NAICS Code: Pulp mills (322110, Kraft variation)

SUMMARY INFO: Kraft pulp plants are central to American paper and packaging manufacturing, producing a majority of the country's pulp used in commercial products.[1] Pulp is produced by separating cellulose fibers from impurities in wood and suspending it in water, which is then sold to paper and paperboard mills. Kraft pulp is used in high quality and durable papers, including printer, copy, and note paper. 65% of a pulp and paper mill's carbon dioxide emissions come from the recovery boilers used in pulp production.[2] Pulp mills have been evolving amidst a changing consumer landscape, with products going more towards packaging uses and less towards traditional printing paper and newsprint uses.[3]

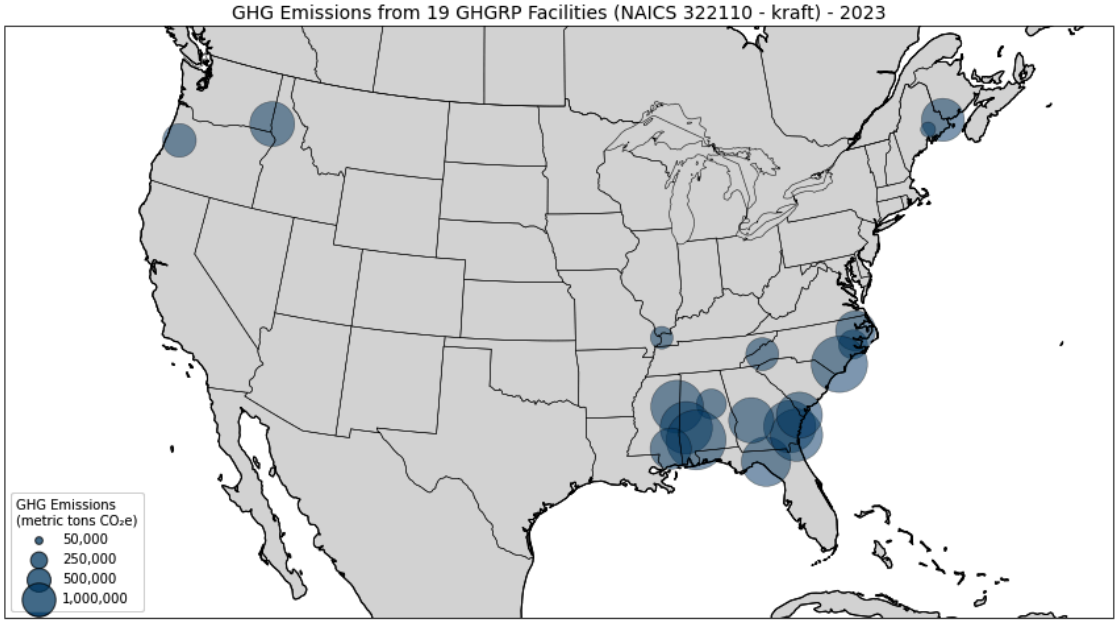
Date Updated: 3/19/2026

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Link to archetype code:
https://github.com/ISALGroup/archetypes/blob/main/archetypes_list/kraft_pulp_mill.py

Archetype Name: Pulp mill Kraft

Emissions and facility overview: According to the United States Census Bureau, there are 35 establishments associated with NAICS 322110 in the United States in 2023, 26 of which report annual GHG emissions in the GHGRP.[4] According to the criteria outlined in the Technical Appendix (i.e. presence of a recovery boiler and a lime kiln onsite in the GHGRP dataset), 19 of the 26 pulp mills have been classified as mills using a Kraft process. Reported emissions from GHGRP amounted to 33.3 Mt CO_2e in 2023 for the 26 plants with the 322110 NAICS code, including biogenic emissions. The 19 plants classified as Kraft mills account for 32.2 Mt CO_2e, or 96.8% of the emissions reported in the GHGRP. The majority of these plants are concentrated in the Southeast U.S., as summarized in the map below.



[1] Electric Power Research Institute. Pulp, Paper, and Paperboard Mills. March 2011.
[2] Andrew Moore. NC State Researchers Developing Climate-Friendly Solution for Pulp and Paper Industry. September 2023.
[3] Forest Data Network. The Shifting Landscape of the U.S. Pulp and Paper Mill Industry. September 2023.
[4] U.S. Census Bureau. 2023: ECNSVY Business Patterns County Business Patterns CB2300CBP. 2023.; U.S. Environmental Protection Agency. Greenhouse Gas Reporting Program (GHGRP). 2025.

Sector outputs: Pulp mills manufacture pulp without producing end products such as paper or paperboard.

Process pathways: Pulp manufacturing consists of extracting cellulose fibers to make pulp. In terms of the origin of these fibers, they come from two main sources:

- Recovered paper
- Virgin fibers

Recovered fibers come from used paper that gets cleaned, de-inked, and re-pulped and dried to make market pulp. The U.S. has a fairly high rate of recovered paper at 65.8% in 2017,[5] and this means that recycling of pulp cannot be ignored and will be included in the presented models.

When fibers come from virgin sources (i.e. wood cut for the express purpose of manufacturing paper products), there are several pathways available to recover cellulose from the wood matrix, which contains cellulose, lignin, and hemicellulose. These pathways are typically classified into mechanical processes, which grind the wood to release the fibers, and chemical processes, which use chemical reactions to dissolve lignin and free the fibers. According to FAO,[6] the Kraft process is responsible for 90% of the production capacity of paper pulp in the U.S. and 47.2% of pulp is bleached. As such, bleaching of pulp cannot be ignored and will be included in the models. Furthermore, according to Ek et al.,[7] the majority (75%) of virgin paper produced worldwide is obtained through chemical processes, while mechanical and semi-chemical (which includes both chemical separation and mechanical grinding) methods are responsible for around 20% and 5% of global production respectively. Among chemical methods, the Kraft process is responsible for the vast majority of production (~90%), while the main other production route is the sulfite method. Tran and Vakkilainnen[8] also support that assessment, stating that ⅔ of global virgin fiber production comes from the Kraft process among all processes, and 90% of the total chemical processes. That pulp can then be made into different products, like paper, paperboard or specialized paper products. This specific document focuses on the Kraft process for pulp production.

Process overview: Figure 1 represents the process flow diagram of a pulp production mill that uses the Kraft process. A large part of the present process overview is based on the "Pulp and Paper Chemistry and Technology" series.[9]

The Kraft pulping process can be broadly separated into 6 distinct phases: wood handling, digestion/cooking, chemicals recovery, bleaching and finishing for the main kraft production line, as well as a paper recycling phase for recovering waste paper.

[5] James L. Howard and Shaobo Lang. U.S. Timber Production, Trade, Consumption, and Price Statistics, 1965-2017. USDA. 2019.
[6] Food and Agriculture Organization of the United Nations. Pulp and Paper Capacities Survey 2023-2025. 2024.
[7] Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
[8] Honghi Tran and Esa K. Vakkilainnen. The Kraft Chemical Recovery Process. 2008.
[9] Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 1: Wood Chemistry and Wood Biotechnology. 2009; Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009; Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 3: Paper Chemistry and Technology. 2009; Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 4: Paper Products Physics and Technology. 2009.

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Wood Handling Production Line: This first phase consists of cutting logs to produce wood chips that can be treated in the digesters and impregnated in chemicals. There are four process units in that phase: debarking, bark press, chipping and screening.

Debarking (sometimes also called "barking") consists of removing bark from other wood material. In general, bark refers to the outer layer of the tree, but can also refer to a large variety of cells.Some of them have a morphology similar to the rest of the wood and similar composition in terms of cellulose, hemicellulose and lignin, but other cells are mostly composed of extractives and minerals. While bark does contain cellulose that could be used to produce paper pulp, it is not typically used for making pulp and is discarded to be burned instead. The reasons for not using bark in pulp making are numerous: the fiber content of bark is fairly low (~20%),[10]making it relatively unprofitable to recover that low quantity of fibers. Bark can also contain a variety of impurities like grains of sand that would induce heavy wear on the chipper. Some of those impurities, if undegraded in the digestion and bleaching steps, could also be left in the fibers and stain pulp or paper. The proportion of bark can vary depending on a wide variety of factors, like a tree's species, its size and age, or even climate factors. According to the USDA Forest Service[11], a typical range would be between 13 and 21% of bark proportion by dry weight. Barking is typically done in rotary drum barkers, in which logs rub against each other to create friction to remove the bark. As bark gets separated from the logs, it gets collected for further processing. It should be noted that debarking does not remove the entirety of bark, and some of it remains after treatment. An estimated 1% of bark by dry weight remains in debarked logs, but this can vary.[12]

The removed bark can then be used as hog fuel to be burned in stoker (solid fuel) boilers. Bark contains a lot of moisture, between 55% and 60% for birch, pine and spruce, and high moisture contents make burning of bark difficult. To that end, a bark press is typically used to remove moisture from detached bark.

The debarked logs are then processed to become smaller chips of wood in a chipper unit. Making smaller pieces is a necessary step in chemical processes to ensure an optimal distribution of chemicals and heat. The most common machines are disk chippers, which consist of radially arranged blades, which logs are fed into, often either through feeders that use gravity or horizontal conveyor belts. Chips dimensions are typically between 20-30mm in length, 3-8mm in thickness, and 15-30 mm in width.[13]

The last step of wood handling consists of screening the wood chips to ensure a uniform chip size to allow for uniform digestion. Depending on the chipper blade wear or the type of logs being processed, larger chips (overthick) or larger pieces of wood can remain present in the outlet of the chippers. Similarly, thinner chips and fines like sawdust can appear in the outlets as well. Screening is necessary to recirculate the larger chips and wood pieces back into the chippers so they reach the right thickness, while the finer chips and sawdust are filtered out to be burned or processed out of the facility. Screens or disks can be used to sieve the different chip sizes. The amount of fines proportionate to the processed wood varies greatly depending on wood type, but also on screening technology. Some sources[14] estimate an overall balance of 90% accepted chips, and hence 10% fines and thinner chips.

[10] Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
[11] John M. Harkin and John W. Rowe. Bark and its Possible Uses. USDA. 1971.
[12] Johan Gullichsen et al. Papermaking Science and Technology, Book 6B, Chemical Pulping. 2000; Jyrki Laitinen. Determination of residual bark in debarked pulpwood using image analysis. January 2001.
[13] Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
[14] Desmond E. Smith and Shannon R. Javid. New approaches to fines and pins screening. January 1992.

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Finally, the moisture content of wood can vary widely depending on weather, wood type and storage conditions. Larger ranges of wood moisture content in the USDA report[15] are 25.9-75.1%.

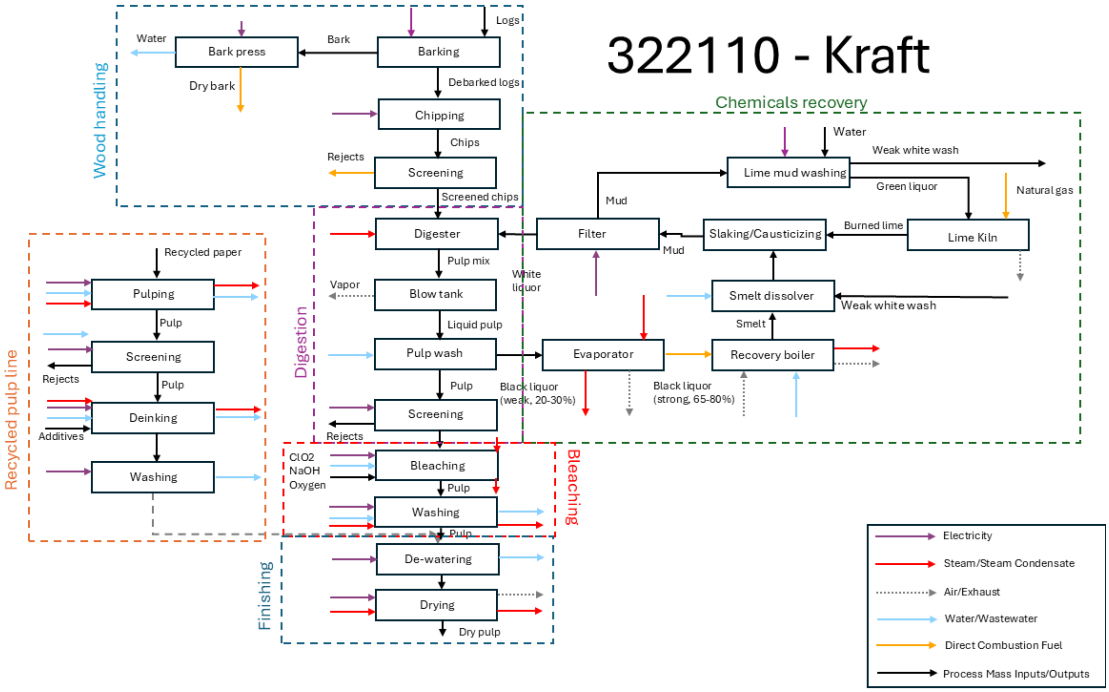


Figure 1: Kraft Mills Archetype Process Flow Diagram

Once properly-sized chips have been obtained, they are sent to the digester to begin the chemical delignification of the wood. In the kraft process, a majority of the chemicals used in the digestion process are recovered to be reused. The kraft process line will then be separated into 2 parts for the description in this work: digestion and the recovery of chemicals.

Digestion Production Line: Lignin, which holds the cellulose fibers together, is made water soluble thanks to the action of hydroxide and hydrosulfide ions. Digestion is done by mixing wood chips with white liquor—a mixture of water, sodium sulfide (Na_2S) and sodium hydroxide (NaOH)—and saturated steam into a pressurized vessel. Digesters can come in a variety of configurations, typically separated into batch digesters, which typically consist of a vertical, closed off cylinder filled with chips, white liquor and steam. Continuous process digesters rely on continuous screw feeders for the cooking process. The typical range for cooking temperature is 150-180°C.[16] Delignification is possible at lower temperature ranges, but is much slower at temperatures below 140°C, and reaction rates increase exponentially with temperature.

The pressurized pulp mixture is then sent to a blow tank in order to separate the liquid pulp and steam and send the liquid pulp for washing and treatment. The blow tank operates at atmospheric pressure and will separate the liquid and gas phases.

Liquid pulp is then sent for washing, separating cellulose fibers and the dissolved lignin. To that end,

[15] John R. Erickson. The Moisture Content and Specific Gravity of the Bark and Wood of Northern Pulpwood Species. USDA. 1972.
[16] Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.

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water is circulated through the pulp in order to extract non-cellulose materials. The washing water takes away the now water-soluble dissolved lignin and other wood carbohydrates. That mixture of water and dissolved solids and chemicals is known as black liquor.[17] On the other hand, the fibers are extracted in another end of the washer by filters. Around 50% of dry wood is digested and ends up as dry solids in the black liquor. Black liquor is then sent to the chemicals recovery loop, while pulp is sent to screening. Pulp is screened and an amount of 2% is assumed to be rejected. Screened pulp is then sent for bleaching.

Chemical Recovery Production Line: The chemicals recovery loop consists of concentrating black liquor to an acceptable level, to burn it in recovery boilers to recover heat from the dissolved solids, and then to regenerate the chemicals from the smelt generated in the recovery boilers. Black liquor after the washing step has a low dry content of less than 20%, which makes it highly unsuitable for combustion.

The first step of treating black liquor then consists of concentrating the dry solids. Dry solids are concentrated to a dry content of 70%, which is the lower bound of Ek et al.[18] and the upper bound of Biermann.[19] To lower energy demand while concentrating black liquor, multiple effect evaporators are used. These consist of evaporation units put one after the other, whose function is to separate the mixture incoming into a concentrated fraction and remove moisture in the form of steam. The steam removed from each of the evaporation units is used as the heating steam of the next unit, each unit being at higher pressure than the next to lower the boiling point. This means that while the first unit receives live steam, its heat is reused by using the steam produced by the first unit in the second one and so on. In modern plants, a counter-current configuration is typically used, meaning the input weak black liquor with the highest moisture content is put last in line, while the evaporation unit that produces strong black liquor that will be sent for combustion receives live steam. While a single effect evaporation configuration would only allow to evaporate less than 1 ton of water from the product for every ton of live steam fed into the unit, multiple effect evaporators allow to evaporate multiple tons of water for every ton of steam fed. This ratio of amount of water evaporated and amount of input steam is called steam economy. This ratio is dependent on several factors, the most important of which is the amount of evaporation units used. It can be argued multiple effect evaporators in large modern plants rely on a high number of units, and would consequently have a larger steam economy factor. To keep a general approach that would include older and smaller plants, a conservative estimate is kept, but can be modified in the models to suit modern processes.

After evaporation, strong black liquor is then sent to the recovery boilers for combustion. This combustion fills two important purposes:

- It valorizes the digested wood that does not end up in the pulp by producing a large amount of heat in the form of steam that can be used for the other process units, like the digester or the evaporators, but also to produce electricity that can power the process or be sold to utilities.
- The combustion products contain the reacted chemicals from the white liquor that can be recovered to be reinjected into the digester through a recovery loop.

Strong black liquor is combusted in the recovery boilers. It has an energy content similar to typical woody fuels. This combustion releases energy and is valorized in the form of steam, and the byproducts of this combustion consist of a smelt composed of Na_2S and sodium carbonate (Na_2CO_3). Combustion of black liquor allows recovery of Na_2S, but to recover NaOH, further treatment is necessary.

[17] Lawrence Berkeley National Laboratory. Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the U.S. Pulp and Paper Industry. July 2000.
[18] Ibid.
[19] Christopher J. Biermann. Handbook of Pulping and Papermaking. 1996.

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The smelt is sent to a dissolver to make it into a solution called green liquor. The water coming in the dissolver comes both from utilities, but also from the white wash, which consists of the washing water from treating the lime mud in another unit.

The green liquor is then sent to a slaker/causticizer when it is mixed with quicklime (CaO) so that Na_2CO_3 reacts with it to produce NaOH and calcium carbonate ($CaCO_3$) through an exothermic reaction. The resulting product is sent to be filtered to reobtain white liquor to be injected into the digester and complete the chemicals recovery loop. The other output of the filter is a calcium carbonate ($CaCO_3$), or lime mud that will be sent for treatment to recover CaO in a lime kiln.

The lime mud filter will output white liquor in the same conditions as the input of the digester, and the resulting water and lime mud mixture is sent to be washed. Lime mud washing consists of washing the mud and pressing it to limit moisture content before the mud is sent to the lime kiln. Washed lime mud is sent to the lime kiln and the white wash (the lime wash water) is reused for the smelt dissolver. The lime kiln consists of bringing the lime to calcination temperature (850°C) usually with direct combustion of natural gas to initiate the endothermic reaction of transforming calcium carbonate into quicklime. The resulting quicklime is conveyed to the slaking process with green liquor to recover NaOH, completing the loop. CO_2 is released as a reaction product of calcination.

Bleaching Production Line: While not always a necessary step, sometimes a brighter pulp or paper is desired. In that case, the pulp is sent to be bleached to remove the darker color of the pulp after cooking, which comes from residual lignin. It is included in this model as a majority of chemically produced pulp is bleached to obtain brighter pulp and paper. Bleaching stages are typically done in sequence with a different chemical for each stage, even if sometimes several chemicals can be used at the same time in the same stage. Due to the breadth of chemicals that can be used for bleaching—acid treatment, chlorine, chlorine dioxide, oxygen, hydrogen peroxide, ozone, etc.—and the lack of a standard for which chemicals are applied, many degrees of freedom are possible for this step. After the bleaching stages, bleached pulp is washed to remove bleached material and chemicals.

Finishing Production Line: Finally, pulp will be sent to be de-watered, dried and packaged. In integrated plants, pulp would be kept at low consistency to form paper, but to produce market pulp it needs to be dewatered. It is assumed to be done in a screw press, even if other technologies like belt presses or centrifuges can also be used.

De-watered pulp is then sent to pulp dryers in which market pulp has a typical moisture content of around 10%.

Recycling Production Line: Pulp can also be sourced from recycling paper at its end-of-life by re-pulping the waste paper and treating it to remove impurities. It is assumed to be divided broadly into four steps: pulping, screening, de-inking and washing.

Pulping typically takes place in drum pulpers or high-consistency batch pulpers which have a consistency of 12%-18%.[20] They run at higher temperatures than ambient and require electricity to circulate the pulp.

Pulp is screened and an amount of 2% is assumed to be rejected. Screened pulp is then sent for de-inking. De-inking is a flotation process that usually takes place between 1% and 2% consistency and

[20] Pratima Bajpai. Recycling and Deinking of Recovered Paper. 2024.

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stays at temperatures between 40°C and 45°C.[21]

Finally, a washing step takes place to remove impurities separated from the fibers in the de-inking step.

Archetype Unit Process Assumptions: In this work, we assume that wood and bark have moisture contents of 55% in weight. The model used is depicted in Figure 1, and Table 1 contains the assumptions made in each process unit of the model.

Limitations and future work: Generic units were modeled for dryers and evaporators. Additives use modeling lacks some details, but these would have a low impact on overall process heat demand. At the time of report production, numbers from DOE[22] were used in order to supplement energy demand per process unit as the recycled paper line was not yet included in the models.

Table 1: Kraft Pulp Mill Archetype Unit Process Assumptions

Unit Process Name	Assumptions	Parameter Basis	Source
Barking	Bark : 15.0% of dry weight	Literature-derived	Johan Gullichsen et al. Papermaking Science and Technology, Book 6B. Chemical Pulping. 2000; Jyrki Laitinen. Determination of residual bark in debarked pulpwood using image analysis. January 2001.
Bark press	Bark moisture drop: 15%	Literature-derived	André Holmberg and Stig Stenström. Dewatering and Drying of Bark. 2014.
	Bark heating value: 5900 kJ/kg	Literature-derived	Dan Gavrilescu. Energy from biomass in pulp and paper mills. 2008.
Chippers	Chippers electricity use: 30.3 kWh/ton	Literature-derived	Lawrence Berkeley National Laboratory. Opportunities to Improve Energy Efficiency and Reduce Greenhouse Gas Emissions in the U.S. Pulp and Paper Industry. July 2000.
Screening	Rejects ratio: 5%	Engineering judgment	Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
Digester	Steam temperature: 165 ℃	Literature-derived	Monica Ek et al. Pulp and Paper Chemistry and

[21] Pratima Bajpai. Recycling and Deinking of Recovered Paper. 2024.
[22] U.S. Department of Energy. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing. 2015.

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			Technology Volume 2: Pulping Chemistry and Technology. 2009.
	White liquor temperature: 45 ℃	Engineering judgment	
	White liquor/chips ratio: 1.0	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996. Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
	White liquor composition: NaOH: 1 mol/liter Na2S: 0.2 mol/liter	Literature-derived	CNBM International Pulp and Paper. Introduction to Liquor of Pulp and Paper. 2018.
Pulp wash	Electricity:3 kWh/ ton liquid pulp	Literature-derived	Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
	Water-to-pulp ratio: 1.0	Literature-derived	Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
Evaporators	Steam economy: 4	Literature-derived	David T. Clay. Evaporation Principles & Black Liquor Properties. 2008.
Recovery boilers	Dry black liquor energy content: 15MJ/kg	Literature-derived	Honghi Tran and Esa K. Vakkilainnen. The Kraft Chemical Recovery Process. 2008; International Flame Research Foundation. What is black liquor? April 2003.
	Black liquor elemental carbon content: 35%	Literature-derived	David T. Clay. Evaporation Principles & Black Liquor Properties. 2008.
	Outlet steam temperature: 300 ℃	Engineering judgment	
Smelt dissolver	Dry solids content: 5%	Engineering judgment	
Lime mud washing	Electricity: 3kWh/ton mixture	Engineering judgment	
	Water-to-pulp ratio: 1.0	Engineering judgment	
	Moisture content after wash: 30%	Engineering judgment	
Bleaching	Number of steps: 3	Engineering judgment	
	Chemicals used in each step: NaOH, O_2, ClO_2	Literature-derived	European Commission. Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board. 2015.

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	Chemicals amount per stage: ClO_2: 1.5% pulp mass O_2: 10 kg/ton of pulp NaOH: 20 kg/ton of pulp	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996. Confederation of European Paper Industries. Best Available Technology in the Manufacturing of Pulp. 1997
	Dry content: 10%	Literature-derived	Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
	Bleaching losses: 10%	Literature-derived	Harry L. Brown et al. Energy Analysis of 108 Industrial Processes. 1996.
	Bleaching temperature: 100 ℃	Literature-derived	Monica Ek et al. Pulp and Paper Chemistry and Technology Volume 2: Pulping Chemistry and Technology. 2009.
Dewatering	Electricity: 1.2 kWh/ton dry pulp	Literature-derived	Bouchaib El Idrissi et al. Dewatering parameters in a screw press and their influence on the screw press outputs. 2019.
	Moisture change: 10% or up to total of 78% moisture	Literature-derived	Bouchaib El Idrissi et al. Dewatering parameters in a screw press and their influence on the screw press outputs. 2019.
Pulp dryer	Market pulp moisture content: 10%	Engineering judgment	
	Air temperature: 110℃	Engineering judgment	
	Exhaust temperature: 100℃	Engineering judgment	
Recycling line pulper	Temperature: 80℃	Literature-derived	Jerry Aue et al. Fiber Recovery from Waste Paper: A Breakthrough in Re-Pulping Technology. 2004.
	Electricity: 28 kWh/ton pulp	Literature-derived	Pratima Bajpai. Pulp and Paper Industry: Energy Conservation. 2016.

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