**
Biodiversity Indicator per Functional Unit	**0,0208**	**BVI/FU**

Table 31: Biodiversity Increment of forest management for bioproduct mill Äänekoski

The damage to biodiversity done by forest management is described by ΔQ. For forest management at the Äänekoski bioproduct mill, the ΔQ is very low at a value of 0,0424 (Table 31), compared to forest management in Bahia, Brazil with a value ΔQ 0,072 (see Table 33).

Short description, following (Lindner, 2020)	Value	BV
16 criteria are aggregated to Biodiversity Value land use forest	0,2633	BV_{lu}
The range of value of different biodiversity values from diverse types of landuse are brought to in a common interval of values. So the possible specific niveaus of hemerobie for specific types of land use came to comparability	0,8188	BV_{norm}
BV_{lu} is brought to Biodiversity Value local by integrating Biodiversity Value norm max (1) and Biodiversity Value norm min (0,75) as description of Hemerobie Level 1 till 5.	0,9532	BV_{loc}
Western European Broadleaf Forest (Eco Region)	0,127	EF
BV_{loc} is multiplied with Ecoregion Factor (0,127) of chosen ecoregion "PA0445 Western Europe Broadleaf Forests" and give Biodiversity Value global.	0,1211	BV_{glo}
Quality difference, resulting from forest management	**0,0230**	**ΔQ**
Biodiversity Indicator per Functional Unit	**0,0265**	**BVI/FU**

Table 32: Biodiversity Increment of assumed forest management for model 01 and 02, average pulp mills in Europe.

4.2.19 Evaluation of Biodiversity in wood feedstock for ECF pulp mill in Region of Latin America

To enable an assessment of the impact of the cultivation of eucalyptus in plantation farming, the biodiversity index was determined for the economic cultivation area of a pulp mill in the region of Bahia, Brazil. As no detailed primary data is available, the information from a sustainability report from 2021 was used (Bracell, 2021).

In addition to the economically used cultivation areas, the pulp producer also operates activities on leased forest areas. Since no information on the liability of the leasing contracts can be taken from the report, the assumption is made that only the economically used cultivation area is used for the determination of the biodiversity index.

The result is that the management of the forest system used as feedstock at Bahia region of Brazil shows a local Biodiversity Value [BVI_{loc}] of 0,7552 what is lower than the 0,9858 BV_{loc} of the forest management around Äänekoski. Also the quality difference ΔQ 0,0722 is more impacting than the lower quality difference ΔQ 0,0416 in forest management around Äänekoski. It can be stated, that the highly biodiversity of ecoregion Bahia (NT0103 with a factor 0,345) endures the stress of monoculture forest management.

Short description, following (Lindner, 2020)	Value	BV
16 criteria are aggregated to Biodiversity Value land use forest	0,1487	BV_{lu}
The range of value of different biodiversity values from diverse types of landuse are brought to in a common interval of values. So the possible specific niveous of hemeroby for specific types of land use came to comparability	0,7906	BV_{norm}
Ecoregion Bahia (Ecoregion Factor)	0,3450	EF

BV_{lu} is brought to Biodiversity Value local by integrating Biodiversity Value norm max (1) and Biodiversity Value norm min (0,75) as description of Hemerobie Level 1 till 5.	0,7552	BV_{loc}
BV_{loc} is multiplied with Ecoregion Factor (0,285) of chosen eco region "N0102 Bahia Costal Forest" and give Biodiversity Value global.	0,3369	BV_{glo}
Quality difference, resulting from forest management	**0,0722**	**ΔQ**
Biodiversity Indicator per Functional Unit	**0,0088**	**BVI/FU**

Table 33: Biodiversity Increment of forest management for a Region Latin America-based pulp mill, in the region of Bahia, Brazil.

4.2.20 Comparing results of Biodiversity in wood feedstocks

In the biodiversity contribution land use (BV_{lu}), according to the information to land management activities provided by the client on forest management in the boreal forest in Northern Europe, the use of birch shows a comparatively high land use-specific biodiversity contribution, compared to forest management for the cultivation of beech in Western Europe, and eucalyptus in monoculture (see Figure 05).
The biodiversity contribution global (BV_{glo}) is calculated based on BV_{lu} in several steps (see 3.1.17). Accordingly, the BV_{glo} shows the biodiversity contributions from the land management activities with reference to the local biomes, based on the weighting with the strongly varying Eco Region Factor (EF). The results of BV_{glo} are not yet related to the product, there is no reference to the mass of wood produced. Only the impacts of the respective management are shown, multiplied with the biodiversity normally found locally in the biome (using the Eco Region Factor).

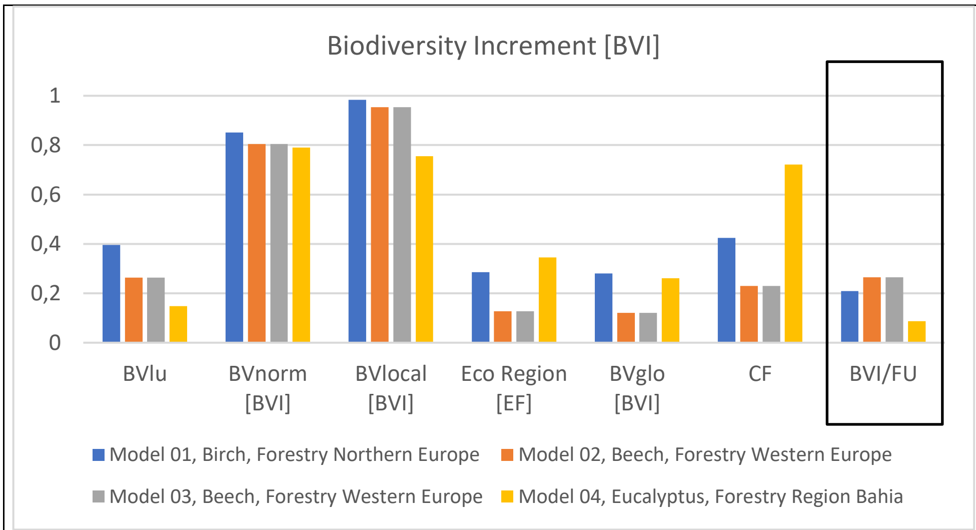


Figure 05: Calculation steps to derive Biodiversity Increment per Functional Unit (BVI/FU) following (Lindner, Fehrenbach, Winter, Bloemer, & Knuepffer, Valuing Biodiversity in Life Cycle Impact Assessment, 2019). To see from left, in column 04 is added given the Eco Region Factor [EF] and in column 6 the derived Correction Factor [CF] for orientation. Please note that in accordance with the LCA method, the BVI/FU (market with black frame) represents the impact on the environment.

The BV_{glo}, related to the functional unit 1 ADMT of bleached pulp, is shown in right sided coloumn of Figure 05. Here, the area and time required for producing of the raw material wood (Table 30) are integrated and broke down to the functional unit.

It must be point out, that investigation of biodiversity following this framework doesn't account for land use changes. This means, that a transformation phase happening before the investigated occupation phase (as must be expected in case of agroforest cultivation of eucalyptus in a rain forest region Bahia) is not reflected in this investigation of biodiversity, nor the possible degradation of occupied surface areas for cultivation of eucalyptus.

4.3 Results of sensitivity analysis

To investigate the robustness of allocation procedures a sensitivity analysis of allocation of wood based feedstock was carried out.

4.3.1 Sensitivity analysis of model 01, bioproduct mill Äänekoski

Based on description given in 1.2.4 The allocation procedures, there was at least four methods of allocation derived and used for the sensitivity analysis.

In following the results of a sensitivity analysis comparing two mass based allocation methods and the economy allocation is shown in Table 34.

The columns A, B, and C in Table 34 showing the impact results for the mass-based variation of allocated wood (A and B), whereas column C shows the economy allocation with given values in Eurocent.

- Column A exergy: allocation of exergy in by products
- Column B mass: mass-based allocation
- Column C econ: economic allocation

All three methods where normalized (sum up to 100%) to derive the standard deviation as indicator for possible significant deviation between the allocation procedures.
As shown in Table 34 the standard deviation (std. dev.) is maximum 2,8 for the impact category "12 Land use, soil quality index".
All other impact categories below 1,5 so no significant irregularities are to find, and the chosen mass-based allocation method is robust.

	Environmental Impact Category
1	acidification, accumulated aexceedance (ae)
2	climate change (GWP 100)
3	climate change: fossil, gloabal warming potential [GWP 100]
4	Ecotoxicity: freshwater, comparative toxic unit for ecosystems (CTUe)
5	Resource utilisation-fossil, Abiotic Depletion Potential (ADP): fossil fuels
6	Eutrophication, freshwater, fraction of nutritions reaching freshwater end compartment (P)
7	Eutrophication: marine, fraction of nutritions reaching freshwater end compartment (N)
8	Eutrophication: terrestrial, accumulated exceedance (ae)
9	Human toxicity carcinogenic, comparative toxic for human (CTUh)
10	Human toxicity: non carcinogenic, comparative toxic unit for human (CTUh)
11	Ionising radiation: human health, human exposure efficiency relative to u235
12	Land use, soil quality index
13	Material ressources, meatl/minerals, abiotic depletion potential (ADP): elements (ultimative reserves)
14	Ozone depletion, ozone depletion potential (ODP)
15	Particulate Matter formation, impact on human health
16	Photochemical ozone formation: human health, tropospheric ozone concentration increase

		sum of main- and by-products (pulp, heat, and electricity)			normalized to 100%			
	unit	A exergy	B mass	C econ	A exergy %	B mass %	C econ %	std. dev. %
1	mol H+-eq	2,91522639	3,02522662	3,01001498	32,570659	33,799647	33,629694	0,5437373
2	kg CO2-eq	251,7184845	271,3275174	269,2682881	31,77003	34,244935	33,985035	1,1105032
3	kg CO2-eq	247,5474342	266,7630171	265,3938591	31,748886	34,213357	34,037757	1,1226645
4	CTUe	6.192,614316	6.436,844796	6.350,666574	32,626835	33,913605	33,45956	0,5328501
5	MJ	3.917,519861	4.192,257755	4.176,282137	31,885893	34,122069	33,992038	1,0248706
6	kg PO4-eq	0,13764617	0,14262469	0,14169552	32,620175	33,800013	33,579813	0,5122295
7	kg N-eq	1,06432882	1,10398906	1,10204896	32,544631	33,757346	33,698023	0,5582224
8	mol N-eq	11,40006323	11,81367884	11,78053051	32,57694	33,758892	33,664167	0,536247
9	CTUh	2,93012E-07	3,07323E-07	3,05534E-07	32,345949	33,925737	33,728314	0,7028224
10	CTUh	0,00000624	0,00000639	0,00000639	32,807571	33,596215	33,596215	0,3717701
11	kg U235-eq	65,15657383	67,54556186	67,38728817	32,563727	33,757687	33,678586	0,5451511
12	dimensionless	256.841,8296	309.150,1002	309.116,2285	29,349724	35,327073	35,323203	2,8168376
13	kg Sb-eq	0,00343439	0,00352879	0,00335691	33,278683	34,193403	32,527914	0,6810305
14	CFC-11-eq	0,00004291	0,00004682	0,00004672	31,447417	34,312935	34,239648	1,3338801
15	disease incid.	0,00005277	0,00005355	0,00005341	33,037	33,525324	33,437676	0,2125726
16	kg NMOV-eq	3,21306707	3,40348871	3,39732525	32,086132	33,987709	33,926159	0,8822625

Table 34: sensitivity analysis is showing good comparability between three allocation methods, with acceptable low standard deviation. The highest standard deviation is to note at:"12 Land use, soil quality index" with a standard deviation of 2,8 % between all allocation methods.

A further sensitivity analysis was carried out, by variation of a main emission factor relevant in ECF bleaching, the emission of AOX.

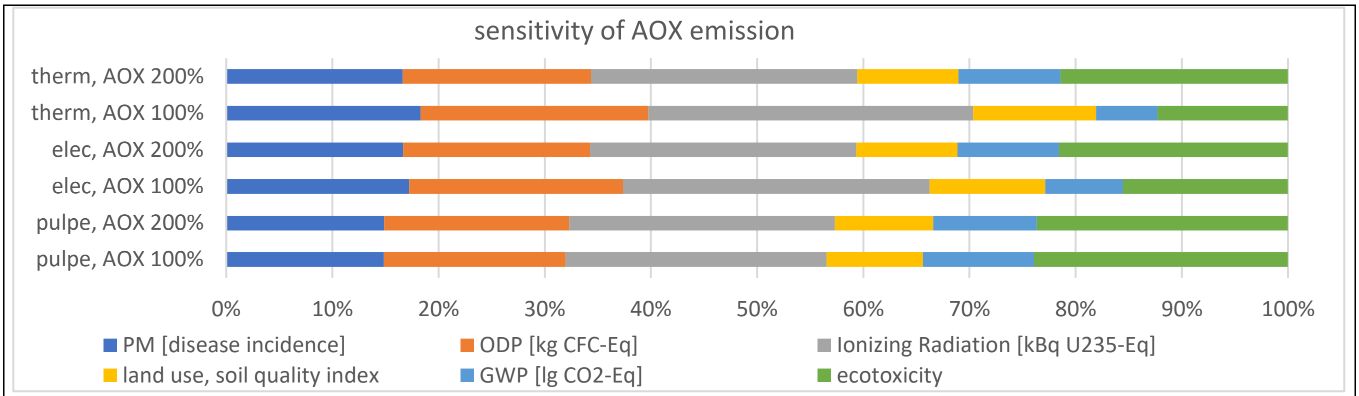


Figure 06: Variation of parameter AOX in model 01, normalized, so the area of the stacked columns represents the partition of the by-products electricity and heat in relation to the pulp-production of 1 ADMT.

The Variation of Parameter halogen compounds in model 01 was carried out to evaluate the impact of a double amount of AOX in an ECF pulp mill. It is expected a gained environmental impact in category ecotoxicity (Robustness Level III). The variation to double of AOX Emissions shows no significant change in ecotoxicity in the main product (pulp). Only the by-product thermal energy shows a near to significant increase of ecotoxicity, when AOX emission is doubled in model 01 (Figure 06). Model 01 shows the expected sensitivity to ecotoxicity under varying AOX emission.

5 Normalisation

As a supplementary presentation, the results are shown in a normalised format, related to the results of model 1. This normalisation step is intended to facilitate the assessment of the effectiveness of individual indicators in comparison with model 1.

Normalisation here refers to the mathematical reference of the results of all models to the results of model 1 as the reference value. For this purpose, the indicator values of all environmental impact categories examined are set to 100% for model 1 and the indicator values of the models to be compared are set proportionally to model 1. In this way, the contributions to the environmental impacts of the other three models are shown in relation to the environmental impacts of model 1 under investigation (Figure 07).

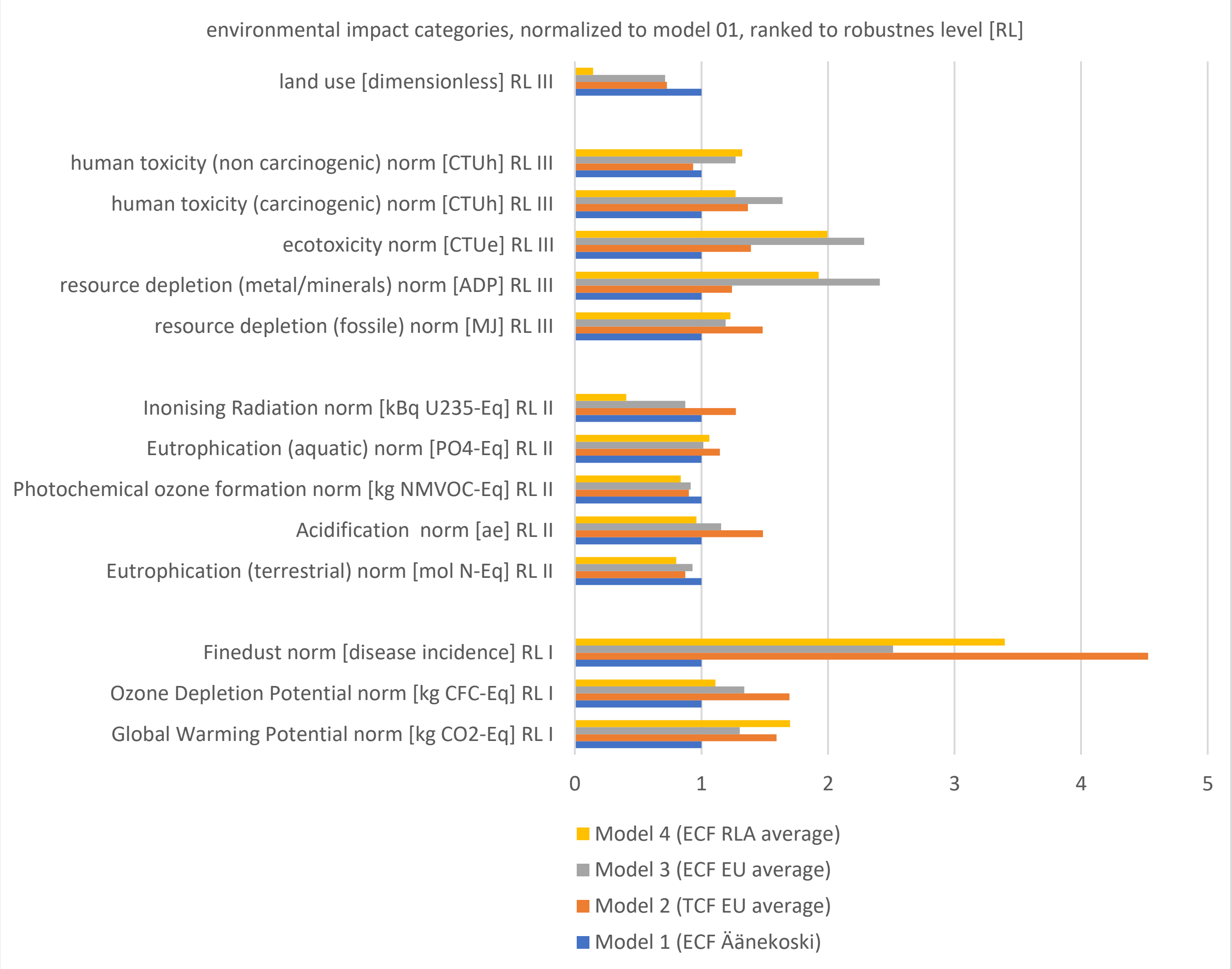


Figure 07: Environmental Impact, with (RL) robustness level I (GWP, Particulate Matter, Ozone Depletion Potential), and RL II (Eutrophication terrestrial, Acidification, Photochemical Ozone Formation, Eutrophication aquatic, Ionising radiation), and III (resource depletion fossil, resource depletion metal/minerals, ecotoxicity, human toxicity carcinogenic, human toxicity non carcinogenic, land use), is shown normalized to model 01 (ECF Äänekoski).

In the categories of robustness I, the models consistently show stronger influences on the environmental properties compared to model 01, significantly in the category of fine dust emission.

In the categories of robustness II, the models show slightly lower influences on the environmental properties compared to model 01; in the category of ionising radiation, model 04 shows a significantly reduced emission compared to the comparison models.

In the categories of robustness III, the environmental impacts of the comparative models are predominantly slightly above the significance threshold of 10%, with the environmental impacts above those of model 01. The categories human toxicity (carcinogenic), ecotoxicity, land use, and resource depletion of models 03 and 04 are significantly above the environmental impacts of model I. Especially for the land use category, the comparatively highest deviation in the sensitivity analysis should be pointed out, which suggests additional caution in the evaluation of this category.

6 Evaluation

Under the aspects of the objective of the study and the results shown in chapters 4 and 5, an evaluation now follows as a basis for the conclusions and recommendations in chapter 7.
All key determinations and assumptions, as well as the quality and uncertainty of data and information, and the selection and methods of impact assessment will be considered in the evaluation.

6.1 Completeness, consistence and data quality

The primary data submitted by the client were available in full for the planned consideration within the framework of "cradle to gate".

System boundaries, allocation rules and the calculations for impact assessment were applied uniformly to all four models. The relevance of the results of model 1 was tested by means of two sensitivity analyses. For this purpose, a sensitivity analysis was carried out by varying the emission of pollutants (AOX) and another sensitivity analysis was carried out on basis of two allocation rules for the wood raw material used (unweighted energy content, energy content weighted according to the principle of exergy).

The data quality and data symmetry of the LCA considered to be of good use from the point of view of the implementation of the LCA.

6.2 Significance of resulting values

Due to the data structure in LCAs, with partly unavailable statistical data and instead necessary estimations, error calculations with error propagation are not robust.

Ordered to identify relevant differences between the models, it should be noted that small differences in the indicator values are less significant than large differences. To provide guidance, a threshold value of 10% was used as the significance threshold. The LCA practitioners thus follow a pragmatic approach that is quite common in LCA practice. Due to the clear accounting framework, the LCA practitioners consider the results obtained here to be robust.

6.3 Assessment strategy

In order providing the target groups of the LCA comprehensive information on the environmental impacts of pulp production, the results of the study were classified according to the assessment proposal of the German Federal Environment Agency (Schmitz, 1999).

In the interpretation of the overall perspective, the robustness levels of the scientific methods (Table 03) on which the selected categories are based are also discussed and included in the ordering.

The impact categories with ordering descriptions for "ecological threat" and "distance to target" given from UBA are listed in Table 04.

Since the impact category Particulate matter has Robustness Level I and the Ionizing radiation potential has Robustness Level II, it is worth discussing whether these categories should be included in the overall perspective by implementing it in the Assessment strategy.
This also counts for the PM impact category, it may be assumed that the distance to target is to be classified as high, considering the development of the last decades for compliance with particulate matter pollution.

With regards to the increasing age of nuclear power plants and the ultimately open handling of nuclear waste, a large distance to target can also be assumed for the ionising radiation potential from the perspective of LCA practitioners. Regarding biodiversity also a large distance to target is assumed in general.

To include this further impact categories from EF 3.0 in order for assessment strategy, the robustness level was used, as described in following lines:

Impact categories without description of ecological stress and distance to target were in a first step grouped by robustness level. In a second step the not by UBA evaluated impact categories were valued with the average quality in its group of robustness level. Impact categories without a evaluation by UBA and a Robustness Level III were marked as "without ecological priority in context of this study" to give the indicated attention to the need for prudent assessment.

The resulting order for all investigated impact categories is shown in right column of Table 35.

Environmental impact category	Ecological threat	Distance to target	Robustness level (RL)	Ecological priority
Global Warming Potential	Very large (A)	Very large (A)	RL I	(A)
Ozone Depletion Potential	Very large (A)	Low (D)		(B)
Particulate Matter (fine dust)	not evaluated by UBA			(B)
Eutrophication (terrestrial)	Large (B)	Large (B)	RL II	(B)
Acidification	Large (B)	Large (B)		(B)
Photochemical Ozone formation	Low (D)	Large (B)		(D)
Eutrophication (aquatic)	Large (B)	Middle (C)		(B)
Ionizing radiation	Not evaluated by UBA			(B)
Resource depletion (fossil)	Large (B)	Large (B)	RL III	(B)
Ecotoxicity	not evaluated by UBA			n.n.
Land use	not evaluated by UBA			n.n.
Biodiversity Value	not evaluated by UBA		not eval.	n.n.

Table 35: Impact categories ordered under robustness level (RL), and following UBA recommendation also the "Ecological threat": grey (very large) and light grey (large priority), and "Distance to target": grey (very large) and light grey (large priority). Where the Ecological priority is n.n. means "without ecological priority in context of this study"..

The following prioritisation of the categories results from quality order, as shown in table 35, for the evaluation strategy:

1. very large ecological priority
- Global Warming Potential

2. large ecological priority
- Ozone Depletion Potential
- Particulate Matter
- Eutrophication (terrestrial)
- Acidification
- Ionising Radiation
- Resource Depletion (fossil)

3. middle ecological priority
- Eutrophication (aquatic)

4. Low ecological priority
- Photochemical Ozone formation

Without ecological priority in context of this study
- Ecotoxicity
- Land use
- Biodiversity Value

In chapters 3.1.1 to 3.1.19, the comparison between the models was already carried out and the influences on biodiversity from the production of hardwoods for pulp production were compared.

6.4 Interpretation of the results

Global Climate related impact:
Without model 01, in all production processes the production of pulp (pulp mill Hardwood in stacked bar chart coloured dark orange, pulp mill Softwood coloured orange) can be named as hot spot, or driver of **GWP 100a**. This results from the efficient use of energy from renewable resources at Äänekoski bioproduct mill for ECF pulp production from northern Europe hardwood and softwood (model 01). Used chemicals in TCF bleaching also can be named as a hot spot for relatively high GWP in model 02.
It can be sawn, that the **fossil based** raw materials and energy for the pulp mills (without in model 01) plays the important role in **GWP 100a**. Only model 4 shows a significant difference in the forest management. Because of using heavy machinery for Eucalyptus monoculture, the comparable low GWP in Forest management of model 04 is intending, that seedling production in Brazil is less energy intensive than seedlings production in northern hemisphere.

The potential for the formation of **ozone layer-depleting** molecules is quite similar in all ECF processes, where the TCF process shows significant intense potential compared to ECF process at Äänekoski. This is related to nitric oxide emissions from energy- intensive processes during chemical production or transport (model 02).

Human health related impact:
All model for pulp production using ECF bleaching processes show a comparable low fine dust load. The process at Äänekoski has significantly reduced **fine dust**, which demonstrates the technical possibilities in the use of pulp mills, as the main contributor in all cases is the production process for the pulp. The high emission of fine dust from the eucalyptus forestry (green coloured bar in stacked bar chart) in Latin America is worthy of note and related to plantation as forest management. Particulate Matter is emitted from transport, plowing and tilling the surface before planting each one of the eucalyptus trees (Bracem, 2020).

Combined with the energy mix used for production of the chemicals, all pulp processes show an exposure to **ionising radiation**. In model 04, due to the high share of renewable energy in the Latin American electricity mix given in secondary literature, the hazard potential from ionising radiation is comparatively low. In model 01, the use of sodium chlorate from European market shows the highest impact from ionising radiation related to the European energy mix.

Ozone formation in the lower layers of the Earth's atmosphere is stimulated to a comparable extent in all processes. This is due to nitrogen oxides and volatile organic compounds (VOC) emitted from the energy-intensive pulp mills.

The ECF pulp mill Äänekoski shows a comparable low value for Comparative Toxic Unit für humans (CTUh) stemming from category **Human toxicity, carcinogenic**, with almost no impacts from pulp processing, because of the avoided burning of fossil fuels (reduced amount of hydrocarbons aromatic, chloride and fluoride near to the ground). The comparable high impact from the

European market for softwood chips in model 03 is related to transport of the wood chips during marked activities and their production.

The average ECF processes show a higher CTUh stemming from category **human toxicity, non-carcinogenic**, compared to TCF bleaching, but the ECF pulp mill Äänekoski shows a comparable low impact as the model 02 with ECF bleaching.

Resource utilisation:
Abiotic Depletion Potential (ADP) related to the use of fossil fuels reflects in all models the needed amount of chemicals for pulping and bleaching, because of their need of facilities and energy during their production. Also, required energy during processing is counted in ADP related to fossil fuels and transport, as model 02 for European averaged TCF pulping shows with comparable high impact.

The ECF process at Äänekoski resulting in nearly the same **abiotic depletion potential (ADP), metal/minerals** as the TCF process. In contrast, the ECF in the average pulp mills of Europe and Latin America resulting in a significant stringer impact under aspect of ADP compared to model 01. The construction of facilities for pulp production is a significant contributor to ADP, followed from bleaching agents. In the ECF process in average Latin American mills, the chemicals are the main driver for ADP. model 03 shows also high impact from softwood chip production to ADP, which reflects transport and warehousing of wood chips.

Land use:
In comparison, the TCF bleaching method shows a significant exceedance of accumulated critical loads in sensitive terrestrial areas and freshwater ecosystems resulting in so called **Acidification**. All ECF-related models show nearly the same accumulation of critical loads, in model 01 and model 02 the lowest values [ae]. In each case, the pulp mill operation itself is the main driver (orange stacks in stacked columns), wherein the TCF pulp production shows a significant accumulation of critical loads, followed by bleaching agents (blue stacks in stacked columns) with nearly the same contribution in each production system.

Main impact to category of **Eutrophication, terrestrial** stems in all models from pulp mill operation, related to inert wastes and use of sludge. The impacts from forest management to eutrophication terrestrial, accumulated exceedance are related to fertilizers in breeding and soil management in forest.

The influence on eutrophication in freshwater is about the same in all ECF models in **phosphorus transported to the freshwater system**, and results from the use of bleaching agents. model 02 TCF bleaching is showing higher amount of phosphorus transported to the freshwater system.

The influence on eutrophication in freshwater is about the same in models 1, 2 and 4 regarding **nutrition transported to marine water systems**, and results from pulp processing, followed by forest management and pulping chemicals. model 3 as ECF pulp from European production is showing the highest transport of N to freshwater end compartment.

Except for the ECF pulp production based on eucalyptus in the average Latin American pulp mills, both ECF and TCF systems in the European average and at Äänekoski show a high indicator value for **land use** according to the current **Soil Quality Index (SQI**). The comparatively low indicator value in model 04 can be attributed to agroforest plantation management of eucalyptus with a comparable strong reduction of SQI because of short harvest rotation of 7 years for eucalyptus, compared to birch 60 years or beech 150 years.

The SQI as result in model 01 bioproduct mill Äänekoski showing the comparable largest number of points, because the use of wood from thinning activities for pulping in Äänekoski results in a larger area of land, needed for forest management. But herein arises a methodological question, because the LANCA® based indicator SQI in category land use actual does actual not reflect the different qualities of forest management in needed resolution. (De Laurentiis, et al., 2019) A significant difference in quality of forest management is to see in values of BV_{lu}, see Figure 04, whereas the forest management of wood feedstock for bioproduct mill Äänekoski showing a high biodiversity value, compared to the cultivation of eucalyptus.

<u>Biodiversity</u>:
The method of biodiversity assessment is carried out for all four models within the framework of the present study, but with comparative assessment to be limited to the raw material hardwood. The investigation of eucalyptus cultivated in agroforest monoculture has to interpreted cautiously.

Due to the activities of sustainable forestry (soil cultivation, plant protection, etc.), management in the Northern European Forest leads to a high contribution to biodiversity, while the contribution to biodiversity from eucalyptus cultivation in monoculture in the Bahia region, in comparison, is low. This is reflected by the biodiversity contribution related to land use (BV_{lu}), describing the contribution to biodiversity resulting from activities in local forest management.

After weighting the BV_{lu} with the Eco Region Factor, it becomes apparent that the contributions to biodiversity are strongly influenced by the local biomes. Despite the lower BV_{lu}, the plantation operation for production of eucalyptus shows a comparatively high biodiversity in BV_{glo}, due to the high biodiversity basically present in Bahia, compared to the biodiversity in Northern Europe, according to the Eco Region Factor.

In relation to the production of the amount of wood required to produce the Functional Unit 1 ADMT, eucalyptus shows a comparatively low impact on biodiversity. However, this results from drastically shorter cultivation cycles (eucalyptus 7 years, birch 60 years), which also compensate for the lower wood yield in relation to area in eucalyptus cultivation.

6.5 Evaluation in line with assessment strategy

In the following, the balance results from 4.1.1 to 4.1.19 are evaluated using the significance threshold and the evaluation strategy.

Table 36 shows the results of the life cycle assessment comparison of the models according to the evaluation strategy, using a colour code. In the colour code, "green" stands for lower and red for higher indicator results of model 01 compared to the models 01, 03 and 04 to be compared. The colour "grey" marks differences that are below the significance threshold. The rules for the assessment strategy is to find in chapter 6.3.

	model 01	model 02	model 03	model 04
Very large ecolgical priority				
Gloabal Warming Potential				
Large ecological priority				
Ozone Depletion Potential				
Particulate Matter				
Eutrophication (terrestrial)				
Acidification				
Ionising radiation				
Ressoruce Depletion (fossil)				
Middle ecological priority				
Eutrophication (aquatic)				
Low ecological priority				
Photochemical ozone formation				
Without ecological priority in context of this study *** cautious interpretation, because quality of land use is not reflected in used type of SQI** **** cautious interpretation needed, because changes of land use is not reflected within BVI**				
Ecotoxicity				
Land use (SQI)				*
Biodiversity Increment (BVI)				**

Table 36: Evaluation of the LCA results according to the evaluation strategy, orientated to UBA method considering "biological thread" and "distance to target" and "Robustness Level" (Schmitz, 1999)

As can be seen from the colour coding in *Table 36*, model 01 shows the lowest environmental impacts across all ecological priorities, compared to models 02, 03 and 04. In the second most important ecological priority, the categories Ionising radiation and Eutrophication (terrestrial) point to model 04 as the one with the lowest environmental impacts. Models 02 and 03 show similarly high environmental impacts.

The indicators on land use and biodiversity show a contrasting assessment, in Table 36, which points to the need for caution in the evaluation of these results.

As discussed above, both methods, land use and biodiversity contribution, show a methodological gap in the relevant aspect of land conversion.
In context of this study, this becomes visible in the investigation of the biodiversity increment BVI, where the biodiversity contribution from the quality of land use (the respective practised forest management) shows a high performance for the conservation and promotion of biodiversity in forest

management for the bioproduct mill Äänekoski, while in relation to the area and time used for wood production in the BVI/FU, an inverted picture emerges. This is mainly due to the short harvesting rotation of agroforestry management of eucalyptus plantations in geographical regions of the rainforest and secondly due to the non-robustly assessed aspects of land conversion for periods before and after agroforestry use.
Since the secondary data set used for the agroforestry rainforest already shows a 15% decline in timber yield in the second harvest rotation, the LCA stakeholders consider the evaluability of the results obtained here to be uninterpretable based on the currently available evaluation criteria in the given study framework.

6.6 Constraints

Within the framework of the defined boundary conditions, the results of the comparative investigations carried out on pulp production are, in the opinion of the authors, reliable. If the defined boundary conditions are deviated from, the following restrictions must be taken to account for a further application of the results.

Limitations regarded to the biodiversity assessment:

- A simplifying assumption was made in relation to the cultivation of forest wood by only including the sourcing of hardwood in the biodiversity assessment (in northern Europe birch and in Region Latin America eucalyptus).
- A simplifying assumption was made regarding the cultivation of eucalyptus in the Latin American region, in which the methods of agroforest plantation management were taken from a sustainability report of a pulp producer made available to the general public.
- A simplifying assumption regarding harvest rotation in short rotation eucalyptus was adopted from secondary literature (ecoinvent, 2021), according to which the yield already in the second harvest rotation after 7 years the yield of eucalyptus wood decreases significantly by 15 to 20%.
- In order to carry out the investigation of the biodiversity contributions from sustainable forestry and the cultivation of Eycalyptus in plantations, the simplifying assumption was made that the method used here (Lindner, Fehrenbach, Winter, Bloemer, & Knuepffer, Biodiversität in Ökobilanzen - Weiterentwicklung und vergleichende Studien, 2020) the agroforest of eucalyptus wood can be assigned to the land use type of forestry.
- The used method for biodiversity assessment does not reflect influences from land use changes in a robust way

Limitations with regard to land use category

- for LANCA® based impact category in EF 3.0 for Land Use (Robustness Level III) challenges to further development of characterisation factors, special for changes of land use identified: "The lack of characterisation factors to be used for reversible land transformation that already include considerations on the regeneration time." (De Laurentiis, et al., 2019)

Limitations regarding the data used:

- The use of other secondary data sets, or other primary data may lead to a different assessment of the comparative evaluation.
- The results of this study only apply to the use of the primary data provided by the client for this study, and the secondary data stemming from the the environmental database in release versions stated above.

Restriction in view of the global pulp trade and geographical scope:

- It should be clearly noted that no transcontinental transports of raw materials, semi-finished products or products are included in this study, as the focus was on a comparison of pulp production.

Limitations due to the choice of valuation methods:

- The selection of indicators was made in consensus with critical experts.
- The procedure of the UBA for the assessment of environmental impacts was used as a guideline.
- The use of other indicators can lead to a different assessment of the comparative evaluation; this is due to the LCA method.

7 Conclusions and Recommendations

In this chapter, special aspects of this study are dealt with again in a compact form. It discusses the insights that can be derived from the results presented above.
Here, the target aspects of the study are briefly presented once again:

- Technologies producing pulp fibres from hardwood and softwood were comparatively investigated. The focus was on the two bleaching processes chlorine-free and total chlorine-free. Four models were used to compare pulp mills, representing the European average of pulp mills for both bleaching processes (ECF and TCF) as well as the bioproduct mill Äänekoski (ECF). In addition, an average pulp mill (ECF) for the Latin American region was included in the comparison.
- Primary data was used in the foreground system of the Bioprodukt Mill, which depicts the average annual production of this mill, which has been operating since 2016. 2021 was chosen as the reference year. The modelling of the paper mills includes fibre production including purification of the auxiliary materials and partly the production of energetic by-products thermal and electrical energy. As no primary data on the production of bleaching chemicals or the operation of average paper mills in Europe or the Latin American region could be made available, secondary data was used:
    - The data sets used for the average pulp mills in Europe and Latin America come from the ecoinvent 3.8 database and are based on surveys from 2015 with an extrapolated validity until 2020.
    - Chemicals required for fibre extraction and fibre bleaching, data on raw material extraction, production and transport were taken from the ecoinvent 3.8 database. This database also contains background data on the energy mix used in each region. Since the study compares the technologies in the "cradle to gate" balance framework, no intercontinental transports were accounted for.
    - Hardwoods and softwoods as feedstock for pulp production come mainly from the geographical regions of pulp production (150 to 500 km surrounding area) and predominantly from certified forestry, according to FSC. The data on forestry in all four models come from the ecoinvent 3.8 database. For the Äänekoski bioproduct mill, primary forestry data was provided in interviews and used for a Biodiversity Increment (BVI) study.
- To investigate the impact of pulp production on regional biodiversity, the novel method of biodiversity increment (BVI) was used. Due to data gaps on the yield of Eucalyptus monocultures and due to open questions regarding the sustainable land use by Eucalyptus monocultures, the BVI can only provide a rough orientation and is seen from the actors of this LCA as not interpretable.
    - Aspects of biodiversity pose growing challenges for the preservation of global ecosystems, which is why the method for representing the BVI was used here as an example despite questions that are still open.

- In the present study, an evaluation strategy was used to make the results usable in the target groups:
    - By following the UBA methodology (Schmitz, 1999), environmental impact categories are classified under the aspects of "ecological priority" and "distance to the ecologically desirable state" and are thus more easily accessible for comparative assessments.
    - Robustness Levels I to III of the indicators underlying the environmental categories were highlighted
    - The results are presented in summary form according to the categories of climate impact, impact on human health and impact on land use:

Global climate related impact:
The contribution of model 01 “bioproduct mill Äänekoski” to the **Global Warming Potential (Robustness I)** is reduced in comparison to the average European pulp production with ECF bleaching, although the contribution from the mill operation (orange colour code in stacked bar charts) of the bioproduct mill is significantly reduced compared to ECF pulp mills in the European average. Compared to TCF pulp mills the bioproduct mill shows a significantly reduced GWP impact, as well as compared to ECF production in the Latin American average.

Beside the mill operation as a hot spot for GWP, it has to pointed out, that production and supply of process chemicals also significantly determine the GWP impact.
Production and Transport of Chemicals shows main impact under aspect of **Ozone Depletion Potential (Robustness I)** in all average technology pulp mills, only in bioproduct mill Äänekoski the forest system contributes as a hot spot to ODP.

Human health related impact:
The mill operation of bioproduct mill Äänekoski is relevant for low emission of **Particulate Matter (Robustness I)** in comparison to the average pulp mills with ECF and TCF bleaching. The main impact to PM in model 01 is stemming from used chemical, so mill operation is second stage of impact. Also hotspot are the used chemicals in impact category **Ionising radiation (Robustness Level II)**, what is related to used energy mix for chemicals production, as can be seen in comparable low impact in Latin America average pulp mill. (Energy mix in RLA uses large potential of hydropower and other renewables).

The impact on **human toxicity (Robustness III)** from Äänekoski bioproduct mill is tending low, in comparison to average ECF and TCF mills, but there is no significant difference.

Land use related impact:
The **Soil Quality Index** from the aggregated impact category Land Use **(Robustness III)** is related to the forest as feedstock used in pulp mills. Äänekoski bioproduct mill shows a high range of Soil Quality Index points in comparison to the ECF pulp production on the European average and all other models, because of the modelled use of wood from thinning out for pulp production a larger area of forest is needed. From the data collection for the optionally determined **Biodiversity Indicator (no robustness estimated)**, the index of the feedstock for the bioproduct mill, it is known that the secondary dataset for Swedish forest management is sufficiently accurate and represents a conservative assumption for the accounting of land use, especially with regard to clear-cutting because of use of wood from thinning out for bioproduct mill Äänekiski.
The Soil Quality Index points for forest used as feedstock for the average Latin American ECF pulp production is quiet low compared to the average use of Northern European hard- and softwood. This is related to short crop rotation of agroforest management in eucalyptus cultivation, but the accessible state of the art indicator sets for BVI and SQI do not reflect aspects of changes in land use. From sight of the LCA actors a conclusion based on state of the art is not possible and further scientific investigations are needed.

7.1 Summary

In parallel to evaluation strategy oriented to UBA method using the ordering principles of "ecological thread" and "distance to target" and "Robustness Level" (*Table 36*) the Äänekoski bioproduct mill shows advantages also when a simple comparison of the impact categories from the average pulp mills (ECF and TCF bleaching) is done.
As to find in Figure 06, setting a significance threshold of 10% to ensure significance of resulting values, the bioproduct mill shows advantages in all environmental impact categories of Robustness Level I:

- **Global Warming Potential (Robustness I)**
- **Ozone Depletion Potential (Robustness I)**
- **Particulate Matter (Robustness I)**
- **Human toxicity (Robustness Level III)**
- **Resource utilisation (Robustness Level III)**
- **Ecotoxicity (Robustness Level III)**

The Äänekoski bioproduct mill shows equivalent results (significance threshold 10%) in the impact categories of the life cycle assessment comparison with the average pulp mills that using also ECF bleaching:

- **Acidification (Robustness Level II)**
- **Eutrophication (Robustness Level II)**
- **Photochemical Ozone formation (Robustness Level II)**
- **Ionising radiation (Robustness Level II)**
- **Human toxicity (Robustness III)**
- **Water user deprivation potential (Robustness Level III)**

The average Latin American based paper mill with ECF bleaching shows advantage results (significance threshold 10%) in the impact categories of the life cycle assessment comparison with the average European pulp mills and bioproduct mill Äänekoski:

- **Ionising radiation (Robustness Level II)**
- **Photochemical Ozone formation (Robustness Level II)**

Diametral to bioproduct mill Äänekoski (25% difference in numbers) the average European paper mill with TCF bleaching shows disadvantages (significance threshold 10%) in comparison to the average pulp mills (ECF bleaching) and the Äänekoski bioproduct mill in the following impact categories:

- **Ozone Depletion Potential (Robustness Level I)**
- **Particulate Matter Formation (Robustness Level I)**
- **Acidification (Robustness Level II)**
- **Ionising Radiation (Robustness Level II)**

7.2 Conclusion and recommendation to the client

The environmental goals in the operation of bioproduct mill Äänekoski are climate protection, protection of fossil resources, minimisation of pollutant emissions and maximised biodiversity in the forestry operations for the provision of the wood raw material.

The results obtained in this system study for the Environmental Footprint categories show that the required use of chemicals for fibre production and bleaching has an influence on the majority of the environmental impact categories.
For the conservation and enhancement of biodiversity, the forestry practices reported by the client are suitable for a further reduction of the "distance to target" in the area of biodiversity.

Based on the results of the study, possible "levers" for a further reduction of the environmental impact of bioproduct mill Äänekoski are listed here:

- Strengthen cooperation with suppliers of essential chemicals to gain further insight into the environmental impacts of chemical production and transport. Primary data on the production and transport of essential chemicals can further improve the assessment of environmental impacts. Approaches for further reduction of environmental impacts include optimising the energy mix for the production of the necessary chemicals or expanding the recovery or on-site production of required chemicals, using the energy from renewable sources available at bioproduct mill Äänekoski.

- Constructive cooperation with the forestry sector should be further developed and recommended in paper industry bodies for further dissemination.
- Similarly, the efficient design and operation of high temperature heat recovery boilers and chemical recovery systems should be recommended for further dissemination in paper industry bodies.
- Communication to end-users should follow the resource-efficient paper approach, proactively pointing out that forestry is available but not infinite.

7.3 Conclusion and recommendation to stakeholders

The sensitivity analyses show a robustness of the results of this study, nevertheless it should be noted that the method of LCA results in an assessment of a variety of differently robust indicators.
In order to give objective assessment as possible, the results were classified according to an evaluation strategy (see Chapter 6.5) based on the UBA method. Accordingly, it can be concluded that the Äänekoski bioproduct mill, compared to the technical average in pulp production, can be assessed as advantageous in both ECF and TCF bleaching regarding to the environmental impact categories investigated.

It became clear that the investigation of the biodiversity contribution of forest management in the feedstock for the Äänekoski bioproduct mill allows a well-founded assessment of the biodiversity increment. When investigating the biodiversity contribution of eucalyptus cultivation on land in rainforest regions, questions are raised about land use that make it necessary to specify the method, what also is mentioned in scientific literature (De Laurentiis, et al., 2019) and (Vidal-Legaz B & RFM, 2016)

7.4 Conclusion and recommendation to the interested public

The sensitivity analyses show that the results of this study are robust, but it should be noted that the LCA method results in an assessment of large number of indicators within varying robustness. A final evaluation of the results presented can be significantly influenced by subjective value attitudes towards the individual environmental impact categories examined. For this reason, too, according to the LCA standard, a focus on individual environmental categories is not permissible, since only the overall view of the indicator sets of the Environmental Footprint provides the basis for an objective assessment.
In order to objective assessment as possible, the results were classified according to an evaluation strategy (see Chapter 6.5) based on the UBA method. Accordingly, it can be concluded that the Äänekoski bioproduct mill, compared to the technical average in pulp production, can be assessed as advantageous in both ECF and TCF bleaching regarding to the environmental impact categories investigated.

It is recommended that those involved in the public discussion point out the advantages of virgin fibre pulp from the Äänekoski bioproduct mill as shown in the life cycle assessment, without concealing disadvantages, or pointing out further optimisation potential, such as the (environmentally) conscious use of renewable raw materials.

Since the sum parameter AOX is a main point of interest for the assessment of human toxicity (Robustness Level III), detailed explanations and studies on AOX are attached in the Annex for the interested reader.

7.5 Outlook

The client has indicated that, due to the successful operation of the Äänekoski bioproduct mill, the use of efficient systems for the recovery of processing chemicals and process energy will be taken to account for further planning of production sites. An example of this is the commissioning of the production facility in Kemi, Finland.

Additional information´s: Water emissions from the bioproduct mill Äänekoski, pulp transport impact, tissue product analysis and an overview of existing reference works and LCA studies

Briefly description of Äänekoski bioproduct mill water emissions

With the highest levels of energy, material and environmental efficiency in the world today's bioproduct mill in Äänekoski stands out. Although the modernization to a bioproduct mill has almost tripled the production capacity compared to that of the previous pulp mill at Äänekoski, it can operate within the emission limits of the previous mill's environmental permit and wastewater permit conditions. Its emissions do not affect the recreational or other use of the natural water system. An advanced closed cycle in which water and chemicals are recycled and returned to the process for reuse is key in the bioproduct mill's processes.

Chemical analyses to ECF wastewater in Äänekoski bioproduct mill:

In addition to regular long time running measurements in processes controlling the Äänekoski bioproduct mill has adopted a detailed analysis of wastewater. That results show that the data from the international studies are consistent with the measurements at Äänekoski. Metsä fibre Äänekoski bioproduct mill uses the best available techniques (BAT) and is based on current most modern ECF bleaching technology. Water emissions and wastewater flow has been minimized and most of the values are even below BAT-AEL limit values. In BAT BREF document both bleaching methods (ECF, TCF) are accepted.
General BAT conclusions for the pulp and paper industry, BAT-associated emission levels for bleached kraft pulp mills. BAT comparison to Äänekoski bioproduct mill. Additional to the regular wastewater tests in the Äänekoski bioproduct mill were in May 2022 analyzes from the Fresenius Institute performed. The Fresenius Institute measured in 2022 as well emissions clearly lower as the BAT-AEL limit values. Especially the new AOX, COD and Phosphorus measurements from May 2022 were even lower compared to the average values from 2021.

AOX is a sum parameter. It does not allow any implications of the harmfulness of the effluent as such. The level of AOX indicates only the possibility for multiple chlorination. With values of AOX above 1 kg/ADMT, the probability of multiple chlorination is elevated. With values lower than 0,5 kg/ADMT practically no tetrachlorinated substances are created, the Äänekoski bioproduct mill has a 4 times lower AOX emission of 0,11 kg/t. Eurofins has tested waste waters and no dioxins nor furans can be detected from the waste water effluents. The data was shown in section 2.1. Data collection Table 05: emission values from ECF technology in comparison with Äänekoski mill showing values significant below the emissions of Best Available Technologies (BAT).

In studies carried out after the research rounds in 1995, concentrations of almost all chlorophenols in shellfish were zero (0). Studies carried out in the 2000s showed that concentrations were further reduced. The literature studies as well as the present analysis in this study show that modern pulp mills using elemental chlorine-free (ECF) bleaching, with wastewater being treated in an active sludge plant, do not cause harmful emissions of organochlorine compounds into watercourses.

For decades, wastewater from the forest industry and its effects have been the subject of extensive scientific research. These studies have addressed the chemical composition of wastewater and its transformation in water bodies and the resulting effects, both through laboratory tests and field studies. The main-focus of the studies was on major process changes (bleaching and wastewater treatment) in the 1980s and 1990s. Among other things, AOX, measured from wastewater, was an essential variable in wastewater impact studies. Since then, research activity has clearly decreased and most recent studies have mainly been related to observation studies and monitoring. This explains the fact that most of the references are also derived from studies carried out in the aforementioned decades. Summaries of these studies and their results have been regularly carried out. Based on these summaries, information was collected on the environmental impact of ECF and total chlorine-free (TCF) bleaching factories in the aquatic environment for both Metsäteollisuus ry (Finnish Forest Industry Association) and the Nordic Swan Ecolabel (Tana et al. 2009 and 2011).
In practice, treated wastewater from pulp and paper mills using ECF bleaching does not contain polychlorinated dibenzodioxins or other persistent bio accumulative toxic compounds. Chlorine-containing organic compounds resulting from ECF bleaching are comparable to natural compounds, are naturally biodegradable, are not persistent in nature and do not pose risks to the environment in aquatic ecosystems. Overall, total wastewater toxicity in modern mills is very low and does not correlate with AOX concentrations. At present, there is no evidence to show that reducing the AOX content of wastewater from 0.5 kg per tonne would bring demonstrable environmental benefits and there is no international consensus on AOX emission limits. The effects of modern mills (e.g. sublethal toxicity to aquatic organisms) cannot be predicted solely on the basis of bleaching fractions. In the future, environmental impact assessments should focus on aspects of mill production other than bleaching (e.g. wood treatment, pulping, washing, temporary leaks and condensates). The organic halogens (OX) contained in the mass of pulp or paper are an appropriate parameter for assessing the environmental friendliness of the ECF mass. In the last five years, no studies have been published to the same extent on wastewater from the production of ECF-bleached pulp. In Canada, the effects of wastewater from pulp and paper mills have recently been studied. This research activity has mainly focused on fish reproductive impact studies and on environmental monitoring of methodological development and the impact at the ecosystem level. However, recent studies have not revealed any changes to the above conclusions from the 1990–2002 studies. Based on current knowledge, there are no demonstrable differences in the environmental impact in relation to AOX emissions between 0,05 and 0,20 kg per tonne.

Impact of pulp transport on Global Warming Potential

Pulp Fibres for European paper production are usually scoured in Europe or in Latin America. In a sensitivity analyses, the environmental impact of transport routes was investigated. Significant relevance for the Global Warming Potential was found, the transport from Helsinki to Rotterdam was 5 times lower compared to the carbon footprint of a transportation from Brazil to Rotterdam.

The aggregated ecoinvent 3.8 data set for sea transport was used to map the environmental impact from the transport effort for marketing in Europe (destination port Rotterdam).
According to this, the sea transport of 1 t pulp Helsinki-Rotterdam causes 24,25 kg CO_2-eq and the sea transport of 1 t pulp Barao De Teffe (Brazil) - Rotterdam 120,15 kg CO_2-eq.

Chemical analysis of tissue end products from ECF and TCF and toxicity analysis of tissue and waste water

Since the produced pulp fibres from bio product or pulp mills are not the final end product additional analysis were done by the SGS Fresenius institute to complement the study with information's of impurities and toxicology differences of end products. Since hygienic products like tissue paper are used for food and skin contact, impurity analysis can reveal potential differences which could have impact on the usage in skin or food contact.

14 different German toilet paper and household towel samples were according to DIN and EN ISO methods of mineral oil, bisphenol, Chloride, Nitrate, chlorinated organic compounds, 3-MCPD (3-chloro-1,2-propandiol), 1,3 DCP (1,3-Dichloro-2-propanol), EDTA, DTPA, Bisphenol A-Z, luminescent bacteria toxicity analyzed. The detailed description of methods and results can be found in the full SGS Fresenius report in the appendix.

The target was to find out if products made from TCF, ECF or recycling show different impurities and as well different levels of toxicology.

Impact of bleaching on AOX and OX levels:

Recycling fibres are always a mix of different wood fibres which were bleached with ECF or TCF, however since worldwide 96% of the chemical pulp is bleached with ECF the recycling products contain mainly ECF bleached fibres. The OX and AOX values are the sum of all organically bound halogens, OX = components in the paper and AOX are absorbable organically bound halogens. Since OX and AOX are a sum of unidentified components the values cannot indicate if the single components can be harmful to the skin or in food contact OX represents the total sum of all organically bound halogens in the products and AOX is the value of extracted organically bound halogens. Since the AOX and OX values can`t be used to indicate if products are harmful, the "Bundesintitut für Risikobewertung" (BFR) has no limits for AOX nor OX in the regulation BFR XXXVI for paper, carton and paper for food contact. Thus, AOX and OX values are only additional information, the BFR has clear limits for harmful single components such as MCPD, DCP as well as Bisphenol A and S which were measured as well.

The recycling samples had an OX between 72-121 mg/kg, revealing that the recycling products were a mix of fibres with a high share of ECF pulp, which is not surprising since the ECF bleaching technology is nowadays the dominating bleaching technology.
Pure TCF fresh fibre products showed an OX between 0 and 35 mg/kg.
The remaining fresh fibre tissue samples were either a mix of ECF and TCF or pure ECF products with an OX level between 68 mg/kg up to 141 mg/kg.

The AOX level of all products was between 0,2 and 3,1 mg/kg depending of the bleaching method and paper additives used for the fibres. TCF samples had a AOX of 0,2-1,4 mg/kg, recycling tissues were between 0,7-1,8 mg/kg, the wood fibre based ECF/TCF mix products had a AOX of 1,1 - 2 mg/kg. Only the bamboo tissue sample showed an exceptional high AOX level of 3,1 mg/kg.

Residual peroxide was not found.

Chloride values variated for recycling and fresh fibre samples between 45 and 520 mg/kg, the highest Chloride value was found in a TCF household towel product, but in recycling were as well values up to 300 mg/kg found.

Nitrate values variated as well the highest values were found in the TCF samples and in the Bamboo sample.

Crucial for the evaluation of critical components for food contact are MCPD and DCP. According to BFR XXVI and ÖKO-TEST considers a too high MCPD and DCP value as most critical for food contact. Since MCPD and DCP are a by-products of the wet strength resins used especially for the household towel production, in higher levels occurred in the household towel products. All MCPD and DCP values were below the BFR XXXVI limit of 12 µg/l for MCPD and 2 µg/l for DCP, however some producers seem to use higher shares of wet strength resins or additives with higher MCPD and DCP shares. The average MCPD share for the towel products was 2,59 µg/l, but the product made of wood Fibre and grass particles had a exceptional high MCPD value of 4,8 µg/l. The reason could be the lower strength of the fine grass particles and the higher demand of wet strength resin to achieve the target towel quality. Grass particles have no ability to form a tissue network and can be seen as a kind of fine filler material which could result in a higher chemical additive dosage in tissue products.

DCP was only found in four products again the product made of wood fibre and grass particles had the highest value with 0,3 µg/l, 0,1 µg/l higher compared to the other products.

EDTA values between 0,06 and 0,3 mg/kg were measured only some samples didn`t contain EDTA. The EDTA values of the recycling and fresh fibres followed no trend, EDTA was present in recycling and fresh fibre products in same size.

DTPA was not detected in the samples.

Mineral oil impurities were found partly of high levels in the recycling tissue, only the printed fresh fibre tissue sample contained small mineral oil amounts.

One recycling sample had an exceptional high mineral oil level above 300 mg/kg.

Bisphenol A and Bisphenol S are according to BFR XXVI critical for paper with food contact. Due to the fact that Bisphenols only occur in recycling products only few fresh fibre products were tested to ensure that in fresh fibre products are really no Bisphenols, which was the case. Therefore, not all fresh fibre products were analyzed of Bisphenols.
Since 2016 Bisphenol A is according to the European chemical association classified as toxic for the reproduction of humans. The limit before the chemical becomes toxic was set from BFR to only 0,04 ng/kg body weight. The Bisphenol occurs in recycling products. When recycling towel products are used in contact with fat, oil, meat the Bisphenol can contaminate the food. Bisphenol A and S are currently seen as most critical. Fresenius analyzed all Bisphenol variations from A to Z in all recycling products and some chosen fresh fibre products as a control. Only Bisphenol A was found in all recycling products and Bisphenol S in one recycling product, the fresh fibre products didn`t contain any Bisphenol. Other Bisphenol variations were not found.

Toxicity analysis were performed by Fresenius according to DIN 38412-L34 with luminescent bacteria. The detailed method can be found in the Fresenius toxicity report appendix. The tissue samples were extracted with 500 ml of water and the water was applied at the bacteria culture. The GL level describes the toxicity / inhibition effect on the luminescent bacteria. As higher the value as more dilutions were need until less 20% of the bacteria were not inhibited, thus as higher the GL level as higher the toxicity for the bacteria culture.

The G2 is the lowest value, which was achieved, here only one dilution was needed until less than 20% of the bacteria were inhibited.

The lowest level G2 was achieved most of the sample revealing general a low level of toxicity in average. However, three recycling tissue samples had higher GL toxicity values between 6-8.
The fresh fibre tissue products were very low in toxicity with a GL level of 2, only the product with a mix of gras fibres showed a slightly higher GL of 3, which is still at a very low level compared to the three recycling products with a GL between 6-8.

As well the Äänekoski incoming and outgoing water was analysis. The incoming water had a level of G2 and the wastewater only of G3 which indicates a very low impact on the inhibition / toxicity of the bacteria.

		Recycling				
Sample		**220371990**	**220371996**	**220371991**	**220371997**	**220371998**
Product type		**Toilet**	**Toilet**	**Household towel**	**Household towel**	**Household towel**
Fibre material		Recycling	Recycling	Recycling	Recycling	Recycling
Bleaching method		ECF-TCF	ECF-TCF	ECF-TCF	ECF-TCF	ECF-TCF
AOX	mg/kg	1,5	0,8	1,8	0,7	1,1
OX	mg/kg	107	72	121	81	116
Chloride	mg/kg	140	114	240	210	300
Nitrate	mg/kg	4,2	2	3	1,6	10
3-MCPD	µg/L	0,2	0,7	1,3	1,9	2,8
1,3-DCP	µg/L	0,2	n.d.	n.d.	n.d.	0,2
EDTA	mg/kg	0,1	n.d.	0,09	n.d.	n.d.
DTPA	mg/kg	n.d.	n.d.	n.d.	n.d.	n.d.
SUM MOSH/MOAH	mg/kg	11	100	13	305	96
Aromatic MOAH	mg/kg	n.d.	n.d.	0,7	0,9	n.d.
Bisphenol A	mg/kg	3	6	11	5	6
Bisphenol S	mg/kg	n.d.	n.d.	n.d.	n.d.	1
Bisphenol AF-Z	mg/kg	n.d.	n.d.	n.d.	n.d.	n.d.
Toxicity lum. Bacteria	GL	8	2	8	2	6

Table 37: Result of chemical analysis of recycling fibre based tissue products.

		Fresh Fibre Mix ECF & TCF and full ECF				
Sample		**220371992**	**220371993**	**220372152**	**220372153**	**220372000**
Product type		**Toilet**	**Household towel**	**Household towel**	**Household towel**	**Household towel**
Fibre material		Fresh Fibre - wood	Fresh Fibre - wood	Fresh Fibre - wood	Fresh Fibre - wood-gras	Fresh Fibre - bamboo
Bleaching method		mix ECF-TCF	ECF	mix ECF-TCF	mix ECF-TCF	ECF
AOX	mg/kg	2	1,5	1,1	1,1	3,1
OX	mg/kg	115	141	99	68	140
Chloride	mg/kg	45	140	280	440	200
Nitrate	mg/kg	3,2	3	6	9	17
3-MCPD	µg/kg	n.d.	2,2	3,4	4,9	2,3
1,3-DCP	µg/kg	n.d.	n.d.	0,2	0,3	n.d.
EDTA	mg/kg	0,06	0,3	0,16	0,13	n.d.
DTPA	mg/kg	n.d.	n.d.	n.d.	n.d.	n.d.
SUM MOSH/MOAH	mg/kg	n.d.	n.d.	11	13	n.d.
Aromatic MOAH	mg/kg	n.d.	n.d.	n.d.	0,7	n.d.
Bisphenol A	mg/kg	Not tested	Not tested	n.d.	n.d.	n.d.
Bisphenol S	mg/kg	Not tested	Not tested	n.d.	n.d.	n.d.
Bisphenol AF-Z	mg/kg	Not tested	Not tested	n.d.	n.d.	n.d.
Toxicity lum. Bacteria	GL	2	2	2	3	2

Table 38: Result of chemical analysis of fresh fibre based mix or ECF tissue products.

		Fresh Fibre full TCF			
Sample		**220371994**	**220371995**	**220371999**	**220372151**
Product type		**Toilet**	**Household towel**	**Household towel**	**Household towel**
Fibre material		Fresh Fibre - wood	Fresh Fibre - wood	Fresh Fibre - wood	Fresh Fibre - wood
Bleaching method		TCF	TCF	TCF	TCF
AOX	mg/kg	0,4	0,2	0,5	1,3
OX	mg/kg	18	35	30	n.d.
Chloride	mg/kg	100	150	520	190
Nitrate	mg/kg	4	2,2	28	17
3-MCPD	µg/kg	0,8	2	2,8	2,3
1,3-DCP	µg/kg	n.d.	n.d.	n.d.	0,2
EDTA	mg/kg	0,07	0,07	0,1	n.d.
DTPA	mg/kg	n.d.	n.d.	n.d.	n.d.
SUM MOSH/MOAH	mg/kg	n.d.	n.d.	n.d.	n.d.
Aromatic MOAH	mg/kg	n.d.	n.d.	n.d.	n.d.
Bisphenol A	mg/kg	Not tested	n.d.	Not tested	Not tested
Bisphenol S	mg/kg	Not tested	n.d.	Not tested	Not tested
Bisphenol AF-Z	mg/kg	Not tested	n.d.	Not tested	Not tested
Toxicity lum. Bacteria	GL	2	2	2	2

Table 39: Result of chemical analysis of fresh Fibre based TCF tissue products.

Conclusion of chemical analyses to ECF and TCF bleached fresh fibre:

To conclude all recycling products showed a higher content of contamination with impurities, thus recycling fibres should be seen more critical for the usage in hygienic products like tissue and rather be used for non-hygienic or food contact like cardboard packaging. ECF and TCF wood fresh fibre products were equally low in terms of impurities. Only the nitrate values were for some TCF products higher. Fresh Fibre products with a mix of grass Fibre and bamboo Fibre had surprisingly high impurities and should be questioned in terms of hygienic or food contact usage.

Conclusion of toxicity analyses of tissue products and effluent water in Äänekoski:

The toxicity level of the bioproduct mill effluent water compared to the incoming water (2 GL) increased only slightly (to 3 GL) revealing significant low toxicity levels.
Tissue sample toxicity of ECF vs. TCF was similar, no impact from AOX nor OX in toxicity was found. In general, freshfibre tissue at low toxicity levels (2 - 3 GL), only three recycling products were at a higher toxicity level (6 – 8 GL).
APPENDIX

The LCI of the four models are shown in Tables 40 to 43, please see below.

The first 8 Lines in model 01 and model 03 are to read as the allocated by-products from ratio 36/64 from HardWood/SoftWood produced kg of pulp. The following linses in model 01 and model 03 giving the input-output related to 1 kg in case of mass (pulp) and 1 kWh in case of energy (by-product heat or electricity).

Because of model 02 gives no by-products, as no secondary data for by-product from TCF pulp mill is available (see chapter assumptions) there is a simple input-output balance. That's also the case for model 04 ECF pulp from RLA based mills, because of single used feedstock eucalyptus.

Input model 01 ECF Äänekoski

Material	Coefficient	Unit
by-product heat from prod 0,64 kg SW pulp	[redacted]	kWh
by-product electricity from prod 0,64 kg SW pulp	[redacted]	kWh
by-product electricity from prod 0,36 kg HW pulp	[redacted]	kWh
by-product heat from prod 0,36 kg HW pulp	[redacted]	kWh
pulp bleached from HW	[redacted]	kg
pulp bleached from SW	[redacted]	kg

Output model 01 ECF Äänekoski

Material	Coefficient	Unit
by-product electricity	[redacted]	kWh
by-product heat	[redacted]	kWh
pulp bleached	[redacted]	kg

Input SW pulp production

Material	Coefficient	Unit
wood chips, wet, measured as dry mass	[redacted]	kg
sulphuric acid	[redacted]	kg
Water, unspecified natural origin [natural resource/in water]	[redacted]	m3
sodium chlorate, powder	[redacted]	kg
magnesium sulphate	[redacted]	kg
ethylene glycol	[redacted]	kg
carbon dioxide, liquid	[redacted]	kg
trichloroacetic acid	[redacted]	kg
cleft timber, measured as dry mass	[redacted]	kg
oxygen, liquid	[redacted]	kg
methanol, from biomass	[redacted]	kg
hydrogen peroxide, without water, in 50% solution state	[redacted]	kg
malusil	[redacted]	kg
quicklime, milled, loose	[redacted]	kg
sodium hydroxide, without water, in 50% solution state	[redacted]	kg
sodium formate	[redacted]	kg
transport, freight train	[redacted]	metric ton*km
transport, freight, lorry >32 metric ton, EURO5	[redacted]	metric ton*km
pulp factory	[redacted]	unit
electricity, high voltage, renewable energy products	[redacted]	kWh

Output SW pulp production

Material	Coefficient	Unit
pulp bleached	[redacted]	kg
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	[redacted]	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Chlorine [air/urban air close to ground]	[redacted]	kg
COD, Chemical Oxygen Demand [water/surface water]	[redacted]	kg
hazardous waste, for incineration	[redacted]	kg
inert waste	[redacted]	kg
Methane, non-fossil [air/urban air close to ground]	[redacted]	kg
Nitrogen [water/surface water]	[redacted]	kg
Nitrogen oxides [air/urban air close to ground]	[redacted]	kg
Non-hazardous waste disposed [inventory indicator/waste]	[redacted]	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	[redacted]	kg
Phosphorus [air/urban air close to ground]	[redacted]	kg
Phosphorus [water/surface water]	[redacted]	kg
Sulphur dioxide [air/urban air close to ground]	[redacted]	kg
Suspended solids, unspecified [water/surface water]	[redacted]	kg
Water [air/unspecified]	[redacted]	m3
Water [water/unspecified]	[redacted]	m3

Input SW by-product electricity

Material	Coefficient	Unit
cleft timber, measured as dry mass	[redacted]	kg
Water, unspecified natural origin [natural resource/in water]	[redacted]	m3
sodium hydroxide, without water, in 50% solution state	[redacted]	kg
sodium chlorate, powder	[redacted]	kg
hydrogen peroxide, without water, in 50% solution state	[redacted]	kg
sodium sulphate, anhydrite	[redacted]	kg
methanol	[redacted]	kg
sulphuric acid	[redacted]	kg
calcium carbonate, precipitated	[redacted]	kg
sodium formate	[redacted]	kg
methanol, from biomass	[redacted]	kg
ozone, liquid	[redacted]	kg
quicklime, milled, loose	[redacted]	kg
sodium sulphite	[redacted]	kg
chemical, organic	[redacted]	kg
sodium hypochlorite, without water, in 15% solution state	[redacted]	kg
sulphur	[redacted]	kg
malusil	[redacted]	kg
sulphur dioxide, liquid	[redacted]	kg
pulp factory	[redacted]	unit
chemical, inorganic	[redacted]	kg
magnesium sulphate	[redacted]	kg
oxygen, liquid	[redacted]	kg
wood chips, wet, measured as dry mass	[redacted]	kg

Output SW by-product electricity

Material	Coefficient	Unit
electricity, high voltage	[redacted]	kWh
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	[redacted]	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Chlorine [air/urban air close to ground]	[redacted]	kg
COD, Chemical Oxygen Demand [water/surface water]	[redacted]	kg
Formaldehyde [air/urban air close to ground]	[redacted]	kg
hazardous waste, for incineration	[redacted]	kg
Hydrogen chloride [air/urban air close to ground]	[redacted]	kg
Hydrogen fluoride [air/urban air close to ground]	[redacted]	kg
Hydrogen sulphide [air/urban air close to ground]	[redacted]	kg
inert waste	[redacted]	kg
Methane, non-fossil [air/urban air close to ground]	[redacted]	kg
Nitrogen [water/surface water]	[redacted]	kg
Nitrogen oxides [air/urban air close to ground]	[redacted]	kg
Particulates, < 2.5 um [air/unspecified]	[redacted]	kg
Particulates, > 10 um [air/urban air close to ground]	[redacted]	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	[redacted]	kg
Phosphorus [air/urban air close to ground]	[redacted]	kg
Phosphorus [water/surface water]	[redacted]	kg
Sulphur dioxide [air/urban air close to ground]	[redacted]	kg
Suspended solids, unspecified [water/surface water]	[redacted]	kg
Water [air/unspecified]	[redacted]	m3
Water [water/unspecified]	[redacted]	m3

Input SW by-product heat

Material	Coefficient	Unit
cleft timber, measured as dry mass	[redacted]	kg
sodium hydroxide, without water, in 50% solution state	[redacted]	kg
sodium chlorate, powder	[redacted]	kg
hydrogen peroxide, without water, in 50% solution state	[redacted]	kg
sodium sulphate, anhydrite	[redacted]	kg
methanol	[redacted]	kg
sulphuric acid	[redacted]	kg
calcium carbonate, precipitated	[redacted]	kg
sodium formate	[redacted]	kg
wood chips, dry, measured as dry mass	[redacted]	kg
methanol, from biomass	[redacted]	kg
ozone, liquid	[redacted]	kg
quicklime, milled, loose	[redacted]	kg
sodium sulphite	[redacted]	kg
chemical, organic	[redacted]	kg

Output SW by-product heat

Material	Coefficient	Unit
heat, district or industrial, other than natural gas	[redacted]	MJ
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	[redacted]	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Chlorine [air/urban air close to ground]	[redacted]	kg
COD, Chemical Oxygen Demand [water/surface water]	[redacted]	kg
Formaldehyde [air/urban air close to ground]	[redacted]	kg
hazardous waste, for incineration	[redacted]	kg
Hydrogen chloride [air/urban air close to ground]	[redacted]	kg
Hydrogen fluoride [air/urban air close to ground]	[redacted]	kg
Hydrogen sulphide [air/urban air close to ground]	[redacted]	kg
inert waste	[redacted]	kg
Methane, non-fossil [air/urban air close to ground]	[redacted]	kg
Nitrogen [water/surface water]	[redacted]	kg
Nitrogen oxides [air/urban air close to ground]	[redacted]	kg

sodium hypochlorite, without water, in 15% solution state	[redacted]	kg
sulphur	[redacted]	kg
malusil	[redacted]	kg
sulphur dioxide, liquid	[redacted]	kg
pulp factory	[redacted]	unit
chemical, inorganic	[redacted]	kg
magnesium sulphate	[redacted]	kg
oxygen, liquid	[redacted]	kg
Water, unspecified natural origin [natural resource/in water]	[redacted]	m3

Particulates, < 2.5 um [air/unspecified]	[redacted]	kg
Particulates, > 10 um [air/urban air close to ground]	[redacted]	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	[redacted]	kg
Phosphorus [air/urban air close to ground]	[redacted]	kg
Phosphorus [water/surface water]	[redacted]	kg
Sulphur dioxide [air/urban air close to ground]	[redacted]	kg
Suspended solids, unspecified [water/surface water]	[redacted]	kg
Water [air/unspecified]	[redacted]	m3
Water [water/unspecified]	[redacted]	m3

Input HW pulp production

Material	Coefficient	Unit
pulp factory	[redacted]	unit
Water, unspecified natural origin [natural resource/in water]	[redacted]	m3
trichloroacetic acid	[redacted]	kg
transport, freight, lorry >32 metric ton, EURO5	[redacted]	metric ton*km
transport, freight train	[redacted]	metric ton*km
sodium hydroxide, without water, in 50% solution state	[redacted]	kg
sodium chlorate, powder	[redacted]	kg
quicklime, milled, loose	[redacted]	kg
oxygen, liquid	[redacted]	kg
methanol, from biomass	[redacted]	kg
malusil	[redacted]	kg
magnesium sulphate	[redacted]	kg
hydrogen peroxide, without water, in 50% solution state	[redacted]	kg
ethylene glycol	[redacted]	kg
cleft timber, measured as dry mass	[redacted]	kg
carbon dioxide, liquid	[redacted]	kg
sulphuric acid	[redacted]	kg
electricity, high voltage, renewable energy products	[redacted]	kWh

Output HW pulp production

Material	Coefficient	Unit
pulp bleached	[redacted]	kg
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	[redacted]	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	[redacted]	kg
COD, Chemical Oxygen Demand [water/surface water]	[redacted]	kg
hazardous waste, for incineration	[redacted]	kg
inert waste	[redacted]	kg
Methane, fossil [air/urban air close to ground]	[redacted]	kg
Nitrogen [water/surface water]	[redacted]	kg
Nitrogen oxides [air/urban air close to ground]	[redacted]	kg
NMVOC, non-methane volatile organic compounds, unspecified origin [air/urban air close to ground]	[redacted]	kg
Non-hazardous waste disposed [inventory indicator/waste]	[redacted]	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	[redacted]	kg
Phosphorus [air/urban air close to ground]	[redacted]	kg
Phosphorus [water/surface water]	[redacted]	kg
Sulphur dioxide [air/urban air close to ground]	[redacted]	kg
Suspended solids, unspecified [water/surface water]	[redacted]	kg
Water [air/unspecified]	[redacted]	m3
Water [water/unspecified]	[redacted]	m3

Output HW by-product electricity

Material	Coefficient	Unit
cleft timber, measured as dry mass	[redacted]	kg
sodium formate	[redacted]	kg
calcium carbonate, precipitated	[redacted]	kg
sodium hydroxide, without water, in 50% solution state	[redacted]	kg
quicklime, milled, loose	[redacted]	kg
electricity, high voltage	[redacted]	kWh
sodium sulphate, anhydrite	[redacted]	kg
malusil	[redacted]	kg
hydrogen peroxide, without water, in 50% solution state	[redacted]	kg

Output HW by-product electricity

Material	Coefficient	Unit
electricity, high voltage	[redacted]	kWh
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	[redacted]	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Chlorine [air/urban air close to ground]	[redacted]	kg
COD, Chemical Oxygen Demand [water/surface water]	[redacted]	kg
Formaldehyde [air/urban air close to ground]	[redacted]	kg
Hydrogen chloride [air/urban air close to ground]	[redacted]	kg
Hydrogen fluoride [air/urban air close to ground]	[redacted]	kg

methanol, from biomass	[redacted]	kg
oxygen, liquid	[redacted]	kg
sulphur dioxide, liquid	[redacted]	kg
magnesium sulphate	[redacted]	kg
transport, freight train	[redacted]	metric ton*km
sulphuric acid	[redacted]	kg
pulp factory	[redacted]	unit
sodium chlorate, powder	[redacted]	kg

Hydrogen sulphide [air/urban air close to ground]	[redacted]	kg
inert waste	[redacted]	kg
Methane, non-fossil [air/urban air close to ground]	[redacted]	kg
Methanol [air/urban air close to ground]	[redacted]	kg
Nitrogen [water/surface water]	[redacted]	kg
Nitrogen oxides [air/urban air close to ground]	[redacted]	kg
Particulates, < 2.5 um [air/unspecified]	[redacted]	kg
Particulates, > 10 um [air/urban air close to ground]	[redacted]	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	[redacted]	kg
Phosphorus [air/urban air close to ground]	[redacted]	kg
Phosphorus [water/surface water]	[redacted]	kg
Sulphur dioxide [air/urban air close to ground]	[redacted]	kg
Suspended solids, unspecified [water/surface water]	[redacted]	kg
Water [air/unspecified]	[redacted]	m3
Water [water/unspecified]	[redacted]	m3

Input HW by-product heat

Material	Coefficient	Unit
sulphuric acid	[redacted]	kg
magnesium sulphate	[redacted]	kg
sulphur dioxide, liquid	[redacted]	kg
oxygen, liquid	[redacted]	kg
methanol, from biomass	[redacted]	kg
hydrogen peroxide, without water, in 50% solution state	[redacted]	kg
malusil	[redacted]	kg
sodium sulphate, anhydrite	[redacted]	kg
chemical, organic	[redacted]	kg
quicklime, milled, loose	[redacted]	kg
sodium hydroxide, without water, in 50% solution state	[redacted]	kg
calcium carbonate, precipitated	[redacted]	kg
sodium formate	[redacted]	kg
cleft timber, measured as dry mass	[redacted]	kg
Water, unspecified natural origin [natural resource/in water]	[redacted]	m3
sodium chlorate, powder	[redacted]	kg
pulp factory	[redacted]	unit

Output HW by-product heat

Material	Coefficient	Unit
heat, district or industrial, other than natural gas	[redacted]	MJ
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	[redacted]	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	[redacted]	kg
Chlorine [air/urban air close to ground]	[redacted]	kg
COD, Chemical Oxygen Demand [water/surface water]	[redacted]	kg
DOC, Dissolved Organic Carbon [water/surface water]	[redacted]	kg
Formaldehyde [air/urban air close to ground]	[redacted]	kg
Hydrogen chloride [air/urban air close to ground]	[redacted]	kg
Hydrogen fluoride [air/urban air close to ground]	[redacted]	kg
Hydrogen sulphide [air/urban air close to ground]	[redacted]	kg
Methane, non-fossil [air/urban air close to ground]	[redacted]	kg
Nitrogen [water/surface water]	[redacted]	kg
Nitrogen oxides [air/urban air close to ground]	[redacted]	kg
Particulates, < 2.5 um [air/unspecified]	[redacted]	kg
Particulates, > 10 um [air/urban air close to ground]	[redacted]	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	[redacted]	kg
Phosphorus [air/urban air close to ground]	[redacted]	kg
Phosphorus [water/surface water]	[redacted]	kg
Sulphur dioxide [air/urban air close to ground]	[redacted]	kg
Suspended solids, unspecified [water/surface water]	[redacted]	kg
Water [air/unspecified]	[redacted]	m3
Water [water/unspecified]	[redacted]	m3

Table 40: Life Cycle Inventory of model 01, Sulphate pulp (ECF), Äänekoski bioproduct mill.

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Input model 02 sulphate pulp bleached, Material	Coefficient	Unit
magnesium sulphate	0,00360000	kg
carbon dioxide, liquid	0,00200000	kg
ozone, liquid	0,00300000	kg
malusil	0,00200000	kg
EDTA, ethylenediaminetetraacetic acid	0,00300000	kg
organic nitrogen fertiliser, as N	0,00020000	kg
sulphur dioxide, liquid	0,00600000	kg
hydrogen peroxide, without water, in 50% solution state	0,02640000	kg
oxygen, liquid	0,03700000	kg
sodium hydroxide, without water, in 50% solution state	0,04000000	kg
pulp factory	0,00000000	unit
natural gas, high pressure, vehicle grade	0,01192164	kg
electricity, medium voltage	0,04270000	kWh
electricity, medium voltage	0,05730000	kWh
Water, unspecified natural origin [natural resource/in water]	0,02100000	m3
Water, cooling, unspecified natural origin [natural resource/in water]	0,03600000	m3
transport, freight, lorry 16-32 metric ton, EURO5	0,38700000	metric ton*km
transport, freight train	0,19800000	metric ton*km
sulphuric acid	0,02420000	kg
quicklime, milled, loose	0,01040000	kg
pulpwood, softwood, measured as solid wood under bark	0,00297100	m3
pulpwood, hardwood, measured as solid wood under bark	0,00082000	m3
pulpwood, hardwood, measured as solid wood under bark	0,00061100	m3
heavy fuel oil	0,01030000	kg
hard coal	0,00508000	kg

Output model 02 sulphate pulp bleached, Material	Coefficient	Unit
sulphate pulp, bleached	1,00000000	kg
Acetaldehyde [air/urban air close to ground]	0,00000015	kg
Acetic acid [air/urban air close to ground]	0,00000035	kg
Acetone [air/urban air close to ground]	0,00000006	kg
Aluminium [air/urban air close to ground]	0,00000157	kg
Ammonia [air/urban air close to ground]	0,00000256	kg
Antimony [air/urban air close to ground]	0,00000000	kg
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	0,00002000	kg
Arsenic [air/urban air close to ground]	0,00000001	kg
Barium [air/urban air close to ground]	0,00000002	kg
Benzene [air/urban air close to ground]	0,00000167	kg
Benzene, ethyl- [air/urban air close to ground]	0,00000004	kg
Benzene, hexachloro- [air/urban air close to ground]	0,00000000	kg
Benzo(a)pyrene [air/urban air close to ground]	0,00000000	kg

Beryllium [air/urban air close to ground]	0,00000000	kg
BOD5, Biological Oxygen Demand [water/surface water]	0,00093000	kg
Boron [air/urban air close to ground]	0,00000007	kg
Bromine [air/urban air close to ground]	0,00000009	kg
Butane [air/urban air close to ground]	0,00000045	kg
Cadmium [air/urban air close to ground]	0,00000002	kg
Calcium [air/urban air close to ground]	0,00000886	kg
Carbon dioxide, fossil [air/urban air close to ground]	0,10600000	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	2,26000000	kg
Carbon monoxide, fossil [air/urban air close to ground]	0,00001900	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	0,00007090	kg
Chlorine [air/urban air close to ground]	0,00000027	kg
Chromium [air/urban air close to ground]	0,00000002	kg
Chromium VI [air/urban air close to ground]	0,00000000	kg
Cobalt [air/urban air close to ground]	0,00000001	kg
COD, Chemical Oxygen Demand [water/surface water]	0,01570000	kg
Copper [air/urban air close to ground]	0,00000006	kg
Dinitrogen monoxide [air/urban air close to ground]	0,00000458	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin [air/urban air close to ground]	0,00000000	kg
Ethane [air/urban air close to ground]	0,00000022	kg
Ethanol [air/urban air close to ground]	0,00000013	kg
green liquor dregs	0,00400000	kg
hazardous waste, for incineration	0,00027000	kg
limestone residue	0,00688000	kg
Methane, fossil [air/urban air close to ground]	0,00000401	kg
Methane, non-fossil [air/urban air close to ground]	0,00000059	kg
Methanol [air/urban air close to ground]	0,00000022	kg
Molybdenum [air/urban air close to ground]	0,00000001	kg
municipal solid waste	0,00860000	kg
m-Xylene [air/urban air close to ground]	0,00000018	kg
Nickel [air/urban air close to ground]	0,00000029	kg
Nitrogen oxides [air/urban air close to ground]	0,00148000	kg
Nitrogen, organic bound [water/surface water]	0,00017000	kg
NMVOC, non-methane volatile organic compounds, unspecified origin [air/urban air close to ground]	0,00000114	kg
PAH, polycyclic aromatic hydrocarbons [air/urban air close to ground]	0,00000002	kg
Particulates, < 2.5 um [air/urban air close to ground]	0,00063900	kg
Particulates, > 10 um [air/urban air close to ground]	0,00006200	kg
Particulates, > 2.5 um, and < 10um [air/urban air close to ground]	0,00006900	kg
Pentane [air/urban air close to ground]	0,00000077	kg
Phenol, pentachloro- [air/urban air close to ground]	0,00000000	kg
Phosphorus [air/urban air close to ground]	0,00000045	kg
Phosphorus [water/surface water]	0,00002000	kg
Polonium-210 [air/urban air close to ground]	0,00001250	kBq
Potassium [air/urban air close to ground]	0,00003480	kg

Potassium-40 [air/urban air close to ground]	0,00000198	kBq
Propane [air/urban air close to ground]	0,00000029	kg
Propene [air/urban air close to ground]	0,00000007	kg
Propionic acid [air/urban air close to ground]	0,00000001	kg
Radium-226 [air/urban air close to ground]	0,00000176	kBq
Radium-228 [air/urban air close to ground]	0,00000954	kBq
Radon-220 [air/urban air close to ground]	0,00000015	kBq
Radon-222 [air/urban air close to ground]	0,00000015	kBq
Scandium [air/urban air close to ground]	0,00000000	kg
Selenium [air/urban air close to ground]	0,00000001	kg
Silicon [air/urban air close to ground]	0,00000232	kg
Sodium [air/urban air close to ground]	0,00000233	kg
Strontium [air/urban air close to ground]	0,00000003	kg
Sulphur dioxide [air/urban air close to ground]	0,00084000	kg
Suspended solids, unspecified [water/surface water]	0,00044000	kg
Thallium [air/urban air close to ground]	0,00000000	kg
Thorium [air/urban air close to ground]	0,00000000	kg
Thorium-228 [air/urban air close to ground]	0,00000081	kBq
Thorium-232 [air/urban air close to ground]	0,00000051	kBq
Tin [air/urban air close to ground]	0,00000000	kg
Titanium [air/urban air close to ground]	0,00000006	kg
TOC, Total Organic Carbon [water/surface water]	0,00744000	kg
Toluene [air/urban air close to ground]	0,00000060	kg
Uranium [air/urban air close to ground]	0,00000000	kg
Uranium-238 [air/urban air close to ground]	0,00000147	kBq
Vanadium [air/urban air close to ground]	0,00000110	kg
Water [water/surface water]	0,02100000	m3
wood ash mixture, pure	0,00530000	kg
Xylene [air/urban air close to ground]	0,00000001	kg
Zinc [air/urban air close to ground]	0,00000046	kg

Table 41: Life Cycle Inventory of model 02, Sulphate pulp (TCF), average EUR pulp mills.

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Input model 03

Material	Coefficient	Unit
electricity, high voltage from prod of 0,36 kg pulp from HW	0,06120000	kWh
heat, district or industrial, other than natural gas from prodof 0,64 kg pulp from SW	0,16610000	kWh
electricity, high voltage from prod of 0,64 kg pulp from SW	0,19272000	kWh
heat, district or industrial, other than natural gas from prod of 0,36 kg pulp from HW	0,14827778	kWh
sulphate pulp, bleached from SW	0,64000000	kg
sulphate pulp, bleached from HW	0,36000000	kg

Output model 03

Material	Coefficient	Unit
by-product electricity	0,25392000	kWh
by-product heat	0,31437778	kWh
pulp bleached	1,00000000	kg

Input sulphate pulp, bleached HW		
Material	Coefficient	Unit
Water, unspecified natural origin [natural resource/in water]	0,06706749	m3
natural gas, high pressure	0,00010380	m3
natural gas, high pressure	0,01607603	m3
pulpwood, hardwood, measured as solid wood under bark	0,00314062	m3
sodium chlorate, powder	0,01020701	kg
pulp factory	0,00000000	unit
transport, freight, inland waterways, barge	0,09881303	metric ton*km
sulphuric acid	0,02307427	kg
sand	0,00027294	kg
transport, freight train	0,29235138	metric ton*km
magnesium sulphate	0,00081518	kg
transport, freight, lorry >32 metric ton, EURO5	0,28597189	metric ton*km
sulphur dioxide, liquid	0,00005277	kg
transport, freight, sea, bulk carrier for dry goods	0,01184737	metric ton*km
wood chips, dry, measured as dry mass	0,09869385	kg
oxygen, liquid	0,02070880	kg
light fuel oil	0,00003457	kg
methanol, from biomass	0,00075149	kg
hydrogen peroxide, without water, in 50% solution state	0,00706184	kg
malusil	0,00126826	kg
sodium sulphate, anhydrite	0,00067962	kg
chemical, organic	0,00217805	kg
heavy fuel oil	0,00952466	kg
electricity, high voltage	0,01702685	kWh
quicklime, milled, loose	0,01013150	kg

Output sulphate pulp, bleached HW		
Material	Coefficient	Unit
sulphate pulp, bleached	1,00000000	kg
Acetaldehyde [air/urban air close to ground]	0,00000009	kg
Acetic acid [air/urban air close to ground]	0,00000041	kg
Acetone [air/urban air close to ground]	0,00000006	kg
Ammonia [air/urban air close to ground]	0,00000088	kg
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	0,00008825	kg
Arsenic [air/urban air close to ground]	0,00000001	kg
Benzene [air/urban air close to ground]	0,00000093	kg
Benzene, ethyl- [air/urban air close to ground]	0,00000002	kg
Benzene, hexachloro- [air/urban air close to ground]	0,00000000	kg
Benzo(a)pyrene [air/urban air close to ground]	0,00000000	kg
BOD5, Biological Oxygen Demand [water/surface water]	0,00022017	kg
Bromine [air/urban air close to ground]	0,00000003	kg
Butane [air/urban air close to ground]	0,00000082	kg
Cadmium [air/urban air close to ground]	0,00000000	kg
Calcium [air/urban air close to ground]	0,00000301	kg
Carbon dioxide, fossil [air/urban air close to ground]	0,07377815	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	2,09513018	kg
Carbon monoxide, fossil [air/urban air close to ground]	0,00000500	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	0,00084793	kg
Chlorine [air/urban air close to ground]	0,00000009	kg
Chromium [air/urban air close to ground]	0,00000000	kg
Chromium VI [air/urban air close to ground]	0,00000000	kg
Cobalt [air/urban air close to ground]	0,00000001	kg
COD, Chemical Oxygen Demand [water/surface water]	0,01086752	kg

EDTA, ethylenediaminetetraacetic acid	0,00019561	kg
sodium hydroxide, without water, in 50% solution state	0,02472828	kg
calcium carbonate, precipitated	0,00391395	kg
sodium formate	0,00016194	kg
residual softwood, wet	0,00003677	m3

Copper [air/urban air close to ground]	0,00000002	kg
digester sludge	0,00008509	kg
Dinitrogen monoxide [air/urban air close to ground]	0,00000170	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin [air/urban air close to ground]	0,00000000	kg
DOC, Dissolved Organic Carbon [water/surface water]	0,00430516	kg
Ethanol [air/urban air close to ground]	0,00000012	kg
Fluorine [air/urban air close to ground]	0,00000003	kg
Formaldehyde [air/urban air close to ground]	0,00000036	kg
green liquor dregs	0,00963770	kg
Hydrocarbons, aliphatic, alkanes, unspecified [air/urban air close to ground]	0,00000069	kg
Hydrocarbons, aliphatic, unsaturated [air/urban air close to ground]	0,00000158	kg
Hydrocarbons, aromatic [air/urban air close to ground]	0,00000006	kg
Hydrogen chloride [air/urban air close to ground]	0,00000056	kg
Hydrogen fluoride [air/urban air close to ground]	0,00000002	kg
Hydrogen sulphide [air/urban air close to ground]	0,00005277	kg
inert waste	0,00000263	kg
inert waste	0,00030528	kg
Iron [air/urban air close to ground]	0,00000032	kg
Lead [air/urban air close to ground]	0,00000007	kg
limestone residue	0,00358754	kg
Magnesium [air/urban air close to ground]	0,00000018	kg
Manganese [air/urban air close to ground]	0,00000009	kg
Mercury [air/urban air close to ground]	0,00000000	kg
Methane, fossil [air/urban air close to ground]	0,00000334	kg
Methane, non-fossil [air/urban air close to ground]	0,00000245	kg
Methanol [air/urban air close to ground]	0,00000020	kg
Molybdenum [air/urban air close to ground]	0,00000000	kg
municipal solid waste	0,00020285	kg
m-Xylene [air/urban air close to ground]	0,00000006	kg
Nickel [air/urban air close to ground]	0,00000019	kg
Nitrogen [water/surface water]	0,00011463	kg
Nitrogen oxides [air/urban air close to ground]	0,00148024	kg
NMVOC, non-methane volatile organic compounds, unspecified origin [air/urban air close to ground]	0,00000532	kg
PAH, polycyclic aromatic hydrocarbons [air/urban air close to ground]	0,00000002	kg
Particulates, < 2.5 um [air/unspecified]	0,00027931	kg

Particulates, > 10 um [air/urban air close to ground]	0,00000093	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	0,00000300	kg
Pentane [air/urban air close to ground]	0,00000141	kg
Phenol, pentachloro- [air/urban air close to ground]	0,00000000	kg
Phosphorus [air/urban air close to ground]	0,00000015	kg
Phosphorus [water/surface water]	0,00000910	kg
Potassium [air/urban air close to ground]	0,00001186	kg
Propane [air/urban air close to ground]	0,00000025	kg
Propionic acid [air/urban air close to ground]	0,00000002	kg
Selenium [air/urban air close to ground]	0,00000000	kg
sludge from pulp and paper production	0,00156170	kg
sludge from pulp and paper production	0,00001731	kg
Sodium [air/urban air close to ground]	0,00000095	kg
Sulphur dioxide [air/urban air close to ground]	0,00038211	kg
Suspended solids, unspecified [water/surface water]	0,00054588	kg
TOC, Total Organic Carbon [water/surface water]	0,00430516	kg
Toluene [air/urban air close to ground]	0,00000040	kg
Vanadium [air/urban air close to ground]	0,00000039	kg
waste mineral oil	0,00000121	kg
waste mineral oil	0,00004905	kg
waste packaging paper	0,00009537	kg
waste paper, unsorted	0,00000991	kg
waste paper, unsorted	0,00028228	kg
waste wood, untreated	0,01212904	kg
Water [air/unspecified]	0,03361608	m3
Water [water/unspecified]	0,03341775	m3
Zinc [air/urban air close to ground]	0,00000017	kg

Input sulphate pulp, bleached SW		
Material	Coefficient	Unit
natural gas, high pressure	0,00005239	m3
natural gas, high pressure	0,00811376	m3
pulpwood, softwood, measured as solid wood under bark	0,00130424	m3
pulpwood, softwood, measured as solid wood under bark	0,00230240	m3
oxygen, liquid	0,02424913	kg
magnesium sulphate	0,00260678	kg
chemical, inorganic	0,00005867	kg
light fuel oil	0,00389781	kg

Output sulphate pulp, bleached SW		
Material	Coefficient	Unit
sulphate pulp, bleached	1,00000000	kg
Acetaldehyde [air/urban air close to ground]	0,00000013	kg
Acetic acid [air/urban air close to ground]	0,00000024	kg
Acetone [air/urban air close to ground]	0,00000004	kg
Ammonia [air/urban air close to ground]	0,00000264	kg
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	0,00006292	kg
Arsenic [air/urban air close to ground]	0,00000000	kg
Benzene [air/urban air close to ground]	0,00000163	kg

EDTA, ethylenediaminetetraacetic acid	0,00046592	kg
pulp factory	0,00000000	unit
residual softwood, wet	0,00001282	m3
sulphur dioxide, liquid	0,00038685	kg
malusil	0,00040556	kg
sulphur	0,00006632	kg
transport, freight train	0,33048061	metric ton*km
sodium hypochlorite, without water, in 15% solution state	0,00021170	kg
chemical, organic	0,00199377	kg
sodium sulphite	0,00003401	kg
quicklime, milled, loose	0,00768514	kg
transport, freight, lorry >32 metric ton, EURO5	0,25906211	metric ton*km
ozone, liquid	0,00003061	kg
methanol, from biomass	0,00190649	kg
wood pellet, measured as dry mass	0,00804600	kg
wood chips, dry, measured as dry mass	0,48834271	kg
electricity, high voltage	0,03700669	kWh
sodium formate	0,00076775	kg
heavy fuel oil	0,00605426	kg
transport, freight, sea, bulk carrier for dry goods	0,26246299	metric ton*km
calcium carbonate, precipitated	0,00162307	kg
sulphuric acid	0,02684315	kg
methanol	0,00009453	kg
sodium sulphate, anhydrite	0,00030353	kg
hydrogen peroxide, without water, in 50% solution state	0,01115574	kg
sodium chlorate, powder	0,01211479	kg
sodium hydroxide, without water, in 50% solution state	0,02185916	kg
Water, unspecified natural origin [natural resource/in water]	0,06439738	m3

Benzene, ethyl- [air/urban air close to ground]	0,00000005	kg
Benzene, hexachloro- [air/urban air close to ground]	0,00000000	kg
Benzo(a)pyrene [air/urban air close to ground]	0,00000000	kg
BOD5, Biological Oxygen Demand [water/surface water]	0,00030268	kg
Bromine [air/urban air close to ground]	0,00000009	kg
Butane [air/urban air close to ground]	0,00000050	kg
Cadmium [air/urban air close to ground]	0,00000000	kg
Calcium [air/urban air close to ground]	0,00000886	kg
Carbon dioxide, fossil [air/urban air close to ground]	0,06097525	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	2,15296854	kg
Carbon monoxide, fossil [air/urban air close to ground]	0,00000361	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	0,00094630	kg
Chlorine [air/urban air close to ground]	0,00000027	kg
Chromium [air/urban air close to ground]	0,00000001	kg
Chromium VI [air/urban air close to ground]	0,00000000	kg
Cobalt [air/urban air close to ground]	0,00000001	kg
COD, Chemical Oxygen Demand [water/surface water]	0,01072893	kg
Copper [air/urban air close to ground]	0,00000015	kg
digester sludge	0,00022871	kg
Dinitrogen monoxide [air/urban air close to ground]	0,00000414	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin [air/urban air close to ground]	0,00000000	kg
DOC, Dissolved Organic Carbon [water/surface water]	0,00357348	kg
Ethanol [air/urban air close to ground]	0,00000007	kg
Fluorine [air/urban air close to ground]	0,00000008	kg
Formaldehyde [air/urban air close to ground]	0,00000052	kg
green liquor dregs	0,00865439	kg
hazardous waste, for incineration	0,00000011	kg
hazardous waste, for incineration	0,00000414	kg
Hydrocarbons, aliphatic, alkanes, unspecified [air/urban air close to ground]	0,00000160	kg
Hydrocarbons, aliphatic, unsaturated [air/urban air close to ground]	0,00000469	kg
Hydrocarbons, aromatic [air/urban air close to ground]	0,00000004	kg
Hydrogen chloride [air/urban air close to ground]	0,00000037	kg
Hydrogen fluoride [air/urban air close to ground]	0,00000001	kg
Hydrogen sulphide [air/urban air close to ground]	0,00004081	kg
inert waste	0,00000203	kg

	inert waste	0,00023603	kg
	Iron [air/urban air close to ground]	0,00000020	kg
	Lead [air/urban air close to ground]	0,00000007	kg
	limestone residue	0,01199406	kg
	Magnesium [air/urban air close to ground]	0,00000054	kg
	Manganese [air/urban air close to ground]	0,00000026	kg
	Mercury [air/urban air close to ground]	0,00000000	kg
	Methane, fossil [air/urban air close to ground]	0,00000207	kg
	Methane, non-fossil [air/urban air close to ground]	0,00000692	kg
	Methanol [air/urban air close to ground]	0,00000013	kg
	Molybdenum [air/urban air close to ground]	0,00000000	kg
	municipal solid waste	0,00002466	kg
	m-Xylene [air/urban air close to ground]	0,00000018	kg
	Nickel [air/urban air close to ground]	0,00000013	kg
	Nitrogen [water/surface water]	0,00012583	kg
	Nitrogen oxides [air/urban air close to ground]	0,00133230	kg
	NMVOC, non-methane volatile organic compounds, unspecified origin [air/urban air close to ground]	0,00001585	kg
	PAH, polycyclic aromatic hydrocarbons [air/urban air close to ground]	0,00000002	kg
	Particulates, < 2.5 um [air/unspecified]	0,00026527	kg
	Particulates, > 10 um [air/urban air close to ground]	0,00000059	kg
	Particulates, > 2.5 um, and < 10um [air/unspecified]	0,00000784	kg
	Pentane [air/urban air close to ground]	0,00000081	kg
	Phenol, pentachloro- [air/urban air close to ground]	0,00000000	kg
	Phosphorus [air/urban air close to ground]	0,00000045	kg
	Phosphorus [water/surface water]	0,00001275	kg
	Potassium [air/urban air close to ground]	0,00003532	kg
	Propane [air/urban air close to ground]	0,00000014	kg
	Propionic acid [air/urban air close to ground]	0,00000001	kg
	Selenium [air/urban air close to ground]	0,00000000	kg
	sludge from pulp and paper production	0,00071308	kg
	sludge from pulp and paper production	0,00000790	kg
	Sodium [air/urban air close to ground]	0,00000215	kg
	Sulphur dioxide [air/urban air close to ground]	0,00021681	kg
	Suspended solids, unspecified [water/surface water]	0,00069123	kg
	TOC, Total Organic Carbon [water/surface water]	0,00357348	kg
	Toluene [air/urban air close to ground]	0,00000059	kg
	Vanadium [air/urban air close to ground]	0,00000025	kg

	waste mineral oil	0,00000035	kg
	waste mineral oil	0,00001410	kg
	waste packaging paper	0,00051948	kg
	waste paper, unsorted	0,00000089	kg
	waste paper, unsorted	0,00002546	kg
	waste wood, untreated	0,01920137	kg
	Water [air/unspecified]	0,03734337	m3
	Water [water/unspecified]	0,02705146	m3
	wood ash mixture, pure	0,00003571	kg
	wood ash mixture, pure	0,00173700	kg
	Zinc [air/urban air close to ground]	0,00000058	kg

Table 42: Life Cycle Inventory of model 03, Sulphate pulp (ECF), average EUR pulp mills.

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Input model 04

Material	Coefficient	Unit
electricity, high voltage	0,22400000	kWh
heat, district or industrial, other than natural gas	0,71111111	kWh
sulphate pulp, bleached	1,00000000	kg

Output model 04

Material	Coefficient	Unit
by-product electricity	**0,22400000**	**kWh**
by-product heat	**0,71111111**	**kWh**
pulp bleached	**1,00000000**	**kg**

Input sulphate pulp bleached, Eucalyptus		
Material	Coefficient	Unit
sodium hypochlorite, without water, in 15% solution state	0,00016415	kg
magnesium sulphate	0,00017381	kg
sawlog and veneer log, eucalyptus ssp., measured as solid wood under bark	0,00309436	m3
magnesium oxide	0,00197775	kg
transport, freight, inland waterways, barge	0,02487248	metric ton*km
malusil	0,00138785	kg
sodium sulphate, anhydrite	0,00015274	kg
transport, freight train	0,00236400	metric ton*km
quicklime, milled, loose	0,00162487	kg
sodium hydroxide, without water, in 50% solution state	0,01629080	kg
pulp factory	0,00000000	unit
sulphuric acid	0,01178752	kg
chlorine dioxide	0,00938226	kg
transport, freight, lorry >32 metric ton, EURO5	0,23463999	metric ton*km
Water, unspecified natural origin [natural resource/in water]	0,02580913	m3
light fuel oil	0,00020429	kg
light fuel oil	0,00152539	kg
light fuel oil	0,00021999	kg
heavy fuel oil	0,00145774	kg
heavy fuel oil	0,00960931	kg
heavy fuel oil	0,00250335	kg
diesel	0,00002567	kg
diesel	0,00018155	kg
diesel	0,00000873	kg
natural gas, high pressure	0,02527453	m3
sodium chlorate, powder	0,00324271	kg
chemical, inorganic	0,00020629	kg
hydrogen peroxide, without water, in 50% solution state	0,00528191	kg
sulphur	0,00000088	kg
transport, freight, sea, bulk carrier for dry goods	0,02313701	metric ton*km

Output sulphate pulp bleached, Eucalyptus		
Material	Coefficient	Unit
sulphate pulp, bleached	1,00000000	kg
Acetaldehyde [air/urban air close to ground]	0,00000018	kg
Acetic acid [air/urban air close to ground]	0,00000051	kg
Acetone [air/urban air close to ground]	0,00000008	kg
Ammonia [air/urban air close to ground]	0,00000279	kg
AOX, Adsorbable Organic Halogen as Cl [water/surface water]	0,00004565	kg
Arsenic [air/urban air close to ground]	0,00000001	kg
Benzene [air/urban air close to ground]	0,00000194	kg
Benzene, ethyl- [air/urban air close to ground]	0,00000005	kg
Benzene, hexachloro- [air/urban air close to ground]	0,00000000	kg
Benzo(a)pyrene [air/urban air close to ground]	0,00000000	kg
BOD5, Biological Oxygen Demand [water/surface water]	0,00077776	kg
Bromine [air/urban air close to ground]	0,00000010	kg
Butane [air/urban air close to ground]	0,00000088	kg
Cadmium [air/urban air close to ground]	0,00000000	kg
Calcium [air/urban air close to ground]	0,00000941	kg
Carbon dioxide, fossil [air/urban air close to ground]	0,12991907	kg
Carbon dioxide, non-fossil [air/urban air close to ground]	1,82588966	kg
Carbon monoxide, fossil [air/urban air close to ground]	0,00000654	kg
Carbon monoxide, non-fossil [air/urban air close to ground]	0,00055918	kg
Chlorine [air/urban air close to ground]	0,00000029	kg
Chromium [air/urban air close to ground]	0,00000001	kg
Chromium VI [air/urban air close to ground]	0,00000000	kg
Cobalt [air/urban air close to ground]	0,00000002	kg
COD, Chemical Oxygen Demand [water/surface water]	0,00721753	kg
Copper [air/urban air close to ground]	0,00000011	kg
digester sludge	0,00330591	kg
Dinitrogen monoxide [air/urban air close to ground]	0,00000461	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin [air/urban air close to ground]	0,00000000	kg
DOC, Dissolved Organic Carbon [water/surface water]	0,00288719	kg

ozone, liquid	0,00024228	kg
electricity, high voltage	0,01023025	kWh
hydrochloric acid, without water, in 30% solution state	0,00101828	kg
chemical, organic	0,00059868	kg
calcium carbonate, precipitated	0,00283013	kg
aluminium sulphate, powder	0,00040644	kg
oxygen, liquid	0,01512504	kg

Ethanol [air/urban air close to ground]	0,00000017	kg
Fluorine [air/urban air close to ground]	0,00000008	kg
Formaldehyde [air/urban air close to ground]	0,00000066	kg
green liquor dregs	0,00987297	kg
hazardous waste, for incineration	0,00000966	kg
Hydrocarbons, aliphatic, alkanes, unspecified [air/urban air close to ground]	0,00000183	kg
Hydrocarbons, aliphatic, unsaturated [air/urban air close to ground]	0,00000497	kg
Hydrocarbons, aromatic [air/urban air close to ground]	0,00000009	kg
Hydrogen chloride [air/urban air close to ground]	0,00000080	kg
Hydrogen fluoride [air/urban air close to ground]	0,00000003	kg
Hydrogen sulphide [air/urban air close to ground]	0,00001580	kg
Iron [air/urban air close to ground]	0,00000045	kg
Lead [air/urban air close to ground]	0,00000012	kg
limestone residue	0,01729504	kg
Magnesium [air/urban air close to ground]	0,00000058	kg
Manganese [air/urban air close to ground]	0,00000027	kg
Mercury [air/urban air close to ground]	0,00000000	kg
Methane, fossil [air/urban air close to ground]	0,00000230	kg
Methane, non-fossil [air/urban air close to ground]	0,00000741	kg
Methanol [air/urban air close to ground]	0,00000028	kg
Molybdenum [air/urban air close to ground]	0,00000000	kg
municipal solid waste	0,00009481	kg
m-Xylene [air/urban air close to ground]	0,00000019	kg
Nickel [air/urban air close to ground]	0,00000028	kg
Nitrogen [water/surface water]	0,00010446	kg
Nitrogen oxides [air/urban air close to ground]	0,00110343	kg
NMVOC, non-methane volatile organic compounds, unspecified origin [air/urban air close to ground]	0,00001679	kg
PAH, polycyclic aromatic hydrocarbons [air/urban air close to ground]	0,00000003	kg
Particulates, < 2.5 um [air/unspecified]	0,00036254	kg
Particulates, > 10 um [air/urban air close to ground]	0,00000132	kg
Particulates, > 2.5 um, and < 10um [air/unspecified]	0,00000866	kg
Pentane [air/urban air close to ground]	0,00000147	kg
Phenol, pentachloro- [air/urban air close to ground]	0,00000000	kg
Phosphorus [air/urban air close to ground]	0,00000048	kg
Phosphorus [water/surface water]	0,00004214	kg
Potassium [air/urban air close to ground]	0,00003741	kg
Propane [air/urban air close to ground]	0,00000026	kg

	Propionic acid [air/urban air close to ground]	0,00000002	kg
	residue from cooling tower	0,00000790	kg
	Selenium [air/urban air close to ground]	0,00000001	kg
	sludge from pulp and paper production	0,00405119	kg
	Sodium [air/urban air close to ground]	0,00000249	kg
	Sulphur dioxide [air/urban air close to ground]	0,00011500	kg
	Sulphur oxides [air/unspecified]	0,00000088	kg
	Suspended solids, unspecified [water/surface water]	0,00117015	kg
	TOC, Total Organic Carbon [water/surface water]	0,00288719	kg
	Toluene [air/urban air close to ground]	0,00000074	kg
	Vanadium [air/urban air close to ground]	0,00000055	kg
	waste mineral oil	0,00307768	kg
	waste packaging paper	0,00000646	kg
	waste packaging paper	0,00012005	kg
	waste packaging paper	0,00001833	kg
	waste wood, untreated	0,00044975	kg
	waste wood, untreated	0,00853625	kg
	waste wood, untreated	0,00105990	kg
	Water [air/unspecified]	0,01766197	m3
	Water [water/unspecified]	0,00814715	m3
	Zinc [air/urban air close to ground]	0,00000057	kg

Table 43: Life Cycle Inventory model 04, Sulphate pulp (ECF), average RLA pulp mills.

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8 Literature

Agency, E. E. (2019). *European Union emission inventory report 1990-2017.* Luxembourg: Publications Office of the European Union, 2019.

Bos, U., Horn, R., Beck, T., Lindner, J. P., & Fischer, Matthias. (2016). *LANCA. Characterization Factors for Life Cycle Impact Assessment, Version 2.0.* Stuttgart: Fraunhofer IBP.

Bracell Ltd. (2021). *Bracell Sustainablity Report 2021.* Sao Paulo: Bracell.

De Laurentiis, V., Secchi, M., Bos, U., Horn, R., Laurent, A., & Sala, S. (2019). *Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA.* https://www.sciencedirect.com/science/article/pii/S095965261833960X: Journal of Cleaner Production, Vol 215.

DIN e.V. (kein Datum). DIN EN ISO 14044.

Dreicer, M. T. (1995). *ExternE: External costs of energy.* International Atomic Energy (IAEA): European Commission, Directorate-General XII, Science, Research and Development (Luxembourg).

ecoinvent. (2017). *ecoinvent 3.8 Dataset Documentation "sulfate pulp production, from softwood, bleached - RER".*

ecoinvent. (2021). *ecoinvent 3.8 Datenbank.* Zürich: ecoinvent.

European Commission. (2017). *European Commission (2017). _PEFCR Guidance document, - Guidance for the 13 development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3._ European Commission.*

European Commission. (2021). *Empfehlung (EU) 2021/2279 Der Kommission.* Brüssel.

European Environment Agency. (2019). *European Union emission inventory report 1990-2017.* Luxembourg: Publications Office of the European Union.

Ferrara, C., & De Feo, G. (20212). *Environmental Assessment of the Recycled Paper Production: The Effects of Energy Supply Source.* Sustainability.

Group, M. (2022). *Metsä Group sustainability Report 2021.* spoo, Finland: Metsä Group.

Hischier, R. (2007). *Life Cycle Inventories of Packagings and Graphical Papers.* Dübendorf: Swiss Centre for Life Cycle Inventories.

Lehmann, F. M., Bernasconi, S., Barbieri, A., & McKenzie, J. A. (2002). Preservation of organic matter and alteration of its carbon and nitrogen isotope composition during simulated and in situ early sedimentary diagenesis. *Geochimica et Cosmochimica Acta 66*, S. 3573–3584.

Lindner, J. P., Fehrenbach, H., Winter, L., Bloemer, J., & Knuepffer, E. (12. Oktober 2019). Valuing Biodiversity in Life Cycle Impact Assessment. *sustainability*, S. 24.

Lindner, J. P., Fehrenbach, H., Winter, L., Bloemer, J., & Knuepffer, E. (2020). *Biodiversität in Ökobilanzen - Weiterentwicklung und vergleichende Studien.* Bonn: Bundesamt für Naturschutz.

Masternak-Janus, A., & Rybaczewska-Błażejowska, M. (September 2015). Life Cycle Analysis of Tissue Paper Manufacturing From Virgin Pulp or Recycled Waste paper. *Management and Production Engineering Review*.

Metsä Group. (2022). *Metsä Group sustainability Report 2021.* Espoo, Finland: Metsä Group.

Moya, J. A., & Pavel, C. C. (2018). *Energy efficiency and GHG emissions: Prospektive scenarios for the pulp and paper industry.* Luxembourg: JRC Science Hub, Publications Office of the European Union.

ÖKO-TEST Verlag. (2021/03). *Öko-Test Magazin.*

Posch, M. S.-P. (2008). The role of athmospheric dispersion models and ecosystem sensitivity in the determination of charactersiation factors for acidifying and eutrophying emissions in LCIA. *The International Journal of Life Cycle Assessment 13*, 477.

Salomon, K. R., Bergmann, H. L., Huggett, R., Mackay, D., & Mackay, B. (10 1997). A review and assessment of the ecological risks associated with the use of chlorine dioxide for the bleaching of pulp. With secondary treatment, ClO2 bleaching poses low risk to environment. *Pulp and Paper Canada*, S. 345-354.

Saouter, E. A. (2017). Improving substance information in USEtox®, part 1: Discussion on data and approaches for estimating freshwater ecotoxicity effect factors. *Environmental Toxicology and Chemistry, Volume 36, Issue 12*, 3450-3462.

Schacht, M. (2000). *Vergleichende Untersuchung zur Zellstoffbleiche mit chlorhaltigen und chlorfreien Bleichmitteln.* Darmstadt.

Schmitz, S. (1999). *Bewertung in Ökobilanzen.* Berlin: Umweltbundesamt.

Schultz, T., & Suresh, A. (2017). *Life Cycle Assessment Comparing Ten Sources of Manmade Cellulose Fibre.* Emeryville, CA.

Seppälä, J. P. (2005). country-dependent Charactersiation Factors for Accidificaton ans Terrestrial Eutrophication Based on Accumulated Exceedande asn an Impact Categoriy Indicator. *International Journal of Life Cycle Assessment 11*, 14 pp.

Tana, J., & Lehtinen, K.-J. (1996). *The aquatic environmental impact of pulping and bleaching operations – an overview.*

The European Pulp Industry Sector Association AISBL. (2017). *ecoinvent 3.8 Dataset Documentation "sulfate pulp production, from softwood, bleached - RER".* ecoinvent.

Valmet Oyj. (21. November 2022). *Sulfuric acid plant*. Von https://www.valmet.com/pulp/other-value-adding-processes/sulfuric-acid-plant/ abgerufen

Volta, Y. A., Rusdianasari, & Yusi, S. (2021). *Life Cycle Assessment (LCA) in Pulp & Paper Mills: Comparison Between MFO With Biomass in Lime Kiln.*

Wall, G. (1977). *Exergy - a useful concept within resource accounting.* Göteborg, Sweden: Chalmers University of Technology ans University of Göteborg.

Wellenreuther, F., Detzel, A., Krüger, M., & Busch, M. (2022). *Updated life-cycle assessment of graphic and tissue paper.* Dessau: Umwelt Bundesamt.

Zampori, L., & Pant, R. (2019). *Suggestions for updating the Product Environmental Footprint (PEF) method.* Luxembourg: Publications Ofice of the European Union, 2019.

Zampori, L., & Pant, R. (2019). *Vorschläge zur Aktualisierung der Methode zur Berechnugn des Umweltfussabdruckes von Produkten (PEF).* Luxemburg: Amt für Veröffentlichungen der Europäischen Union.

9 Critical review

Critical Review to LCA Äänekoski

This final report is part of the study "LCA Äänekoski – Life Cycle Assessment of fibres from bioproduct mill compared to fibres from European and Latin American average pulp mills" from Sven Wüstenhagen and Andreas Krombholz, Fraunhofer IMWS, January 2023

Reviewers:

Prof. Dr.-Ing. Andreas Ortwein
Merseburg University of Applied Science

Prof. Dr. Ing. Christoph Wünsch
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Walther Zeug
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1. Occasion, Subject Matter and Objectives of the Critical Review

The final report presented here refers to an order from the METSÄ FIBRE OY, Finland. The subject of the Critical Review is a life cycle assessment commissioned by METSÄ FIBRE OY and prepared by Fraunhofer-Institut für Mikrostruktur von Werkstoffen und Systemen (hereinafter: Fraunhofer IMWS). This final report on the critical review refers to the report submitted by Fraunhofer IMWS and, in accordance with the specifications of the standard, forms an integral part of Fraunhofer IMWS life cycle assessment (LCA) report.

In this LCA, selected configurations of sulphate pulp mills are examined and compared. The reason to carry out this study is to encourage pulp industries to mitigate climate impacts by comparing the relatively new commissioned elemental chlorine free (ECF) ÄÄnekoski pulp mill with its high efficient heat recovery boiler, high efficient elemental chlorine free bleaching process and its high efficient recycling of chemicals with technologically average European total chlorine free (TCF) pulp mills, average European ECF pulp mills and average Latin American ECF pulp mills.

The necessity of subjecting LCAs prepared in this context to a so-called critical review arises from the established technical standards: According to the "framework standard" for life cycle assessments, ISO 14040, the critical review is a process to clarify whether a life cycle assessment meets the requirements for methodology, data, evaluation and reporting, and whether it is consistent with the principles [described in the standard]. The ISO 14044 standard specifies this process in that the critical review must ensure that

- the methods used in carrying out the LCA are consistent with this International Standard;
- the methods used to carry out the LCA are scientifically and technically valid;
- the data used are appropriate and reasonable in relation to the goal of the study;
- the interpretation reflect the limitations identified and the goal of the study; and
- the report is transparent and consistent.

2. Fundamentals of the Critical Review

The Critical Review carried out was based on the following two international standards and regulations:

- DIN EN ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework
- DIN EN ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines

The requirements of the standards (especially with regard to reporting) are partly linked to the intended application and communication of the LCA results. Due to the documented objective of the LCA reviewed here, the critical review was based on those requirements that are to be applied to LCAs in which comparative statements are made for publication. Accordingly, on the one hand the procedure of the critical review carried out here was applied (see chapter 3 of this review report for more details), and on the other hand the reporting requirements according to ISO 14044, Sections 5.1, 5.2 and 5.3 in particular were taken into account.

3. Description of the Review Procedure

3.1. Composition of the Audit Committee

The Critical Review was conducted by the following experts:

- Prof. Dr.-Ing. Andreas Ortwein, Professor of Process Automation and Building Automation, Merseburg University of Applied Science
- Prof. Dr.-Ing. Christoph Wünsch, Professor of Environmental Engineering / Waste Technologies and Emissions, Merseburg University of Applied Science
- M.Eng. Walther Zeug, Research Assistant, Helmholtz Centre for Environmental Research, Leipzig

The auditors are very familiar with the requirements of the LCA and have all the technical and procedural knowledge required to conduct a Critical Review. The auditors declare,

- that they are not and have not been full-time or part-time employees of the client or preparer of the LCA study
- that they were not involved in the definition of the scope of the study and did not carry out any work for the implementation of this LCA study, and
- that they have no personal financial, political or other interests in the outcome of the study.

3.2. Type of Critical Review

The review was conducted as a final review, i.e. the reviewers did not provide opinions and recommendations on steps during the study preparation. They did, however, comment a final draft of the report and discussed it with the authors of the LCA before the final report was available for review (cf. chapter 3.3 of this review report).

The Critical Review was carried out in accordance with ISO 14044 Section 6.3 by a so-called Stakeholder Committee. In this case, the committee may involve other stakeholders affected by the conclusions of the LCA, such as governmental authorities, non-governmental organisations, competitors and affected industries. This was not done in the context of this Critical Review

3.3. Procedure

The Critical Review was commissioned by METSÄ via Fraunhofer IMWS. Another Critical Review Panel (CRP) has conducted a first Critical Review interactively during the LCA process. It was decided to have an additional review a posteriori with a second, different CRP.

The revised version of the LCA has been submitted to the CRP in December 2022. After some organizational preparatory work and first review activities of the CRP members, the CRP had its first meeting on January 27th, 2023, where several aspects of the LCA have been discussed. A second revision of the LCA has been submitted on January 31st, 2023. The final version of the Critical Review has been submitted by the CRP on February 2nd, 2023, and is based upon the LCA version from January 31st. A final discussion took place on February 9th, 2023. In the final version of the LCA, the assessment method has been described with a higher degree of transparency. Information about constraints of the methodology have been added.

4. Result of the Critical Review

4.1. Goal and scope of the study

Objectives, target groups and intended applications of the study are presented and described adequately and differentiated enough.

The selection of the included pulp mill configurations for sulphate kraft pulp production with different bleaching technologies and different wood raw materials was based on a presentation of the pulp mills examined in chapter 2 of the study. The crucial differences in the product system of the "bioproduct mill" in Äänekoski to other Best Available Technology (BAT) pulp mills were described. As the other considered pulp mills only differ in terms of their wood inputs and bleaching stage, they were not described in further detail. It was not further discussed why pulp mills located in Europe with feedstock from northern Europe based forests and a pulp mill located in Brazil with feedstock from Latin American based forest were considered in the study. Since, regarding the requirements of the LCA standards, it is up to the client to decide which systems are to be investigated and which are not, this approach meets the minimum requirements and can be considered comprehensible and transparent.

The Functional Unit (FU) is defined to 1 Air Dry Metric Tonne (ADMT) of bleached pulp from virgin material. The reason for setting this FU is briefly described. Three of the four systems considered generate electricity and heat as a by-product. In order to create system equality and to not to have to expand the functional unit, the "avoided burden approach" was chosen. This approach is considered appropriate and reasonable. The reference flows to be derived from the FU are not shown directly, although they can be taken from the "Bill of Materials" (Chapter 3.2 of the study). The functional performance characteristics of the investigated pulp mills are briefly named, the functional equivalence of the systems is presented as given.

The system boundaries of the LCA are defined in terms technology, geography and time. Since the technical system boundary is more or less equal for all considered pulp mills the technical system boundary was illustrated in one clear and well-structured illustration.

The use of cut-off criteria, i.e. the exclusion of parts of the system under consideration, corresponds to the requirements of the standard in the multi-stage approach (here mass and environmental relevance).

The approach to choose a mass balances cut-off criteria of 0.5% of cumulated mass of a product is comprehensible and objectively justified, since the inputs from the technosphere, like bleaching agents, can have significant impacts to the environment. The specific requirements for studies with comparative statements intended for publication are thus met.

Since pulp mills provide relevant amounts of surplus electricity and process heat, this surplus energy was allocated as by-product. The allocation of wood raw material to the main and by-products was done related to the mass of the product. In order to check the robustness of the allocation procedure, a sensitivity analysis was carried out with regard to the allocation via the exergy and the economic value. The allocation procedures were discussed in detail with the reviewers and can be regarded as appropriate and comprehensible.

For the "Äänekoski pulp mill", secondary data for the background system and available primary data for the foreground system was used. For the other scenarios, only secondary data from the Ecoinvent 3.8 database was used. Relevant processes available in previously issued versions of EcoInvent were updated to the secondary dataset of Ecoinvent 3.8. However, the documentation of input data, calculations and output data does not allow an in-detail check as part of a critical review. This is especially the case for the novel and introduced biodiversity assessment method. While this method seems to produce plausible results, the reviewers cannot assess the scientific quality of this method or how it was conducted. The database for secondary data is state of the art and the most robust and reliable LCA data currently available. The primary data, however, was gained from the clients of the study, which is oftentimes the case but requires special awareness. The reviewers cannot assess the validity of data and technologies. However, it is suggested to check further data from independent and critical parties such as NGO's or national and international autonomous organisations, since resource extraction is a highly sensitive sector not only in Europe but in particular in Latin America.

4.2. Live Cycle Inventory

In a preliminary chapter (4. Production System), the four product systems within their technical system boundaries were again briefly described. The origin of the primary and secondary data used was again assigned. A material and energy flow diagram for the reference product system is shown. The focus of the description is on the raw material input in form of the wood. An equally detailed description of the different bleaching processes and the processes for recovering electricity and process heat would have been desirable here.

The dataset for softwood and hardwood forestry of the EcoInvent 3.8 database was verified through interviews and research regarding forest management in Metsäliitto Cooperative in Finland. A similar approach could have been taken for forest management in Latin America in particular. Here the data situation is certainly less valid and a review of the available database would certainly have been useful.

The model inputs are given in per kg pulp. Here it would have made more sense to indicate the values in relation to the functional unit, i.e. per ADMT pulp.

4.3. Live Cycle Impact Assessment

The 17 impact categories and models included for the impact assessment as well as the indicator values shown correspond to the specifications according to the minimum requirements. The selection of 16 categories is based on the publication by Zamponi and Pant (2019) in which these categories are described as the most relevant impact categories at present. One more and novel impact category biodiversity is introduced. For the investigation of the impacts of forestry on biodiversity in the forest and plantation areas from which the raw material wood for pulp production is sourced, the methods architecture to estimate the biodiversity value (Lindner et al., 2019) was used. The method for determining the "Biodiversity Value Increment" is described in detail. Since this approach is explained in detail it is justified in the view of the auditors. In summary, the handling of the mandatory components of the impact assessment can thus be regarded as conforming to the standard.

Following the ISO 14044 norm the components of standardisation / normalisation and ordering are optional for comparing LCA studies. Normalisation is mostly done based on emission levels compared to the emissions within a national economy. As described in the study, this method is not applicable for the study, as the product systems compared here supply very different markets in a global context. The element order is examined in the study. Since the specific contribution of an impact category is based on the normalisation, only the criteria ecological threat and distance to target was considered. Together with the criterion of the robustness level of each of the impact categories, the results of the study were classified/ordered according to the assessment method of the German Federal Environmental Agency (Schmitz and Paulini, 1999). The procedure of replacing the specific contribution of an impact category with the robustness level for ranking purposes is reasonable. The two additional components (normalisation and order) of the impact assessment carried out are to be regarded as norm-confirming under the conditions of the study.

The results of the "LCIA" were presented graphically as absolute values related to the FU for each impact category. For the respective models, the results are described by means of a colour code for better assignment of the respective LCI elements. Unfortunately, several bars are stacked for the different elements (e.g. for the colour code "chemicals" several bars for several chemicals), without it being possible to assign the bars to the different chemicals.

4.4. Interpretation and Evaluation

For better comparability of the results for the different models considered, a normalisation was carried out based on the results for the reference model. The results show that for the categories with robustness level I, the reference model delivers by far the best results regarding the environmental impacts. In the categories of robustness level II, the reference model show slightly higher influences on the environmental impacts and in the categories of robustness III significantly lower influences.

For the evaluation strategy, a prioritisation/ordering of the categories, based on the criteria ecological threat, distance to target and robustness level, took place. Based on these criteria, the impact categories were assigned to "very large", "large", "middle", "low" and "without ecological priority" in the context of the study. The evaluation strategy used by the LCA compilers is inevitably based on value attitudes here. In the view of the reviewer, these value attitudes should have been made even clearer and the logic and premise of the evaluation and result finding should have been better disclosed.

The interpretation of the results was carried out for all impact categories. In each case, a brief description was given of which processes/substances contributed to the respective emissions and which models delivered good or poor results in each case. The most relevant results are thus explained and interpreted, which is considered appropriate and sufficient.

The evaluation of the LCA results according to the evaluation strategy leads to a final table, again with a colour code, where green stands for the model with best results in the respective impact category, red for results higher than best performing model and grey marks differences that are below the significance threshold. Here, the relative distance of the values to the best value could have been shown additionally. In addition, an indication of the value attitudes contained in the results of the figure could have been given.

The conclusion and recommendations to client, stakeholders and interested public are supported by the results of the LCA.

5. Summary Assessment

The Structure of the study is according to ISO 14040 and 14044. Goal and scope, LIA and LCIA including system boundaries, data, assumptions, and all other standard aspects are mostly well described. An interpretation and critical discussion of the results was carried out. It can be stated that the methods used are consistent with the ISO 14044 and 14044 standards.

In general, the LCA methodology is arranged according to the ISO norms. The used software (Umberto) and databases for secondary data (EcoInvent) are state of the art. Since the CRP evaluated the final study and did not accompany the development process of the study, they did not have a deep insight into the determination of input data, calculations and output data. An in-detail check as part of a critical review was not possible. From the reviewers' point of view, it looks that the methods used are generally scientifically and technically valid but cannot be proved.

Specific primary data was used for the Äänekoski pulp mill and secondary generic data for the other models. Specific data provided by operators should always be treated with some caution. The accuracy of the primary data cannot be assessed by the reviewers. The secondary data used is robust and up-to-date and considered reasonable. For the biodiversity assessment the reviewers suggest a deeper investigation of the forest system in Latin America. The data used seems largely appropriate in relation to the goal of the study.

The interpretation is based on the results of the LCIA and was carried out for all impact categories considered. Constrains and limitations were fundamentally discussed. Conclusions and recommendations were given but could have been elaborated a little deeper. Tables and figures are sometimes poorly presented und should be further improved. The assessment of the interpretation of the results referring limitations and goals is largely in accordance with the goal and scope of the study.

After several comments/remarks and their discussion the final version was reviewed. With the revised structure of the report the comprehensibility was noticeably improved. The report still contains some grammatical and spelling errors. In summary, it can be stated that the report is transparent and comprehensible.

The reviewed LCA study is prepared and documented according to ISO standards, which means that a certain standard of the procedure is met. However, following the ISO standards does not result in robust or valid results automatically. Primary data seems to be a limitation of this study and should be checked and compared to other sources. After revision of the orthography, the report as it was presented can be disclosed to the interested public or other stakeholders.

6. References

DIN EN ISO 14040:2006: Environmental management – Life cycle assessment – Principles and framework

DIN EN ISO 14044:2006: Environmental management – Life cycle assessment – Requirements and guidelines

Lindner, J.P.; Fehrenbach, H.; Winter, L.; Bischoff, M.; Bloemer, J.; Knuepffer, E. (2019): Valuing Biodiversity in Life Cycle Impact Assessment. Sustainability 2019, 11, 5628.

Schmitz, S. and Paulini, I. (1999): Valuation as an element of life cycle assessments - German Federal Environmental Agency method for impact indicator standardization, impact category grouping (ranking), and interpretation in accordance with ISO 14042 and 14043. German Federal Environmental Agency, 1999

Zamponi, L. and Pant, R. (2019): Suggestions for updating the Product Environmental Footprint (PEF) method. Luxembourg, Publications Office of the European Union, 2019