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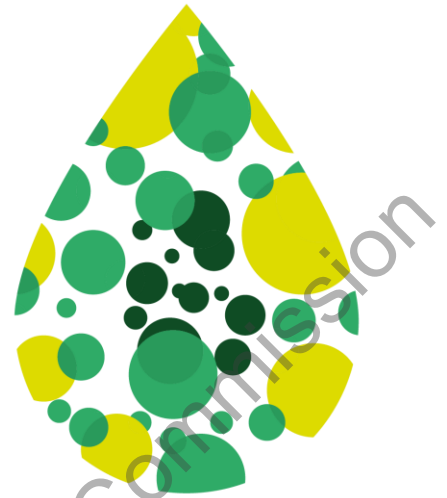
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BL2F

Transforming Black Liquor to Biofuel



Research and Innovation Action

H2020-LC-SC3-2019-NZE-RES-CC

Feasibility assessment of integrating the production of HTL biofuels in conventional pulp mills

WP4 - Task 4.3

Date [M45]

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Abbreviations, acronyms, and symbology

| Acronym/Symbol | Description |
|----------------|--------------------------------|
| HTL | Hydrothermal liquefaction |
| BL | Black liquor |
| IHDO | Integrated Hydrodeoxygenation |
| BEKP | Bleached eucalyptus kraft pulp |
| | |
| | |



Executive Summary

BL2F aims to demonstrate a technological pathway to produce advanced liquid biofuel from the black liquor (BL) based on hydrothermal liquefaction (HTL) technology. In line with this goal, this deliverable reports the economic feasibility analysis of one business case defined for one of NVG's chemical pulp mills with integration of the HTL process under realistic commercial environments. The business model considers the integration into the pulp of the simple HTL plant that can achieve feasible production of a biocrude product compatible as feed to conventional refineries with the lowest investment and operating costs. Main side streams from the HTL plant, i.e. precipitated salts, HTL solids and the aqueous effluent, can be recycled back to the pulp mill at the inlet to the evaporator. The best strategy for integrating HTL biocrude production into a Kraft pulp mill is to co-feed weak black liquor with 20% bark from the power boiler into the HTL plant. In this scenario, the energy yield of the biocrude is above 55%, the energy losses from the black liquor in the recovery boiler are compensated by the recycled sludge from the HTL plant, and the heat demand by the evaporation increases slightly. Considering a typical commercial Kraft pulp mill with an annual production of 500 kt of bleached pulp, diverting between 20 and 30% of the total weak black liquor with 20% bark to the HTL plant, the total annual biocrude production is in the range of 59.3 and 88.9 kton. Assuming a that gives a 10% return of investment to the pulp mill, the biocrude can be sold to a refinery at a minimum price of 1.16-1.07 €/kg, which provide an annual income to the pulp mill of 68.7-94.7 M€. Increasing the bark content in the feed to the HTL process can result in nitrogen concentrations in the biocrude that can exceed the requirements from conventional refineries. Based on the estimated biocrude prices, current oil refineries can produce kerosene and heavy distillates for the aviation and maritime sectors, respectively, with minimum fuel selling prices in the range of roughly 2.3-2.5 €/liter and 1.4-1.5 €/liter, which are high when compared to reference market prices.

Keywords

Black liquor, HTL, integration, pulp mill, business case, biofuel, aviation, shipping

1 Introduction

1.1 Purpose of this deliverable

The primary objective of this deliverable is to evaluate the economic feasibility of the integration of hydrothermal liquefaction into a representative pulp mill of the Navigator Company under relevant commercial environment.

The specific objectives are:

1. Define an industrial representative business case based on one of the Navigator Company (NVG) Kraft pulp mills.
2. Evaluate economic viability indicators for the business case in a timeframe of 30 years based on plausible market and regulatory scenarios.
3. Perform sensitivity analysis of the business case based on critical parameters influencing the economic viability.

1.2 Background information and input data from other tasks

The following information has been used (see also references):

1. General objectives, technological options and process performance targets from the proposal SEP-210593035, " Black Liquor to Fuel by Efficient HydroThermal Application integrated to Pulp Mill."
2. Process performance of a hardwood kraft pulp mill process with the integration of the HTL plant. Reported in the deliverable H2020-LC-SC3-2019-NZE-RES-CC/D4.1, 2021, " Process design and analysis for the integration of the production of HTL biofuels in conventional pulp mills".
3. Mass and energy flows of the HTL plant and the upgrading of HTL biocrude to liquid biofuels. Reported in the deliverable H2020-LC-SC3-2019-NZE-RES-CC/D4.1, 2021, " Process design and analysis for the integration of the production of HTL biofuels in conventional pulp mills".
4. Capital and operating costs associated to the HTL plant integrated in a kraft pulp mill and upgrading of the HTL biocrude to liquid biofuels at refinery. Reported in the deliverable H2020-LC-SC3-2019-NZE-RES-CC/D4.2, 2021, "Scale-up, risks and costing of integrating the production of HTL biofuels in conventional pulp mills"

2 Business model for the integration of HTL biocrude production in Kraft pulp mills

2.1 Description of the business model and the value chain

At present, there is a large demand of advanced liquid biofuels by heavy-duty transport sectors [1] i.e., marine, aviation, and long-haul road transport, which is estimated to be approximately 27% of the total fuel need by 2050 worldwide, with a similar share of about 25% within the European Union by 2030. The black liquor generated at pulp mill has a high lignin concentration, approximately 50% wt. on dry basis, which makes it suitable for conversion to an oil product via hydrothermal liquefaction (HTL), so called biocrude, which can be further upgraded to liquid biofuels in conventional refinery processes. In this scenario, there is a new business model for pulp mills to invest in a HTL plant that uses a fraction of the black liquor for production of biocrude which can be sold to refineries. The revenues from selling biocrude shall compensate the capital investment in the HTL plant as well as the increase in operating cost in the pulp mill.

Analysis of the feasibility of the business model requires to consider an overall value chain perspective as shown in Figure 1, which include the following main aspects:

- Reference pulp mill location, capacity, design, and strategies for integration of the HTL plant.
- HTL plant design specification, material and energy flows, capital investment and operating costs.
- Process and economic impact of integrating the production of HTL biocrude from black liquor on the pulp mill operation related to wood supply, chemicals consumption, and overall heat and electricity balances.
- Biocrude quality specification and minimum prices at refinery.
- Refinery location, design, and specification of biocrude quality specification and minimum prices.
- Material and energy balances of HTL biocrude upgrading and minimum selling prices for aviation and marine fuels at refinery.

2.2 Reference Kraft pulp mill

The business model and analysis consider a reference commercial pulp mill representative of the Navigator Company, located in Setubal (Portugal) and with a nominal annual production capacity of 500 kt of bleached eucalyptus kraft pulp (BEKP). Figure 1 shows a block diagram representing the pulp mill design based on the Kraft process. The main operational parameters together with the material and energy balances for the reference pulp mill are shown in Tables 2, based on information gathered from industry partners within the BL2F project and literature [2]. At present, the production of weak black liquor, separated after the digester, is approximately 8.6 ton per air dry ton of pulp. The totality of the weak black liquor is further processed at the pulp mill in the so-called recovery cycle where the black liquor is first dried in the evaporators, combusted in a recovery boiler for converting the chemical energy to steam



and the remaining inorganic chemicals are re-causticized and recycle back to the digester. Conventional Kraft pulp mills also includes a Rankine cycle for generation of electricity from the steam produced at the recovery boiler and an additional power boiler using bark. The electricity produced from the Rankine cycle is typically higher than the electricity consumed by the pulp mill, the excess electricity being exported.

2.3 HTL plant design

As reported earlier in deliverable D4.2 [3], including partial upgrading of the oil product from HTL by hydrodeoxygenation (IHDO) and production of hydrogen by aqueous phase reforming (APR) of the process water leads to a significant increase of the biocrude production costs above 4€/liter, which is unlikely to be accepted by refineries. Moreover, both IHDO and APR processes exhibit technical risks associated to catalyst poisoning and deactivation, as shown by the experimental work within the BL2F project. Therefore, the business case considers the simplest design of the HTL plant that can achieve feasible production of biocrude with lowest cost of production, as shown in Figure 3. The feed from the pulp mill is stored in a stirred tank and then pressurized and heated before entering the HTL reactor, where the salts are precipitated at the bottom and the remaining desalinated slurry is liquefied. Biocrude is extracted only from the desalinated product of the HTL reactor. The salt brine, which contains a fraction of biocrude, is cooled, decompressed and taken back to the pulp mill together with the HTL solids and the aqueous phase from separation of the biocrude.

2.4 Strategies for the integration of HTL biocrude production in Kraft pulp mills

Figure 4 shows a schematic representation of the reference kraft pulp mill process design with integration of the production of HTL biocrude. The integration strategies, defined in dedicated discussion within the BL2F project involving the Navigator company, Neste Oil and Valmet, includes:

- The feed to the HTL plant includes a fraction of the weak black liquor before the evaporator.
- Co-feed bark and internal sludges from the pulp mill with the weak black liquor into the HTL plant to increase the biocrude yield and compensate the chemical energy losses into the recovery boiler.
- Return the sludge from the HTL plant containing precipitated salts, HTL solids, aqueous phase and non-extracted biocrude back to the evaporator of the pulp mill.
- Use forest residues at the pulp mill to replace bark and compensate the increase of heat demand and maintain the steam supply to the Rankine cycle constant.

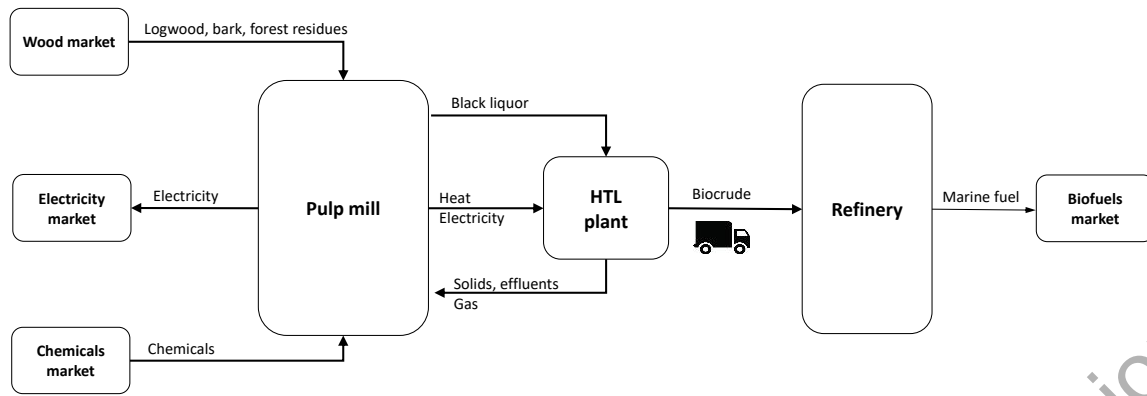


Figure 1: Schematic representation of the value chain associated with the integration of HTL biocrude production into pulp mills.

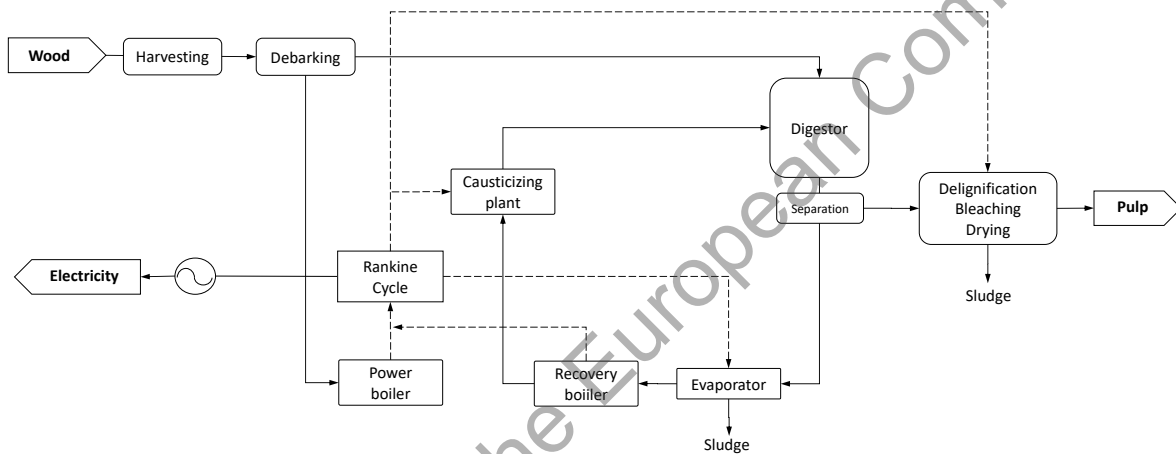


Figure 2: Schematic representation of the reference pulp mill design based on the Kraft process.

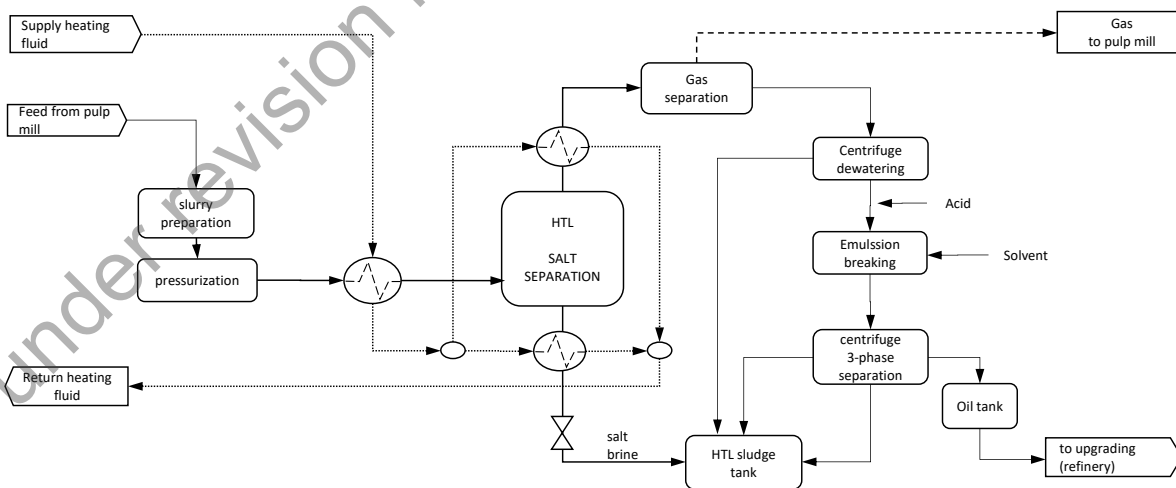


Figure 3: Schematic representation of the HTL plant.

Table 1: Main material and energy flows for the reference Kraft process per air dry ton (adt) of pulp product

| Operational parameters | |
|---|---------|
| Pulp mill capacity (kt bleached pulp / year) | 500 |
| Woodchips moisture content (% wt.) | 45.0 |
| Bark moisture content (% wt.) | 45.0 |
| Bark high heating value, dry basis (GJ/tds) | 20.3 |
| Black liquor (weak) water content (% wt.) | 82.8 |
| Black liquor (weak) temperature (°C) | 105 |
| Black liquor feed pressure (bar-a) | 5 |
| Evaporator capacity (ton water / day) | 10500 |
| Dry mass loss in evaporator (% wt.) | 2,6 |
| Recovery boiler, steam temperature (deg. C) | 505 |
| Recovery boiler, steam pressure (bar-g) | 103 |
| Material flows | |
| Log wood consumption | 3.91 t |
| Woodchips | 3.5 t |
| Bark | 0.41 t |
| Black liquor (weak) production (ton/adt) | 8,6 t |
| Strong black liquor | 1.6 t |
| CaO to recovery cycle | 4.7 kg |
| NaOH to recovery cycle | 4.7 kg |
| Na ₂ SO ₄ to recovery cycle | 10.3 kg |
| NaOH to bleaching | 20.0 kg |
| H ₂ O ₂ to bleaching | 9.3 kg |
| ClO ₂ to bleaching | 19.3 kg |
| Oxygen to delignification | 25.7 kg |
| MgSO ₄ to delignification | 1.1 kg |
| Energy flows | |
| Chemical energy in strong black liquor | 16.6 GJ |
| Chemical energy in bark | 4.0 GJ |
| Chemical energy input recovery boiler | 16.8 GJ |
| Chemical energy input bark gasification | 4.0 GJ |
| Boiler steam production | 19.0 GJ |
| Gas fuel demand lime by kiln | 1.0 GJ |
| Total heat demand | 7.9 GJ |
| Digester | 1.4 GJ |
| Delignification. | 0.1 GJ |
| Bleaching | 1.5 GJ |
| Pulp drying | 2.3 GJ |
| Evaporator | 2.6 GJ |
| Total electricity production | 972 kWh |
| Total electricity consumption | 600 kWh |
| Condenser heat loss | 2.8 GJ |

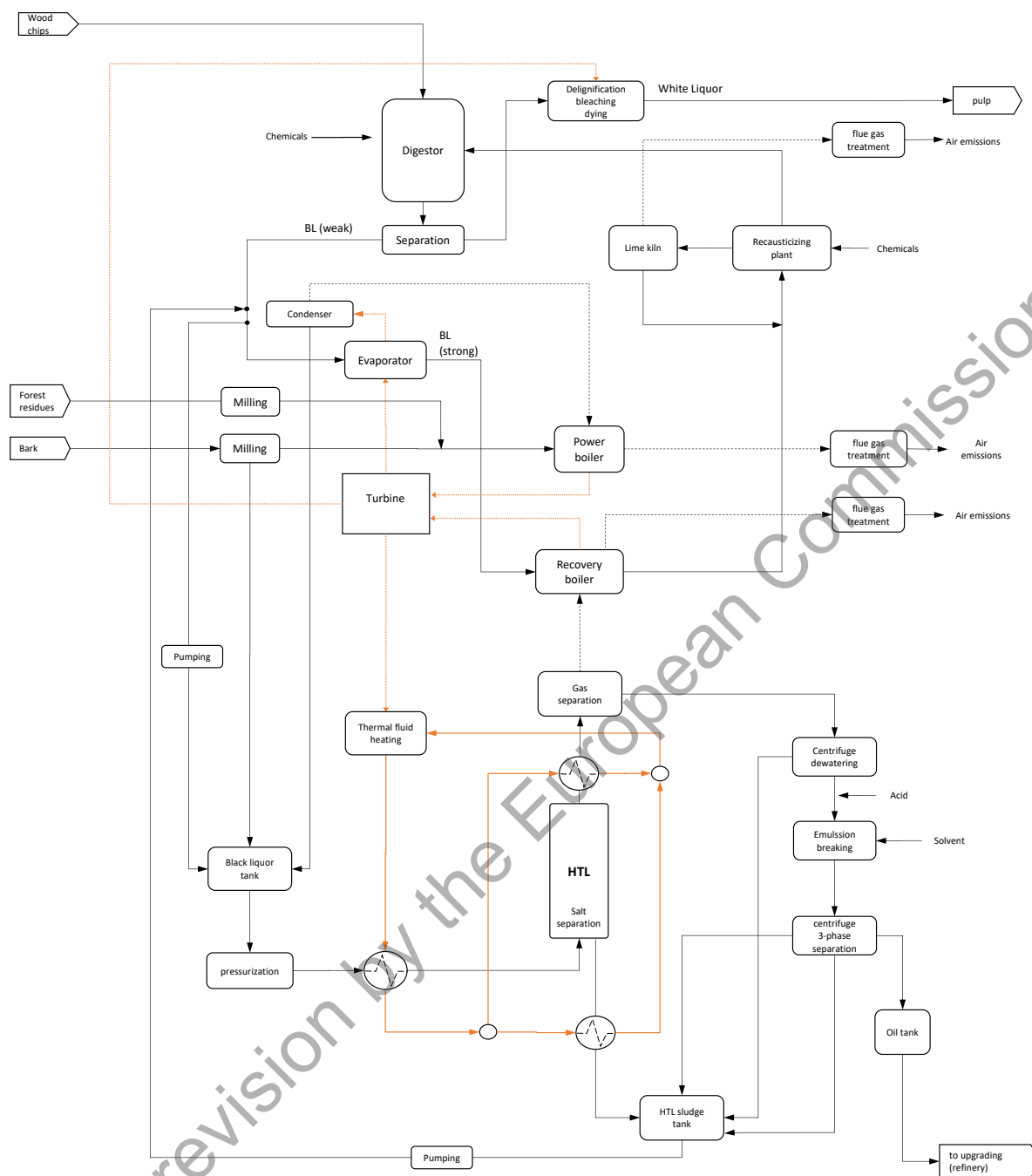


Figure 4: Process block diagram representing the integration of the HTL plant into a Kraft pulp mill. Black solid lines, orange dashed lines, orange solid lines and black dashed lines represent, respectively, main feedstock or slurry flows, steam, thermal fluid streams, and gas flows.



3 Kraft pulp mill operation with integration of HTL biocrude production

3.1 Material and energy flows of the HTL plant

The HTL plant process has been evaluated as a function of the fraction of the total black liquor (weak) from the pulp mill used for production of HTL biocrude and the mass fraction of bark in the feed to the HTL plant, respectively denoted by f_{BL}^{HTL} and y_{bark}^{HTL} . The total mass flow rate of the feed to the HTL plant is then calculated from $\dot{M}_F^{HTL} = \dot{M}_{BL}^{PM} f_{BL}^{HTL} [1 + y_{bark}^{HTL} / (1 - y_{bark}^{HTL})]$. Table 3 shows the main material and energy flows for the HTL plant as a function of the mass fraction of bark in the feed. Figure 5 shows the variation of the dry mass (left) and chemical energy (right) yields of the main streams exiting the HTL plant. Due to the higher organic content of the bark compared to the black liquor, the mass and energy yields of the oil increases with higher content of the bark in the feed to the HTL plant.

Table 2: Main material and energy flows for the HTL plant

| Mass fraction of bark in the feed to the HTL plant | 0% | 10% | 20% | 30% | 50% |
|--|--------|--------|--------|--------|--------|
| Mass oil product (kg/kg dry) | 0.215 | 0.247 | 0.267 | 0.281 | 0.298 |
| Oil High heating value, HHV (MJ/kg dry) | 30.85 | 31.16 | 31.31 | 31.40 | 31.50 |
| Carbon in oil (% wt. dry) | 83.53% | 83.48% | 83.45% | 83.44% | 83.42% |
| Hydrogen in oil (% wt. dry) | 7.02 % | 7.20 % | 7.29 % | 7.34 % | 7.40 % |
| Oxygen in oil (% wt. dry) | 7.29 % | 7.80 % | 8.05 % | 8.20 % | 8.37 % |
| Nitrogen in oil (% wt. dry) | 0.00 % | 0.09 % | 0.14 % | 0.16 % | 0.19 % |
| Sulfur in oil (% wt. dry) | 0.000% | 0.005% | 0.007% | 0.008% | 0.010% |
| Salts brine (kg dry) | 0.326 | 0.285 | 0.261 | 0.244 | 0.223 |
| Water in salts brine (% wt.) | 76.6 | 79.3 | 80.9 | 82.1 | 83.5 |
| Dry solids from desalinated HTL product (kg/kg dry) | 0.162 | 0.179 | 0.189 | 0.196 | 0.204 |
| Water in HTL solids (% wt.) | 70.0 | 70.0 | 70.0 | 70.0 | 70.0 |
| HTL Gas (kg/kg dry) | 0.062 | 0.075 | 0.083 | 0.088 | 0.095 |
| Dissolved material in HTL aq. effluent (kg/kg dry) | 0.235 | 0.214 | 0.200 | 0.192 | 0.180 |
| Water in HTL aqueous effluent (% wt.) | 94.86 | 94.85 | 94.89 | 94.92 | 94.95 |
| Total acid to phase separation (g/kg dry) | 50.4 | 52.4 | 53.6 | 54.4 | 55.4 |
| Total organic solvent to phase separation (g/kg dry) | 4.3 | 4.9 | 5.3 | 5.6 | 6.0 |
| Chemical energy yield in oil product | 0.499 | 0.525 | 0.539 | 0.548 | 0.558 |
| Chemical energy yield in salts brine | 0.134 | 0.141 | 0.145 | 0.147 | 0.150 |
| Chemical energy yield in HTL solids | 0.043 | 0.046 | 0.047 | 0.048 | 0.049 |
| Chemical energy yield in HTL gas | 0.054 | 0.057 | 0.059 | 0.060 | 0.061 |
| Chemical energy yield in HTL aqueous effluent | 0.270 | 0.231 | 0.210 | 0.198 | 0.183 |
| Heat demand (MJ/kg) | 0.242 | 0.255 | 0.304 | 0.339 | 0.383 |
| Electric load (kW/kg) | 10.8 | 11.6 | 12.4 | 13.0 | 14.1 |

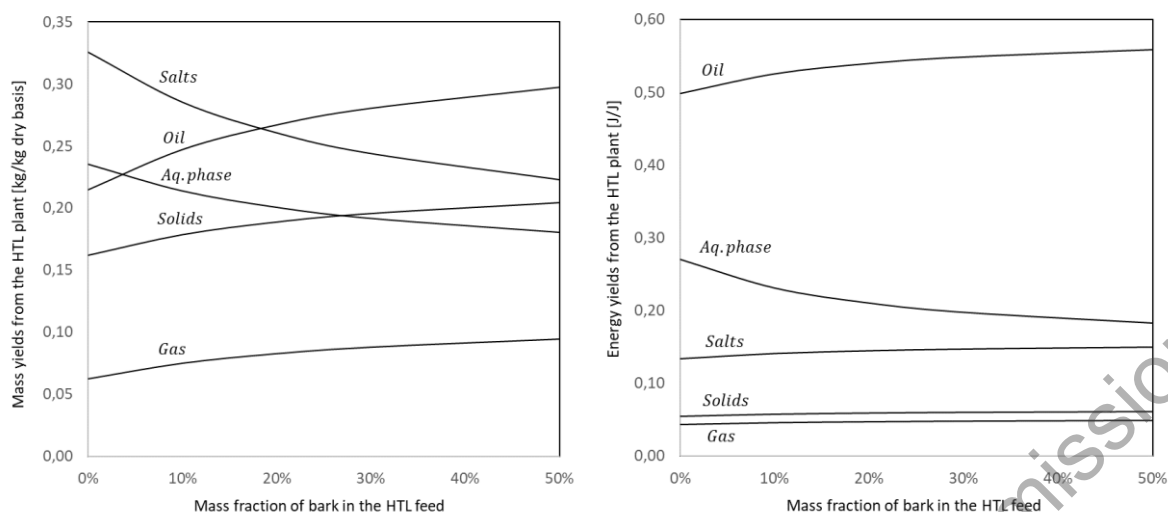


Figure 5: Variation of the mass yields on dry basis (left) and the energy yields (right) as a function of the mass fraction of bark in the feed to the HTL plant.

3.2 Kraft pulp mill operation with integration of HTL biocrude production

Tables 4-8 show the main results from the analysis for the pulp mill process with integration of production of biocrude using black liquor and bark. The analysis of the overall heat balance of the pulp mill with integration of the HTL biocrude production has assumed that the total steam input to the Rankine cycle for production of electricity remains constant. Therefore, the combined heat production from the recovery boiler and the power boiler shall cover the new heat demand of the pulp mill and the HTL plant. The maximum bark used in the power boiler and the HTL plant is not exceeding the original feed to the reference pulp mill.

3.2.1 Impact on the evaporator

Figure 6 shows the impact of integrating the production of HTL biocrude from black liquor and bark on the water content of the sludge to the evaporators and relative heat demand by the evaporators. With low fractions of bark in the feed to the HTL plant, below about 15%wt., increasing the fraction of black liquor used for production of HTL biocrude leads to an increase of the water content of the feed to the evaporator, while the heat demand slightly decreases due to the reduction of mass load with lower dry matter content. Since the water content of the bark is lower than the weak black liquor used at the HTL plant, increasing the fraction of the bark above 15% wt. leads to a decrease of the total water content of the evaporator feed. However, the net heat demand increases due to the increase of the total mass feed to the evaporator, this becoming up to 1.5 times higher than the reference baseline pulp mill when 30% of the weak black liquor with 50% bark is used at the HTL plant.

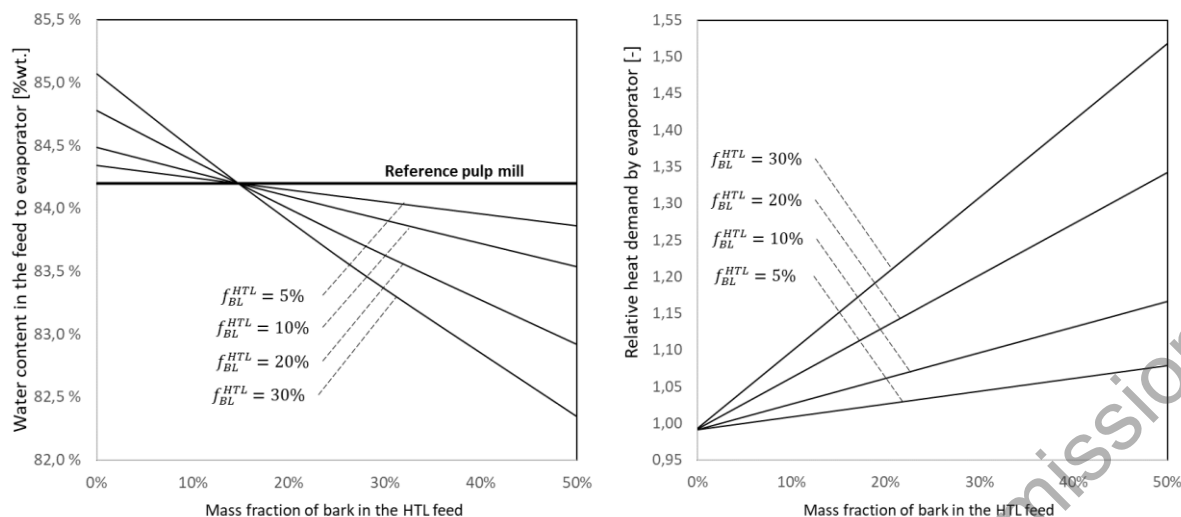


Figure 6: Relative heat production from the recovery boiler (left) and the power boiler (right) between the modified pulp mill with integration of HTL biocrude production and the reference pulp mill without integration. The fraction of the black liquor and bark diverted to the HTL plant vary, respectively, between 5 and 30% and 0-50%

3.2.2 Impact on the recovery boiler

The impact of integrating the production of HTL biocrude from black liquor and bark on operation of the recovery boiler at the pulp mill is shown in Figure 7. With low content of bark in the feed to the HTL plant, increasing values the fraction of black liquor used for production of biocrude leads to a reduction in the input flow rate and the thermal power production in the recovery boiler. As the bark content increases above 20%, the total chemical energy of the return sludge from the HTL plant overcomes the energy losses from the black liquor used for biocrude production leading to an increase in thermal power production. This increase becomes larger with larger fraction of black liquor diverted to the HTL plant.

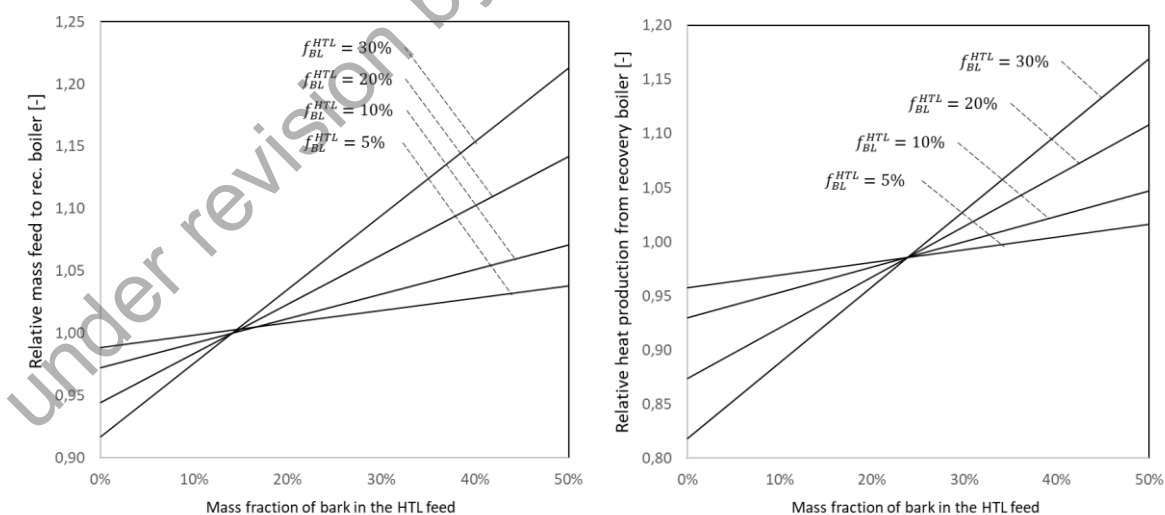


Figure 7: Relative input mass flow rate (left) and thermal power production (right) of the recovery boiler at the pulp mill with integration of HTL biocrude production. The fraction of the black liquor and bark diverted to the HTL plant vary, respectively, between 5 and 30% and 0-50%



3.2.3 Impact on the total heat demand and power boiler capacity

The integration of biocrude production from black liquor and bark leads to an increase in the total heat demand (see Figure 8) due to the demand by the HTL plant and the increased evaporator heat demand. For lower fraction of black liquor diverted to the HTL plant, the increase of heat demand with the bark content behaves monotonically. As the fraction of black liquor increase above about 20%, the relative increase of the total heat demand decays with the bark content. The required total capacity of the power boiler (see Figure 9) also increases with the higher fractions of the black liquor diverted to the HTL plant, but this increase is lower with larger content of bark due to the higher power production in the recovery boiler. The required mass flow rate of forest residue (see Figure 9) to cover both the amount of bark used in the HTL plant and to cover the increase in heat demand increase monotonically with the amount of both the black liquor and bark diverted to HTL.

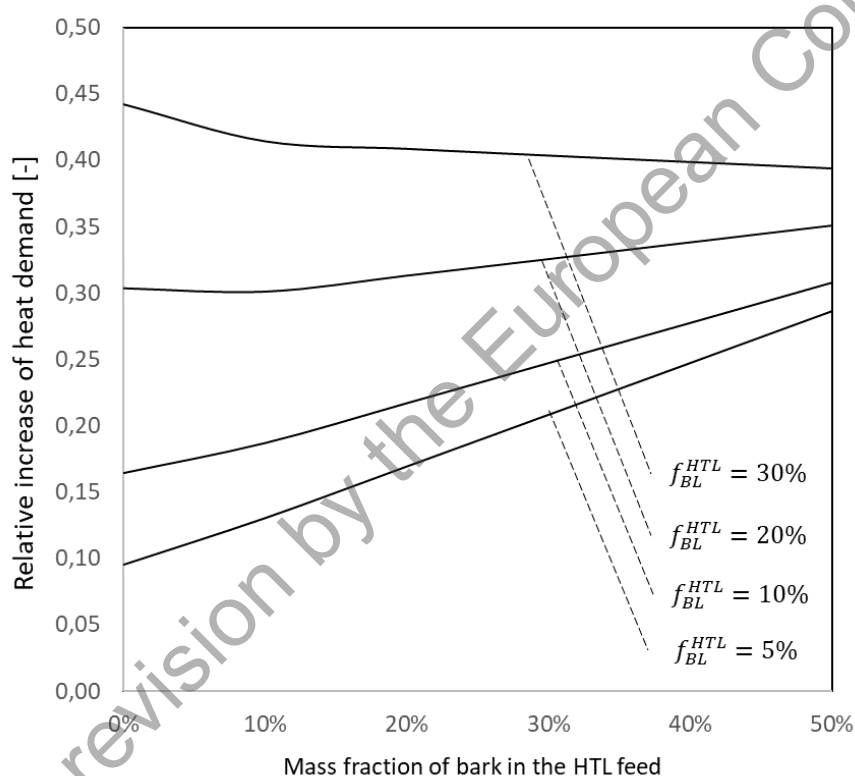


Figure 8: Increase of the total heat demand relative to the reference pulp mill as a function of the fraction of the black liquor and bark content used to feed the HTL plant.

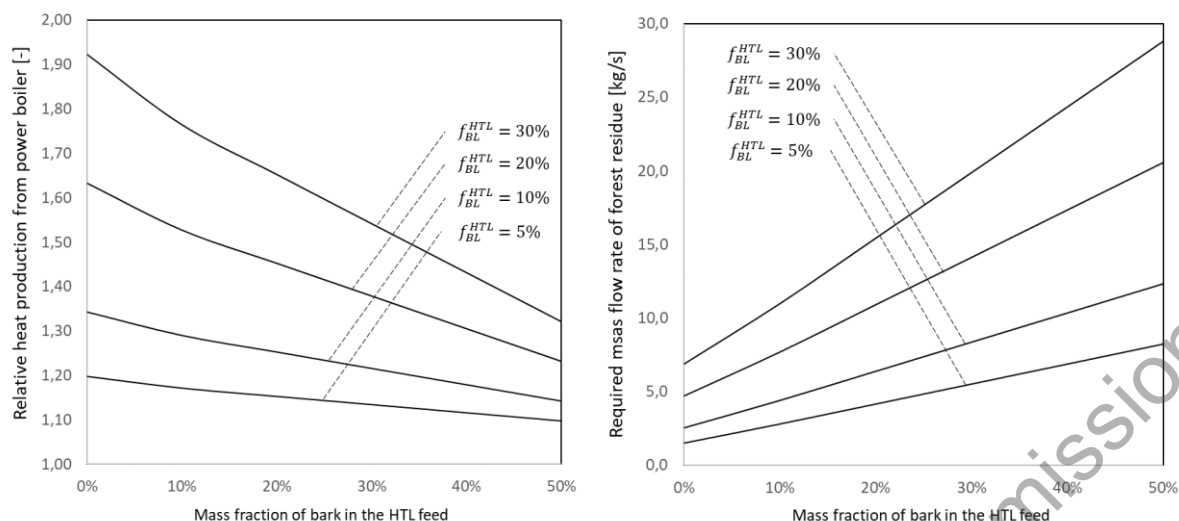


Figure 9: Required consumption of forest residue by the power boiler (right) and relative increase of thermal power production from the power boiler (left) at the pulp mill with integration of HTL biocrude production. The fraction of the black liquor and bark diverted to the HTL plant vary, respectively, between 5 and 30% and 0-50%.

3.2.4 Impact on exported electricity

Figure 10 shows the total electric power production relative to the reference pulp mill, which decreases as the fraction of the black liquor and the content of the bark to the HTL plant increases. Since the total steam input to the Rankine cycle is assumed to be constant in the analysis, the reduction of the electric power is due to the consumption of the HTL plant. For the larger size of the HTL plant consider in the analysis, using 30% of the black liquor with 50% bark content, the reduction in electricity exported to the net is about 13% relative to the reference pulp mill. On the other hand, applying 10% of the weak black liquor to the HTL plant, and 50% bark content in the HTL feed the reduction in the electricity production is remaining around 1%.

under revision by the European Commission

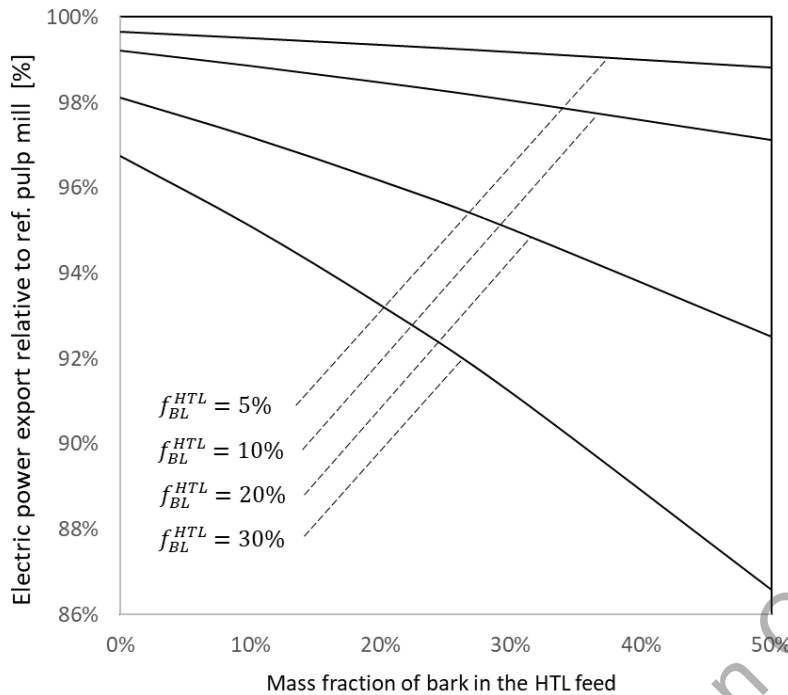


Figure 10: Exported electric power production relative to the reference pulp mill as a function of the fraction of the black liquor diverted from the pulp mill and the mass fraction of black liquor in the feed to the HTL plant.

under revision by the European Commission

D4.3 Feasibility assessment of integrating the production of HTL biofuels in conventional pulp mills.



Table 3: Main material and energy flows for the reference Kraft process per air dry ton (adt) of pulp product as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 0% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 0% | 5% | 10% | 20% | 30% |
|---|-------|-------|-------|-------|-------|
| Material flows | | | | | |
| Woodchips (t) | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Bark to power boiler (t) | 0.41 | 0.41 | 0.41 | 0.41 | 0.41 |
| Bark to HTL plant (t) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Forest residue to power boiler (t) | 0.00 | 0.08 | 0.15 | 0.27 | 0.39 |
| Black liquor (weak) (t) | 8.6 | 8.17 | 7.74 | 6.88 | 6.02 |
| Black liquor (strong) (t) | 1.6 | 1.52 | 1.44 | 1.28 | 1.12 |
| Black liquor (weak) to HTL plant (t) | - | 0.43 | 0.86 | 1.72 | 2.58 |
| Biocrude (t) | - | 14.61 | 29.21 | 58.42 | 87.64 |
| Salt brine (t) | - | 94.5 | 189.1 | 378.1 | 567.2 |
| HTL solid residue (t) | - | 40.4 | 62.2 | 124.3 | 186.5 |
| HTL liquid effluent (t) | - | 113.7 | 227.5 | 455.0 | 682.5 |
| HTL gas (t) | - | 4.2 | 8.5 | 16.9 | 25.4 |
| CaO to recovery cycle (kg) | 4.7 | 4.70 | 4.60 | 4.60 | 4.60 |
| NaOH to recovery cycle (kg) | 4.7 | 5.60 | 6.40 | 8.10 | 9.80 |
| Na2SO4 to recovery cycle (kg) | 10.3 | 10.10 | 10.00 | 9.70 | 9.40 |
| NaOH to bleaching (kg) | 20 | 20 | 20 | 20 | 20 |
| H2O2 to bleaching (kg) | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| ClO2 to bleaching (kg) | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 |
| Oxygen to delignification (kg) | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 |
| MgSO4 to delignification (kg) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Energy | | | | | |
| Chemical energy in weak black liquor (GJ) | 16.6 | 15.77 | 14.94 | 13.28 | 11.62 |
| Chemical energy in strong black liquor (GJ) | 16.27 | 15.45 | 14.64 | 13.01 | 11.39 |
| Chemical energy in bark (GJ) | 4.00 | 4.00 | 4.00 | 4.00 | 4.00 |
| Chemical energy in forest residue (GJ) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Biocrude (GJ) | 0.00 | 0.83 | 1.44 | 2.66 | 3.88 |
| Salt brine (GJ) | 0.00 | 0.45 | 0.90 | 1.80 | 2.70 |
| HTL solid residue (GJ) | 0.00 | 0.12 | 0.24 | 0.48 | 0.72 |
| HTL liquid effluent (GJ) | 0.00 | 0.07 | 0.14 | 0.28 | 0.42 |
| HTL gas (GJ) | 0.00 | 0.09 | 0.18 | 0.36 | 0.54 |
| Chemical energy input recovery boiler (GJ) | 0.00 | 0.05 | 0.10 | 0.20 | 0.29 |
| Chemical energy input power boiler (GJ) | 16.80 | 15.18 | 14.74 | 13.85 | 12.97 |
| Chemical energy | 4.00 | 4.54 | 5.08 | 6.18 | 7.28 |
| Boiler steam production | 19.00 | 19.72 | 19.82 | 20.03 | 20.24 |
| Heat demand by evaporator (GJ) | 2.60 | 2.58 | 2.58 | 2.58 | 2.58 |
| Heat demand by HTL plant (GJ) | 0.00 | 0.10 | 0.21 | 0.42 | 0.62 |
| Other heat demand by pulp mill (GJ) | 5.30 | 5.30 | 5.30 | 5.30 | 5.30 |
| Total heat demand (GJ) | 7.90 | 7.98 | 8.08 | 8.29 | 8.50 |
| Gas fuel demand lime by kiln (GJ) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Total electricity production (kWh) | 972.0 | 972.0 | 972.0 | 972.0 | 972.0 |
| Total electricity consumption pulp mill (kWh) | 600.0 | 601.3 | 602.9 | 607.0 | 612.1 |
| Total electricity consumption HTL plant (kWh) | - | 1.3 | 2.9 | 7.0 | 12.1 |
| Excell electricity sold (kWh) | 372.0 | 370.7 | 369.1 | 365.0 | 359.9 |
| Condenser heat loss (GJ) | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |

Notes: 1.4 GJ by digester, 0.1 GJ delignification, 1.5 GJ bleaching, 2.3 GJ pulp drying

D4.3 Feasibility assessment of integrating the production of HTL biofuels in conventional pulp mills.



Table 4: Main material and energy flows for the reference Kraft process per air dry ton (adt) of pulp product as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 10% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 0% | 5% | 10% | 20% | 20% |
|---|-------|-------|-------|-------|--------|
| Material flows | | | | | |
| Woodchips (t) | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Bark to power boiler (t) | 0.41 | 0.37 | 0.32 | 0.24 | 0.15 |
| Bark to HTL plant (t) | 0.00 | 0.04 | 0.09 | 0.17 | 0.26 |
| Forest residue to power boiler (t) | 0.00 | 0.16 | 0.25 | 0.44 | 0.63 |
| Black liquor (weak) (t) | 8.6 | 8.17 | 7.74 | 6.88 | 6.02 |
| Black liquor (strong) (t) | 1.6 | 1.52 | 1.44 | 1.28 | 1.12 |
| Black liquor (weak) to HTL plant (t) | - | 0.43 | 0.86 | 1.72 | 2.58 |
| Biocrude (t) | | 22.13 | 44.25 | 88.50 | 132.75 |
| Salt brine (t) | | 123.1 | 246.3 | 492.5 | 738.8 |
| HTL solid residue (t) | | 55.3 | 90.0 | 180.0 | 270.0 |
| HTL liquid effluent (t) | | 150.2 | 300.5 | 600.9 | 901.4 |
| HTL gas (t) | | 6.7 | 13.4 | 26.9 | 40.3 |
| CaO to recovery cycle (kg) | 4.7 | 4.70 | 4.60 | 4.60 | 4.60 |
| NaOH to recovery cycle (kg) | 4.7 | 5.60 | 6.40 | 8.10 | 9.80 |
| Na2SO4 to recovery cycle (kg) | 10.3 | 10.10 | 10.00 | 9.70 | 9.40 |
| NaOH to bleaching (kg) | 20 | 20 | 20 | 20 | 20 |
| H2O2 to bleaching (kg) | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| ClO2 to bleaching (kg) | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 |
| Oxygen to delignification (kg) | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 |
| MgSO4 to delignification (kg) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Energy | | | | | |
| Chemical energy in weak black liquor (GJ) | 16.6 | 15.77 | 14.94 | 13.28 | 11.62 |
| Chemical energy in strong black liquor (GJ) | 16.27 | 15.45 | 14.64 | 13.01 | 11.39 |
| Chemical energy in bark (GJ) | 4.00 | 3.58 | 3.16 | 2.32 | 1.48 |
| Chemical energy in forest residue (GJ) | 0.00 | 0.42 | 0.84 | 1.68 | 2.52 |
| Biocrude (GJ) | 0.00 | 1.14 | 1.64 | 2.64 | 3.64 |
| Salt brine (GJ) | 0.00 | 0.69 | 1.38 | 2.76 | 4.14 |
| HTL solid residue (GJ) | 0.00 | 0.18 | 0.37 | 0.74 | 1.11 |
| HTL liquid effluent (GJ) | 0.00 | 0.11 | 0.22 | 0.44 | 0.66 |
| HTL gas (GJ) | 0.00 | 0.14 | 0.27 | 0.54 | 0.82 |
| Chemical energy input recovery boiler (GJ) | 0.00 | 0.08 | 0.15 | 0.30 | 0.45 |
| Chemical energy input power boiler (GJ) | 16.80 | 15.37 | 15.11 | 14.60 | 14.08 |
| Chemical energy | 4.00 | 4.44 | 4.88 | 5.78 | 6.68 |
| Boiler steam production | 19.00 | 19.80 | 19.99 | 20.38 | 20.76 |
| Heat demand by evaporator (GJ) | 2.60 | 2.62 | 2.67 | 2.76 | 2.85 |
| Heat demand by HTL plant (GJ) | 0.00 | 0.14 | 0.29 | 0.58 | 0.86 |
| Other heat demand by pulp mill (GJ) | 5.30 | 5.30 | 5.30 | 5.30 | 5.30 |
| Total heat demand (GJ) | 7.90 | 8.06 | 8.26 | 8.64 | 9.02 |
| Gas fuel demand lime by kiln (GJ) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Total electricity production (kWh) | 972.0 | 972.0 | 972.0 | 972.0 | 972.0 |
| Total electricity consumption pulp mill (kWh) | 600.0 | 601.8 | 604.3 | 610.5 | 618.2 |
| Total electricity consumption HTL plant (kWh) | - | 1.8 | 4.3 | 10.5 | 18.2 |
| Excell electricity sold (kWh) | 372.0 | 370.2 | 367.7 | 361.5 | 353.8 |
| Condenser heat loss (GJ) | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |

Notes: 1.4 GJ by digester, 0.1 GJ delignification, 1.5 GJ bleaching, 2.3 GJ pulp drying

D4.3 Feasibility assessment of integrating the production of HTL biofuels in conventional pulp mills.



Table 5: Main material and energy flows for the reference Kraft process per air dry ton (adt) of pulp product as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 20% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 0% | 5% | 10% | 20% | 30 % |
|---|-------|-------|-------|--------|--------|
| Material flows | | | | | |
| Woodchips (t) | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Bark to power boiler (t) | 0.41 | 0.32 | 0.24 | 0.07 | - |
| Bark to HTL plant (t) | 0.00 | 0.09 | 0.17 | 0.34 | 0.52 |
| Forest residue to power boiler (t) | 0.00 | 0.24 | 0.37 | 0.63 | 0.89 |
| Black liquor (weak) (t) | 8.6 | 8.17 | 7.74 | 6.88 | 6.02 |
| Black liquor (strong) (t) | 1.6 | 1.52 | 1.44 | 1.28 | 1.12 |
| Black liquor (weak) to HTL plant (t) | - | 0.43 | 0.86 | 1.72 | 2.58 |
| Biocrude (t) | | 29.64 | 59.29 | 118.58 | 177.87 |
| Salt brine (t) | | 151.7 | 303.5 | 606.9 | 910.4 |
| HTL solid residue (t) | | 69.8 | 117.8 | 235.7 | 353.5 |
| HTL liquid effluent (t) | | 186.7 | 373.5 | 746.9 | 1120.4 |
| HTL gas (t) | | 9.2 | 18.4 | 36.8 | 55.2 |
| CaO to recovery cycle (kg) | 4.7 | 4.70 | 4.60 | 4.60 | 4.60 |
| NaOH to recovery cycle (kg) | 4.7 | 5.60 | 6.40 | 8.10 | 9.80 |
| Na2SO4 to recovery cycle (kg) | 10.3 | 10.10 | 10.00 | 9.70 | 9.40 |
| NaOH to bleaching (kg) | 20 | 20 | 20 | 20 | 20 |
| H2O2 to bleaching (kg) | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| ClO2 to bleaching (kg) | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 |
| Oxygen to delignification (kg) | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 |
| MgSO4 to delignification (kg) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Energy | | | | | |
| Chemical energy in weak black liquor (GJ) | 16.6 | 15.77 | 14.94 | 13.28 | 11.62 |
| Chemical energy in strong black liquor (GJ) | 16.27 | 15.45 | 14.64 | 13.01 | 11.39 |
| Chemical energy in bark (GJ) | 4.00 | 3.16 | 2.32 | 0.64 | - |
| Chemical energy in forest residue (GJ) | 0.00 | 0.84 | 1.68 | 3.36 | 5.03 |
| Biocrude (GJ) | 0.00 | 1.49 | 1.91 | 2.75 | 3.59 |
| Salt brine (GJ) | 0.00 | 0.93 | 1.86 | 3.71 | 5.57 |
| HTL solid residue (GJ) | 0.00 | 0.25 | 0.50 | 1.00 | 1.49 |
| HTL liquid effluent (GJ) | 0.00 | 0.15 | 0.30 | 0.60 | 0.90 |
| HTL gas (GJ) | 0.00 | 0.18 | 0.36 | 0.72 | 1.09 |
| Chemical energy input recovery boiler (GJ) | 0.00 | 0.10 | 0.20 | 0.40 | 0.61 |
| Chemical energy input power boiler (GJ) | 16.80 | 15.55 | 15.48 | 15.34 | 15.19 |
| Chemical energy | 4.00 | 4.37 | 4.74 | 5.50 | 6.25 |
| Boiler steam production | 19.00 | 19.92 | 20.22 | 20.84 | 21.45 |
| Heat demand by evaporator (GJ) | 2.60 | 2.67 | 2.76 | 2.94 | 3.13 |
| Heat demand by HTL plant (GJ) | 0.00 | 0.21 | 0.43 | 0.85 | 1.28 |
| Other heat demand by pulp mill (GJ) | 5.30 | 5.30 | 5.30 | 5.30 | 5.30 |
| Total heat demand (GJ) | 7.90 | 8.18 | 8.49 | 9.10 | 9.71 |
| Gas fuel demand lime by kiln (GJ) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Total electricity production (kWh) | 972.0 | 972.0 | 972.0 | 972.0 | 972.0 |
| Total electricity consumption pulp mill (kWh) | 600.0 | 602.4 | 605.7 | 614.3 | 625.1 |
| Total electricity consumption HTL plant (kWh) | - | 2.4 | 5.7 | 14.3 | 25.1 |
| Excell electricity sold (kWh) | 372.0 | 369.6 | 366.3 | 357.7 | 346.9 |
| Condenser heat loss (GJ) | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |

Notes: 1.4 GJ by digester, 0.1 GJ delignification, 1.5 GJ bleaching, 2.3 GJ pulp drying

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Table 6: Main material and energy flows for the reference Kraft process per air dry ton (adt) of pulp product as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 30% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 0% | 5% | 10% | 20% | 30 % |
|--|-------|-------|-------|--------|--------|
| Material flows | | | | | |
| Woodchips (t) | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Bark to power boiler (t) | 0.41 | 0.28 | 0.15 | - | - |
| Bark to HTL plant (t) | 0.00 | 0.13 | 0.26 | 0.52 | 0.77 |
| Forest residue to power boiler (t) | 0.00 | 0.32 | 0.48 | 0.81 | 1.15 |
| Black liquor (weak) (t) | 8.6 | 8.17 | 7.74 | 6.88 | 6.02 |
| Black liquor (strong) (t) | 1.6 | 1.52 | 1.44 | 1.28 | 1.12 |
| Black liquor (weak) to HTL plant (t) | - | 0.43 | 0.86 | 1.72 | 2.58 |
| Biocrude (t) | | 37.16 | 74.33 | 148.65 | 222.98 |
| Salt brine (t) | | 180.3 | 360.7 | 721.3 | 1082.0 |
| HTL solid residue (t) | | 84.1 | 145.7 | 291.3 | 437.0 |
| HTL liquid effluent (t) | | 223.2 | 446.5 | 892.9 | 1339.4 |
| HTL gas (t) | | 11.7 | 23.3 | 46.7 | 70.0 |
| CaO to recovery cycle (kg) | 4.7 | 4.70 | 4.60 | 4.60 | 4.60 |
| NaOH to recovery cycle (kg) | 4.7 | 5.60 | 6.40 | 8.10 | 9.80 |
| Na ₂ SO ₄ to recovery cycle (kg) | 10.3 | 10.10 | 10.00 | 9.70 | 9.40 |
| NaOH to bleaching (kg) | 20 | 20 | 20 | 20 | 20 |
| H ₂ O ₂ to bleaching (kg) | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| ClO ₂ to bleaching (kg) | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 |
| Oxygen to delignification (kg) | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 |
| MgSO ₄ to delignification (kg) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Energy | | | | | |
| Chemical energy in weak black liquor (GJ) | 16.6 | 15.77 | 14.94 | 13.28 | 11.62 |
| Chemical energy in strong black liquor (GJ) | 16.27 | 15.45 | 14.64 | 13.01 | 11.39 |
| Chemical energy in bark (GJ) | 4.00 | 2.74 | 1.48 | -1.03 | -3.55 |
| Chemical energy in forest residue (GJ) | 0.00 | 1.26 | 2.52 | 5.03 | 7.55 |
| Biocrude (GJ) | 0.00 | 1.83 | 2.17 | 2.86 | 3.54 |
| Salt brine (GJ) | 0.00 | 1.17 | 2.33 | 4.67 | 7.00 |
| HTL solid residue (GJ) | 0.00 | 0.31 | 0.63 | 1.25 | 1.88 |
| HTL liquid effluent (GJ) | 0.00 | 0.19 | 0.38 | 0.76 | 1.15 |
| HTL gas (GJ) | 0.00 | 0.23 | 0.45 | 0.90 | 1.35 |
| Chemical energy input recovery boiler (GJ) | 0.00 | 0.13 | 0.25 | 0.51 | 0.76 |
| Chemical energy input power boiler (GJ) | 16.80 | 15.74 | 15.85 | 16.08 | 16.31 |
| Chemical energy | 4.00 | 4.30 | 4.60 | 5.22 | 5.84 |
| Boiler steam production | 19.00 | 20.03 | 20.46 | 21.30 | 22.14 |
| Heat demand by evaporator (GJ) | 2.60 | 2.71 | 2.85 | 3.12 | 3.40 |
| Heat demand by HTL plant (GJ) | 0.00 | 0.28 | 0.57 | 1.14 | 1.70 |
| Other heat demand by pulp mill (GJ) | 5.30 | 5.30 | 5.30 | 5.30 | 5.30 |
| Total heat demand (GJ) | 7.90 | 8.30 | 8.72 | 9.56 | 10.40 |
| Gas fuel demand lime by kiln (GJ) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Total electricity production (kWh) | 972.0 | 972.0 | 972.0 | 972.0 | 972.0 |
| Total electricity consumption pulp mill (kWh) | 600.0 | 603.0 | 607.3 | 618.5 | 632.7 |
| Total electricity consumption HTL plant (kWh) | - | 3.0 | 7.3 | 18.5 | 32.7 |
| Excell electricity sold (kWh) | 372.0 | 369.0 | 364.7 | 353.5 | 339.3 |
| Condenser heat loss (GJ) | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |

Notes: 1.4 GJ by digester, 0.1 GJ delignification, 1.5 GJ bleaching, 2.3 GJ pulp drying

D4.3 Feasibility assessment of integrating the production of HTL biofuels in conventional pulp mills.



Table 7: Main material and energy flows for the reference Kraft process per air dry ton (adt) of pulp product as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 50% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 0% | 5% | 10% | 20% | 30 % |
|---|-------|-------|--------|--------|--------|
| Material flows | | | | | |
| Woodchips (t) | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| Bark to power boiler (t) | 0.41 | 0.20 | - | - | - |
| Bark to HTL plant (t) | 0.00 | 0.22 | 0.43 | 0.86 | 1.29 |
| Forest residue to power boiler (t) | 0.00 | 0.47 | 0.71 | 1.19 | 1.66 |
| Black liquor (weak) (t) | 8.6 | 8.17 | 7.74 | 6.88 | 6.02 |
| Black liquor (strong) (t) | 1.6 | 1.52 | 1.44 | 1.28 | 1.12 |
| Black liquor (weak) to HTL plant (t) | - | 0.43 | 0.86 | 1.72 | 2.58 |
| Biocrude (t) | | 52.20 | 104.40 | 208.81 | 313.21 |
| Salt brine (t) | | 237.5 | 475.1 | 950.1 | 1425.2 |
| HTL solid residue (t) | | 112.4 | 201.3 | 402.6 | 603.9 |
| HTL liquid effluent (t) | | 296.2 | 592.5 | 1185.0 | 1777.4 |
| HTL gas (t) | | 16.6 | 33.3 | 66.5 | 99.8 |
| CaO to recovery cycle (kg) | 4.7 | 4.70 | 4.60 | 4.60 | 4.60 |
| NaOH to recovery cycle (kg) | 4.7 | 5.60 | 6.40 | 8.10 | 9.80 |
| Na2SO4 to recovery cycle (kg) | 10.3 | 10.10 | 10.00 | 9.70 | 9.40 |
| NaOH to bleaching (kg) | 20 | 20 | 20 | 20 | 20 |
| H2O2 to bleaching (kg) | 9.3 | 9.3 | 9.3 | 9.3 | 9.3 |
| ClO2 to bleaching (kg) | 19.3 | 19.3 | 19.3 | 19.3 | 19.3 |
| Oxygen to delignification (kg) | 25.7 | 25.7 | 25.7 | 25.7 | 25.7 |
| MgSO4 to delignification (kg) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| Energy | | | | | |
| Chemical energy in weak black liquor (GJ) | 16.6 | 15.77 | 14.94 | 13.28 | 11.62 |
| Chemical energy in strong black liquor (GJ) | 16.27 | 15.45 | 14.64 | 13.01 | 11.39 |
| Chemical energy in bark (GJ) | 4.00 | 1.90 | - | - | - |
| Chemical energy in forest residue (GJ) | 0.00 | 2.10 | 4.20 | 8.39 | 12.59 |
| Biocrude (GJ) | 0.00 | 2.52 | 2.70 | 3.08 | 3.46 |
| Salt brine (GJ) | 0.00 | 1.64 | 3.29 | 6.58 | 9.87 |
| HTL solid residue (GJ) | 0.00 | 0.44 | 0.88 | 1.76 | 2.64 |
| HTL liquid effluent (GJ) | 0.00 | 0.27 | 0.55 | 1.09 | 1.64 |
| HTL gas (GJ) | 0.00 | 0.32 | 0.63 | 1.26 | 1.89 |
| Chemical energy input recovery boiler (GJ) | 0.00 | 0.18 | 0.36 | 0.72 | 1.07 |
| Chemical energy input power boiler (GJ) | 16.80 | 16.11 | 16.59 | 17.56 | 18.53 |
| Chemical energy | 4.00 | 4.16 | 4.33 | 4.66 | 5.00 |
| Boiler steam production | 19.00 | 20.27 | 20.92 | 22.23 | 23.53 |
| Heat demand by evaporator (GJ) | 2.60 | 2.80 | 3.03 | 3.49 | 3.95 |
| Heat demand by HTL plant (GJ) | 0.00 | 0.42 | 0.85 | 1.70 | 2.55 |
| Other heat demand by pulp mill (GJ) | 5.30 | 5.30 | 5.30 | 5.30 | 5.30 |
| Total heat demand (GJ) | 7.90 | 8.53 | 9.18 | 10.49 | 11.79 |
| Gas fuel demand lime by kiln (GJ) | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| Total electricity production (kWh) | 972.0 | 972.0 | 972.0 | 972.0 | 972.0 |
| Total electricity consumption pulp mill (kWh) | 600.0 | 604.4 | 610.7 | 627.9 | 649.9 |
| Total electricity consumption HTL plant (kWh) | - | 4.4 | 10.7 | 27.9 | 49.9 |
| Excell electricity sold (kWh) | 372.0 | 367.6 | 361.3 | 344.1 | 322.1 |
| Condenser heat loss (GJ) | 2.8 | 2.8 | 2.8 | 2.8 | 2.8 |

Notes: 1.4 GJ by digester, 0.1 GJ delignification, 1.5 GJ bleaching, 2.3 GJ pulp drying

4 Economics of the pulp mill with integration of the HTL plant

4.1 HTL plant investment cost

The total investment associated to the HTL plant has been evaluated from

$$C_{INV}^{HTL} = C_{EQ}^{HTL}[(1 + f_{site} + f_{building} + f_{land}) + f_{com}](1 + f_{dev} + f_{eng})(1 + f_{cont}), \quad (1)$$

where C_{EQ}^{HTL} corresponds to the total equipment cost for the HTL plant, calculated from $C_{EQ}^{HTL} = (\sum_k C_{PI,k}^{HTL})[1 + f_{piping} + f_{elect} + f_{I\&C}]$, with $C_{PI,k}$ denoting the installed cost of each equipment included in the process design. The parameters f_i are additional capital cost factors associated with piping, electric system and instrumentation and control, land, civil work for site preparation and construction of buildings, engineering and contingencies for civil work and process equipment, and project development and licenses. Representative values [4] for f_i are listed in Table 9. The installed cost of equipment has been calculated using the methodology described in deliverable D4.2 [3]. Results of the calculation of the investment cost for the HTL plant as a function of the fraction of black liquor and bark in the feed to the HTL plant are shown numerically in Tables 12-16 and graphically in Figure 11. The specific investment cost exhibits a monotonic decrease with increasing quantity of both black liquor and bark to the HTL plant, ranging between 1.5 M€/ton/h, using 5% of the weak black liquor without bark, and 0.7 M€/ton/h, using 30% of black liquor with a 50% mass fraction of bark. For the IHTL plant design considered, the main heater, IHTL reactor and IHTL product cooler contributing around 65% of the total cost for this system. The overall scale factor for the HTL plant equipment cost based using the total mass flow rate of the feed as scale parameter is around 0.63.

4.2 HTL plant operating cost

The total operating cost of the HTL plant is calculated from

$$C_{OP,i}^{HTL} = C_{acid} + \Delta C_{solvent} + C_{maint} + C_{labor} + C_{A,S} + C_{I,T} \quad (2)$$

The annual operating costs are calculated as the sum of variable direct operational cost $C_{op,d}$ proportional the annual operating time, the fixed indirect operational costs $C_{op,i}$ required for having the plant in activity, and the maintenance costs C_{maint} . The direct operational costs, including the purchase of consumables, utilities, disposal of solid residues and effluents, are shown in Table 10 together with the annual flows and unit prices. It has been assumed an annual operating time of 8000 h. The annual indirect operational and maintenance costs are shown in Tables 12-16. The indirect operating cost considered are labour, administration, insurance, and licenses. The total labour cost has been evaluated from $C_{labor} = \sum_j N_j c_{r,j}$, where the subscript j denotes the personnel categories, N_j are the number of each personnel category, and $c_{r,j}$ is the net annual cost for each personnel category. Maintenance, administration, insurance, and licenses are proportional to the total permanent investment, with percentages shown in Table 8. As shown in Figure 12, below 20% of black liquor diverted to the HTL plant, the specific operating costs per ton feed increases with the higher content of bark due to the dominant effect of the cost of acid and solvent, which vary linearly with the mass fraction of bark. As the fraction of black liquor increases above 20%, the contribution



from indirect cost, which are proportional to the total investment cost of the HTL plant, is dominant and the specific operating cost decreases.

4.2.1 Variation of operating costs in the pulp mill

The total variation of operating costs at the pulp mill is calculated from

$$\Delta C_{OP,i}^{PM} = C_{FR} + \Delta C_{el} + \Delta C_{chem}, \quad (3)$$

where C_{FR} is the supply cost for forest residue, ΔC_{el} is the variation of income from electricity, and ΔC_{chem} is the variation of cost of CaO, Na₂SO₄ and NaOH. As shown in Figure 13, the specific operating cost at the pulp mill per ton of feed to the HTL plant increases with increasing quantities of both black liquor and bark used at the HTL plant. This trend is non-linear, the rate of increase being larger with lower content of bark in the feed to the HTL plant.

4.2.2 Minimum biocrude selling price

The overall economic performance of integrating the production of HTL biocrude into the pulp mill is here evaluated through the so called minimum biocrude selling price (MBSP), denoted by c_{bc} , defined as the average prices of the biocrude so that the overall net present value (NPV) for the total permanent investment and operating cost of the HTL plant and the variation of operating costs in the pulp mill over the lifetime of the HTL plant becomes zero. Based on this definition, c_{bc} is calculated using the formula

$$c_{BC} = \frac{\sum_{i=1}^N [(1+r)^{-i} (C_{INV,i}^{HTL} + C_{OP,i}^{HTL} + \Delta C_{OP,i}^{PM})]}{\sum_{i=1}^N [(1+r)^{-i} t_{p,i} \dot{M}_{BC}]} \quad (4)$$

Here, r is the expected return of investment, $C_{INV,i}^{HTL}$, $C_{OP,i}^{HTL}$ and $\Delta C_{OP,i}^{PM}$ are respectively the annual distributions of the annual total investment in the HTL plant operating costs of HTL plant, and variation of operating cost of the pulp mill. In this notation, $t_{p,i}$ is the annual production time assumed to be 8000 hours. The financial assumptions used in Eq. (4) are shown in Table 11. Figure 14 shows the variation of the MBSP as a function of the fraction of black liquor and the content of bark used in the feed to the HTL plant. The overall biocrude production cost decreases significantly both with the amount of black liquor and bark, mainly due to the reduction of the specific investment. Considering the commercial Kraft pulp mill with an annual production of 500 kt of bleached pulp, diverting between 20 and 30% of the total weak black liquor with 20% bark to the HTL plant, the biocrude selling price that gives a 10% return of investment to the pulp mill is below 1€/kg.

under revision by the European Commission



Table 8: Values for the cost parameters used in the calculation of investment cost of the HTL plant.

| | |
|--|-------|
| Piping, f_{piping} | 6.5% |
| Electric system, f_{el} | 5.0% |
| Instrumentation and control, $f_{I\&C}$ | 5.0% |
| Land and site preparation, $f_{land} + f_{site}$ | 16.0% |
| Foundation and buildings, $f_{building}$ | 20.0% |
| Plant engineering and development, $f_{dev} + f_{eng}$ | 25.0% |
| Commissioning, f_{com} | 15.0% |
| Contingency, f_{cont} | 20.0% |

Table 9: Values for the cost parameters used in the calculation of operating costs

| | |
|---|-------|
| Price of citric acid (for phase separation) (€/kg) | 0.645 |
| Price of Methyl Ethyl Ketone (solvent in phase separation) (€/kg) | 1.44 |
| Labour annual income. k€/year | |
| Plant Managers | 162 |
| O&M Manager | 88 |
| Engineers | 96 |
| Maintenance technician | 59 |
| Shift supervisor | 66 |
| Shift operators | 59 |
| Administration | 37 |
| Site and building maintenance | 37 |
| Overhead factor (operators only), % | 20 |
| Labor overhead charge rate fraction | 1.25 |
| Annual maintenance cost | 2 % |
| Insurance and taxes | 3 % |
| Administration and Services | 1 % |

Table 10: Values for the cost parameters used in the calculation of variation of operating costs in the pulp mill and financial assumptions for evaluating the net present value

| | |
|--|-------|
| Forest residue supply cost (€/ton) | 45 |
| Bark supply cost (€/ton) | 45 |
| Price of CaO (€/ton) | 120 |
| Price of NaOH (€/ton) | 340 |
| Price of Na ₂ SO ₄ (€/ton) | 150 |
| Price of electricity (€/kWh) | 0.1 |
| Loan interest rate. % | 7 |
| Return of investment. % | 10 |
| Equity to debt ratio | 30/70 |
| Plant lifetime. years | 25 |
| Construction time. years | 2 |
| Commissioning time. years | 1 |



Table 11: Capital investment, variation of operating costs and income, and cost of biocrude production as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 0% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 5% | 10% | 20% | 30% |
|--|--------------|--------------|---------------|---------------|
| Total Investment (M€) | 39.59 | 64.60 | 105.51 | 140.65 |
| Installed equipment (M€) | 16.09 | 26.26 | 42.89 | 57.17 |
| Piping (M€) | 1.05 | 1.71 | 2.79 | 3.72 |
| Electric system (M€) | 0.80 | 1.31 | 2.14 | 2.86 |
| Instrumentation and control system (M€) | 0.72 | 1.18 | 1.93 | 2.57 |
| Land and site preparation (M€) | 2.57 | 4.20 | 6.86 | 9.15 |
| Foundation and building (M€) | 3.22 | 5.25 | 8.58 | 11.43 |
| Development and engineering (M€) | 6.11 | 9.98 | 16.30 | 21.73 |
| Commissioning (M€) | 2.41 | 3.94 | 6.43 | 8.58 |
| Contingencies (M€) | 6.60 | 10.77 | 17.59 | 23.44 |
| Variation of operating costs (M€/year) | 4.670 | 8.853 | 16.057 | 23.144 |
| Consumables and utilities (M€/year) | 3.150 | 6.826 | 13.198 | 19.570 |
| Forest residue (M€/year) | 1.697 | 2.934 | 5.408 | 7.883 |
| Bark (M€/year) | 0.000 | 1.000 | 2.000 | 3.000 |
| CaO, recovery cycle (M€/year) | 0.000 | -0.006 | -0.006 | -0.006 |
| NaOH, recovery cycle (M€/year) | 0.153 | 0.289 | 0.578 | 0.867 |
| Na ₂ SO ₄ , recovery cycle (M€/year) | -0.015 | -0.022 | -0.045 | -0.067 |
| Acid, HTL plant (M€/year) | 1.105 | 2.211 | 4.421 | 6.632 |
| Solvent, HTL plant (M€/year) | 0.210 | 0.421 | 0.841 | 1.262 |
| Labor, HTL plant (M€/year) | 0.715 | 0.715 | 0.715 | 0.715 |
| Plant managers (no.) | 1 | 1 | 1 | 1 |
| Maintenance technician (no.) | 2 | 2 | 2 | 2 |
| Shift supervisor (no.) | 1 | 1 | 1 | 1 |
| Shift operators (no.) | 5 | 5 | 5 | 5 |
| Administration (no.) | 1 | 1 | 1 | 1 |
| Site and building maintenance (no.) | 1 | 1 | 1 | 1 |
| Maintenance, HTL plant | 0.32 | 0.53 | 0.86 | 1.14 |
| Insurance and taxes, HTL plant | 0.48 | 0.79 | 1.29 | 1.72 |
| Variation in Income (M€/year) | -0.64 | -1.46 | -3.52 | -6.04 |
| Energy (electricity) | -0.64 | -1.46 | -3.52 | -6.04 |
| MBSP (€/kg) | 1.59 | 1.41 | 1.25 | 1.19 |



Table 12: Capital investment, variation of operating costs and income, and cost of biocrude production as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 10% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 5% | 10% | 20% | 30% |
|---|---------------|---------------|---------------|---------------|
| Total Investment (M€) | 48.19 | 78.68 | 128.59 | 171.45 |
| Installed equipment (M€) | 19.59 | 31.98 | 52.27 | 69.70 |
| Piping (M€) | 1.27 | 2.08 | 3.40 | 4.53 |
| Electric system (M€) | 0.98 | 1.60 | 2.61 | 3.48 |
| Instrumentation and control system (M€) | 0.88 | 1.44 | 2.35 | 3.14 |
| Land and site preparation (M€) | 3.13 | 5.12 | 8.36 | 11.15 |
| Foundation and building (M€) | 3.92 | 6.40 | 10.45 | 13.94 |
| Development and engineering (M€) | 7.44 | 12.15 | 19.86 | 26.48 |
| Commissioning (M€) | 2.94 | 4.80 | 7.84 | 10.45 |
| Contingencies (M€) | 8.03 | 13.11 | 21.43 | 28.58 |
| Variation of operating costs (M€/year) | 10.862 | 16.319 | 26.031 | 35.599 |
| Consumables and utilities (M€/year) | 9.167 | 14.005 | 22.702 | 31.399 |
| Forest residue (M€/year) | 3.199 | 5.085 | 8.855 | 12.626 |
| Bark (M€/year) | 4.000 | 5.000 | 6.000 | 7.000 |
| CaO, recovery cycle (M€/year) | 0.000 | -0.006 | -0.006 | -0.006 |
| NaOH, recovery cycle (M€/year) | 0.153 | 0.289 | 0.578 | 0.867 |
| Na2SO4, recovery cycle (M€/year) | -0.015 | -0.022 | -0.045 | -0.067 |
| Acid, HTL plant (M€/year) | 1.511 | 3.023 | 6.045 | 9.068 |
| Solvent, HTL plant (M€/year) | 0.319 | 0.637 | 1.274 | 1.911 |
| Labor, HTL plant (M€/year) | 0.715 | 0.715 | 0.715 | 0.715 |
| Plant managers (no.) | 1 | 1 | 1 | 1 |
| Maintenance technician (no.) | 2 | 2 | 2 | 2 |
| Shift supervisor (no.) | 1 | 1 | 1 | 1 |
| Shift operators (no.) | 5 | 5 | 5 | 5 |
| Administration (no.) | 1 | 1 | 1 | 1 |
| Site and building maintenance (no.) | 1 | 1 | 1 | 1 |
| Maintenance, HTL plant | 0.39 | 0.64 | 1.05 | 1.39 |
| Insurance and taxes, HTL plant | 0.59 | 0.96 | 1.57 | 2.09 |
| Variation in Income (M€/year) | -0.91 | -2.13 | -5.24 | -9.10 |
| Energy (electricity) | -0.91 | -2.13 | -5.24 | -9.10 |
| MBSP (€/kg) | 1.78 | 1.42 | 1.18 | 1.10 |



Table 13: Capital investment, variation of operating costs and income, and cost of biocrude production as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 20% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 5% | 10% | 20% | 30% |
|---|---------------|---------------|---------------|---------------|
| Total Investment (M€) | 57.04 | 93.17 | 152.30 | 203.10 |
| Installed equipment (M€) | 23.19 | 37.87 | 61.91 | 82.56 |
| Piping (M€) | 1.51 | 2.46 | 4.02 | 5.37 |
| Electric system (M€) | 1.16 | 1.89 | 3.10 | 4.13 |
| Instrumentation and control system (M€) | 1.04 | 1.70 | 2.79 | 3.72 |
| Land and site preparation (M€) | 3.71 | 6.06 | 9.91 | 13.21 |
| Foundation and building (M€) | 4.64 | 7.57 | 12.38 | 16.51 |
| Development and engineering (M€) | 8.81 | 14.39 | 23.53 | 31.37 |
| Commissioning (M€) | 3.48 | 5.68 | 9.29 | 12.38 |
| Contingencies (M€) | 9.51 | 15.53 | 25.38 | 33.85 |
| Variation of operating costs (M€/year) | 17.124 | 23.925 | 36.281 | 48.467 |
| Consumables and utilities (M€/year) | 15.250 | 21.316 | 32.470 | 43.624 |
| Forest residue (M€/year) | 4.768 | 7.367 | 12.566 | 17.765 |
| Bark (M€/year) | 8.000 | 9.000 | 10.000 | 11.000 |
| CaO, recovery cycle (M€/year) | 0.000 | -0.006 | -0.006 | -0.006 |
| NaOH, recovery cycle (M€/year) | 0.153 | 0.289 | 0.578 | 0.867 |
| Na2SO4, recovery cycle (M€/year) | -0.015 | -0.022 | -0.045 | -0.067 |
| Acid, HTL plant (M€/year) | 1.917 | 3.835 | 7.669 | 11.504 |
| Solvent, HTL plant (M€/year) | 0.427 | 0.854 | 1.707 | 2.561 |
| Labor, HTL plant (M€/year) | 0.715 | 0.715 | 0.715 | 0.715 |
| Plant managers (no.) | 1 | 1 | 1 | 1 |
| Maintenance technician (no.) | 2 | 2 | 2 | 2 |
| Shift supervisor (no.) | 1 | 1 | 1 | 1 |
| Shift operators (no.) | 5 | 5 | 5 | 5 |
| Administration (no.) | 1 | 1 | 1 | 1 |
| Site and building maintenance (no.) | 1 | 1 | 1 | 1 |
| Maintenance, HTL plant | 0.46 | 0.76 | 1.24 | 1.65 |
| Insurance and taxes, HTL plant | 0.70 | 1.14 | 1.86 | 2.48 |
| Variation in Income (M€/year) | -1.20 | -2.85 | -7.15 | -12.54 |
| Energy (electricity) | -1.20 | -2.85 | -7.15 | -12.54 |
| MBSP (€/kg) | 1.89 | 1.43 | 1.16 | 1.07 |



Table 14: Capital investment, variation of operating costs and income, and cost of biocrude production as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 20% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 5% | 10% | 20% | 30% |
|---|---------------|---------------|---------------|---------------|
| Total Investment (M€) | 65.36 | 106.78 | 174.59 | 232.86 |
| Installed equipment (M€) | 26.57 | 43.41 | 70.97 | 94.66 |
| Piping (M€) | 1.73 | 2.82 | 4.61 | 6.15 |
| Electric system (M€) | 1.33 | 2.17 | 3.55 | 4.73 |
| Instrumentation and control system (M€) | 1.20 | 1.95 | 3.19 | 4.26 |
| Land and site preparation (M€) | 4.25 | 6.95 | 11.36 | 15.15 |
| Foundation and building (M€) | 5.31 | 8.68 | 14.19 | 18.93 |
| Development and engineering (M€) | 10.10 | 16.49 | 26.97 | 35.97 |
| Commissioning (M€) | 3.99 | 6.51 | 10.65 | 14.20 |
| Contingencies (M€) | 10.89 | 17.80 | 29.10 | 38.81 |
| Variation of operating costs (M€/year) | 23.378 | 31.516 | 46.509 | 61.307 |
| Consumables and utilities (M€/year) | 21.335 | 28.631 | 42.245 | 55.859 |
| Forest residue (M€/year) | 6.338 | 9.653 | 16.284 | 22.915 |
| Bark (M€/year) | 12.000 | 13.000 | 14.000 | 15.000 |
| CaO, recovery cycle (M€/year) | 0.000 | -0.006 | -0.006 | -0.006 |
| NaOH, recovery cycle (M€/year) | 0.153 | 0.289 | 0.578 | 0.867 |
| Na2SO4, recovery cycle (M€/year) | -0.015 | -0.022 | -0.045 | -0.067 |
| Acid, HTL plant (M€/year) | 2.323 | 4.647 | 9.294 | 13.940 |
| Solvent, HTL plant (M€/year) | 0.535 | 1.070 | 2.140 | 3.211 |
| Labor, HTL plant (M€/year) | 0.715 | 0.715 | 0.715 | 0.715 |
| Plant managers (no.) | 1 | 1 | 1 | 1 |
| Maintenance technician (no.) | 2 | 2 | 2 | 2 |
| Shift supervisor (no.) | 1 | 1 | 1 | 1 |
| Shift operators (no.) | 5 | 5 | 5 | 5 |
| Administration (no.) | 1 | 1 | 1 | 1 |
| Site and building maintenance (no.) | 1 | 1 | 1 | 1 |
| Maintenance, HTL plant | 0.53 | 0.87 | 1.42 | 1.89 |
| Insurance and taxes, HTL plant | 0.80 | 1.30 | 2.13 | 2.84 |
| Variation in Income (M€/year) | -1.51 | -3.64 | -9.24 | -16.35 |
| Energy (electricity) | -1.51 | -3.64 | -9.24 | -16.35 |
| MBSP (€/kg) | 1.95 | 1.43 | 1.14 | 1.05 |



Table 15: Capital investment, variation of operating costs and income, and cost of biocrude production as a function of the fraction of black liquor (weak) diverted to HTL biocrude production with 20% mass fraction of bark in the feed to the HTL plant.

| Fraction of black liquor to HTL | 5% | 10% | 20% | 30% |
|---|---------------|---------------|---------------|---------------|
| Total Investment (M€) | 80.84 | 132.12 | 216.08 | 288.24 |
| Installed equipment (M€) | 32.86 | 53.71 | 87.84 | 117.17 |
| Piping (M€) | 2.14 | 3.49 | 5.71 | 7.62 |
| Electric system (M€) | 1.64 | 2.69 | 4.39 | 5.86 |
| Instrumentation and control system (M€) | 1.48 | 2.42 | 3.95 | 5.27 |
| Land and site preparation (M€) | 5.26 | 8.59 | 14.05 | 18.75 |
| Foundation and building (M€) | 6.57 | 10.74 | 17.57 | 23.43 |
| Development and engineering (M€) | 12.49 | 20.41 | 33.38 | 44.52 |
| Commissioning (M€) | 4.93 | 8.06 | 13.18 | 17.58 |
| Contingencies (M€) | 13.47 | 22.02 | 36.01 | 48.04 |
| Variation of operating costs (M€/year) | 31.863 | 42.663 | 62.907 | 82.911 |
| Consumables and utilities (M€/year) | 29.505 | 39.263 | 57.800 | 76.338 |
| Forest residue (M€/year) | 9.480 | 14.228 | 23.725 | 33.221 |
| Bark (M€/year) | 16.000 | 17.000 | 18.000 | 19.000 |
| CaO, recovery cycle (M€/year) | 0.000 | -0.006 | -0.006 | -0.006 |
| NaOH, recovery cycle (M€/year) | 0.153 | 0.289 | 0.578 | 0.867 |
| Na2SO4, recovery cycle (M€/year) | -0.015 | -0.022 | -0.045 | -0.067 |
| Acid, HTL plant (M€/year) | 3.135 | 6.271 | 12.542 | 18.813 |
| Solvent, HTL plant (M€/year) | 0.752 | 1.503 | 3.007 | 4.510 |
| Labor, HTL plant (M€/year) | 0.715 | 0.715 | 0.715 | 0.715 |
| Plant managers (no.) | 1 | 1 | 1 | 1 |
| Maintenance technician (no.) | 2 | 2 | 2 | 2 |
| Shift supervisor (no.) | 1 | 1 | 1 | 1 |
| Shift operators (no.) | 5 | 5 | 5 | 5 |
| Administration (no.) | 1 | 1 | 1 | 1 |
| Site and building maintenance (no.) | 1 | 1 | 1 | 1 |
| Maintenance, HTL plant | 0.66 | 1.07 | 1.76 | 2.34 |
| Insurance and taxes, HTL plant | 0.99 | 1.61 | 2.64 | 3.52 |
| Variation in Income (M€/year) | -2.18 | -5.36 | -13.93 | -24.94 |
| Energy (electricity) | -2.18 | -5.36 | -13.93 | -24.94 |
| MBSP (€/kg) | 1.85 | 1.35 | 1.09 | 1.00 |

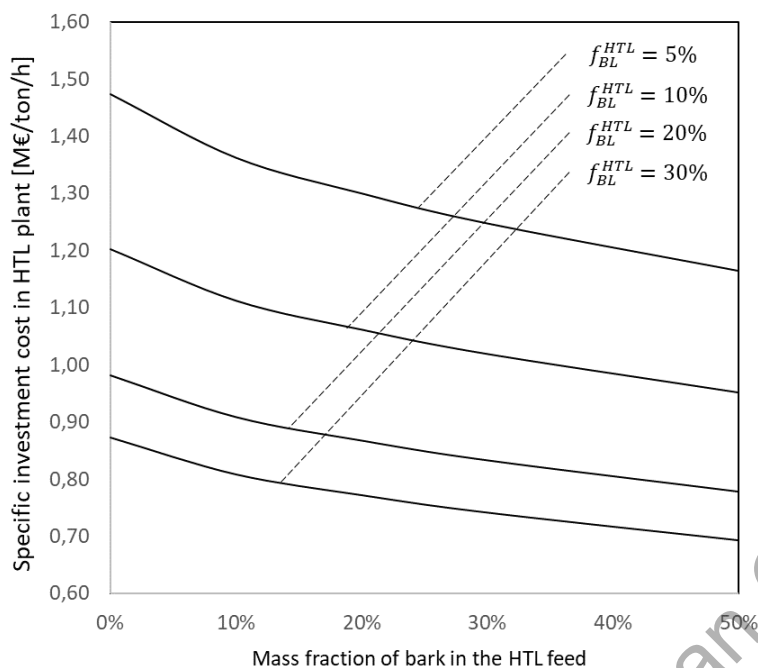


Figure 11: Variation of the specific investment cost per total mass flow rate of the feed to the HTL plant as a function of the fraction of the black liquor used for production of HTL biocrude and the mass fraction of bark in the feed to the HTL plant.

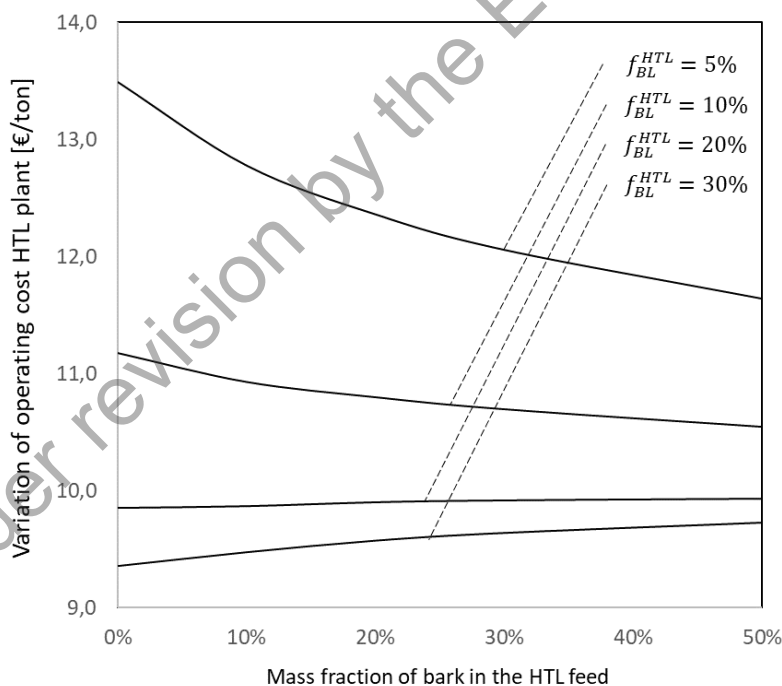


Figure 12: Variation of the specific operating cost per unit mass (ton) of the feed to the HTL plant as a function of the fraction of the black liquor used for production of HTL biocrude and the mass fraction of bark in the feed to the HTL plant.

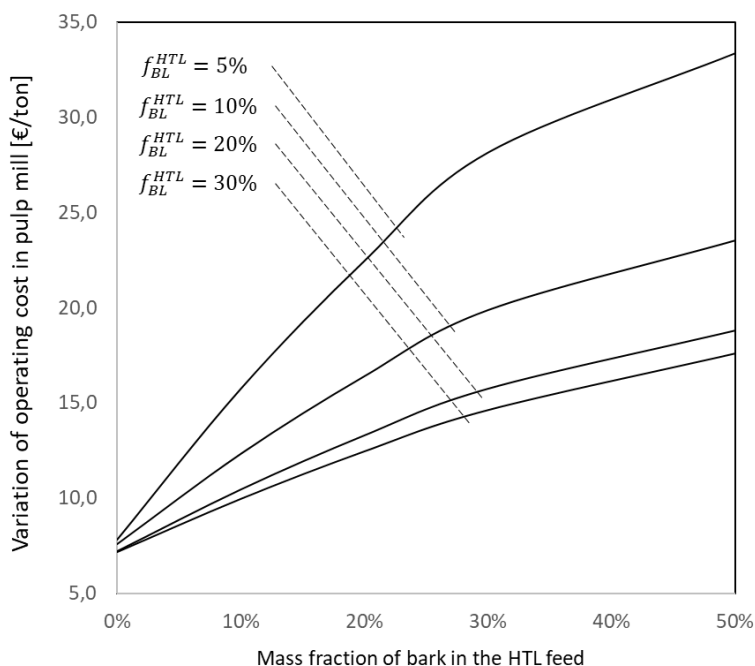


Figure 13: Variation of the specific operating cost per unit mass (ton) of the feed to the HTL plant as a function of the fraction of the black liquor used for production of HTL biocrude and the mass fraction of bark in the feed to the HTL plant.

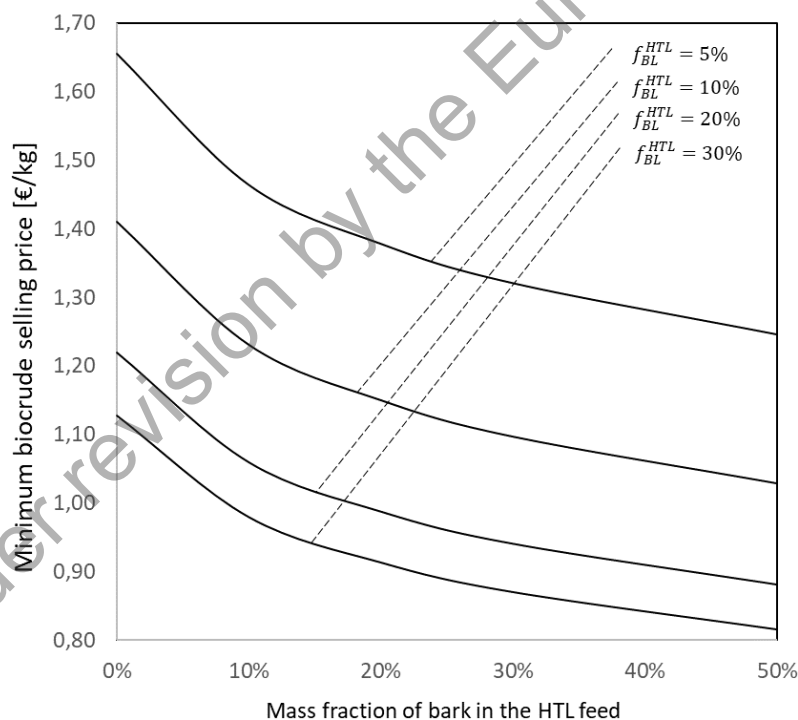


Figure 14: Minimum biocrude selling price as a function of the fraction of the black liquor diverted from the pulp mill and the mass fraction of black liquor in the feed to the HTL plant.



5 Assessment of the HTL biocrude upgrading at refinery

5.1 Biocrude quality

Table 16 shows an indicative specification of the input crude oil used at commercial refineries [4]. Figure 15 compares the composition of the biocrude produced from black liquor and bark with the reference refinery requirements for sulphur and nitrogen concentration, here defined respectively as 0.8% wt. and 500 ppm. For the whole composition of the feed to the HTL plant, varying between 0 and 50% wt. bark, the concentration of sulphur in the biocrude is about one order of magnitude lower than the reference requirement by the refinery. However, co-processing bark with black liquor impacts significantly on increasing the nitrogen content in the biocrude. Mixing low quantities of bark, about 5%, with black liquor in the HTL feed can result in non-compliance with refinery requirements. A possible solution is to include denitrification of the biocrude in the HTL plant, but this has not been considered in the analysis.

Table 16: Representative quality requirements for the biooil produced from HTL as feed in conventional refinery processes.

| | |
|-------------------------|-------------|
| Organic N | < 500 ppm |
| Organic Cl | < 1 ppm |
| Total Acid Number (TAN) | 0.8 mg KOH |
| API gravity at 60 F | 30-45 |
| Sulfur | < 0.8 % wt. |
| Vanadium (V) | < 10 ppm |
| Nickel (Ni) | < 10 ppm |
| Iron (Fe) | < 10 ppm |
| Silicon (Si) | < 10 ppm |

Notes: ^a Specification of the input oil crude used by Continental Refining Company

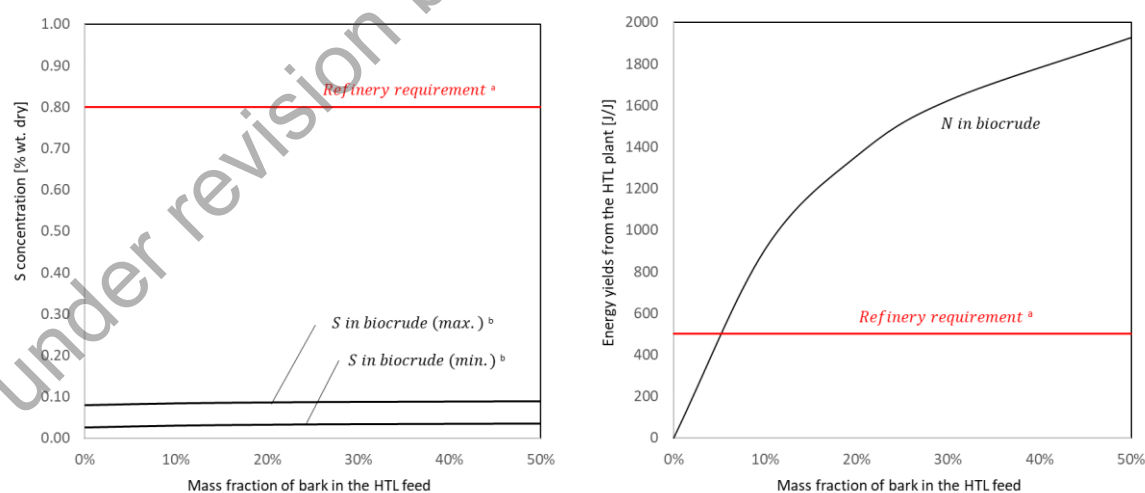


Figure 15: Comparison of the reference refinery requirements for sulphur and nitrogen concentration and the estimated composition of the biocrude derived from black liquor and bark, with the mass fraction of bark in the feed to the HTL process varying between 0 and 50%. The minimum and maximum values of the sulphur concentration in the biocrude have been estimated assuming that between 10 and 30% of the sulphur from BL ends up in the biocrude.



5.2 BL2F upgraded biofuels market assessment

5.2.1 Minimum selling prices for BL2F fuels

Considering the estimated values of the biocrude production cost in Section 5 and based on the techno-economic analysis of the biocrude upgrading at refinery reported in the BL2F deliverable D4.2 [3], shown in Figure 16, the minimum selling prices for kerosene and middle distillate achieved in the BL2F technological pathway are respectively in the range of 2.3-2.5 and 1.4-1.5 €/liter.

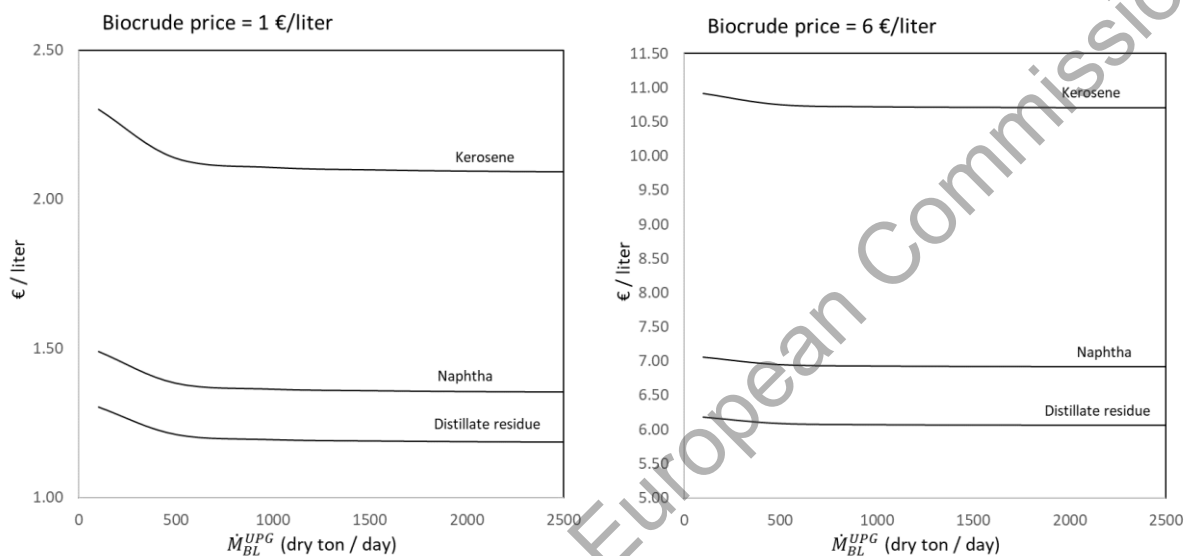


Figure 16: Estimated values of the minimum selling price for naphtha, kerosene and heavy distillate produced from black liquor derived HTL biocrudes based on biocrude production cost at the pulp mill of 1 and 6 €/liter.

5.2.2 Market prices of Sustainable Aviation Fuels and Maritime fuels

The figures below provide approximations to identify a potential price range for the advanced biofuels produced by the BL2F technology in the aviation and marine sectors, which constitute an indication of the price that should be targeted in 2050 to sell the BL2F fuel.

Aviation fuels

Figure 17 shows market prices of November 2023 in the US. Jet fuel prices [6] currently are around 2.85 USD per gallon (0.75 €/liter) while sustainable aviation fuel (SAF) prices are at 6.69 USD per gallon (1.77 €/liter).

Maritime fuels

As illustrated in Figure 18, projected values of fuels for the maritime sector by 2050 at global scale, lay between the lowest values of 7-13 USD per gigajoule (about 0.20 – 0.36 €/liter), corresponding to heavy fuel oil (HFO), and the highest value 28-52.5 USD per gigajoule (about 0.78 – 1.46 €/liter) for marine gas oil combined with hydrogen (e-MGO). Heavy Fuel Oil, Liquefied Natural Gas (LNG), Marine Gas Oil (MGO), Very Low Sulphur Fuel Oil, are fossil fuels and will be sold at a lower price in shipping applications.



SAF trades at a premium compared to conventional jet fuel



Note: All prices in U.S. cents per gallon
 Source: Argus Media | Graphic by Sourasis Bose

Figure 17: Comparison of jet fuel prices and SAF prices in the US (Bose, 2023)

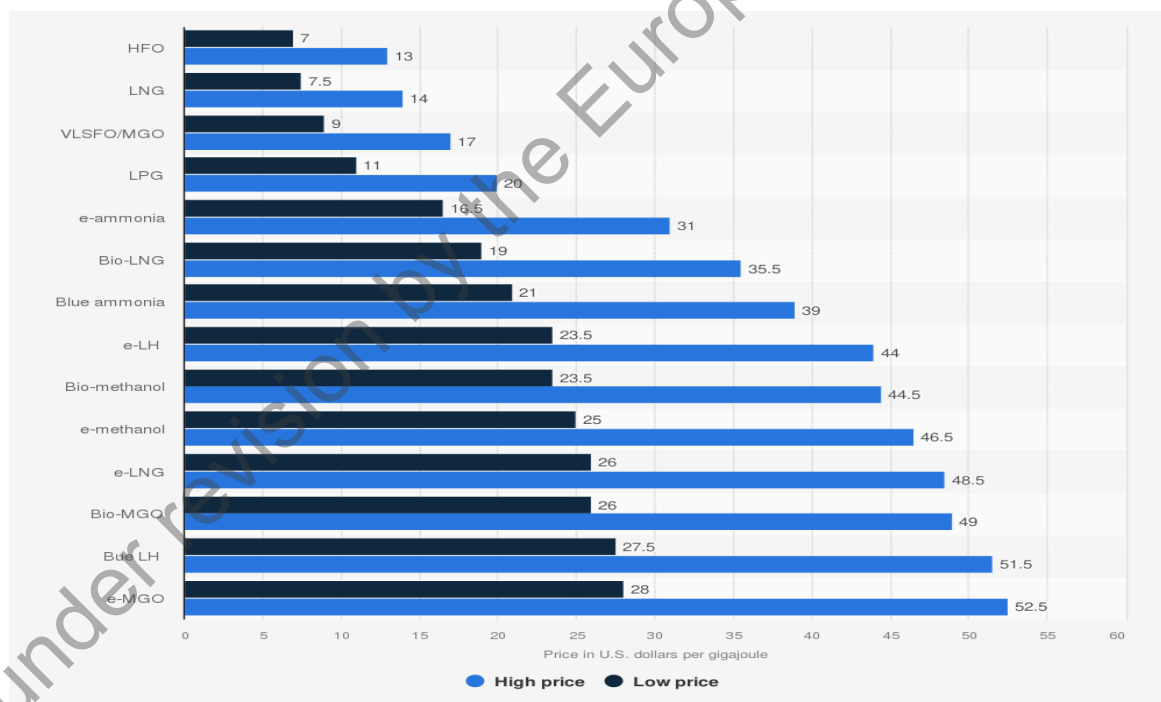


Figure 18: Projected low and high prices for marine fuels (USD/GJ) in 2050 (DNV, Statista estimates, 2023)



6 Conclusions

A new business opportunity for pulp mills to use part of the black liquor for production of advanced liquid biofuels via hydrothermal liquefaction (HTL) can be economically viable under certain conditions. Particularly, the weak black liquor separated directly from the digester has a water content and temperature conditions suitable for direct feeding into an HTL system. The business model shall consider the integration of a simple HTL plant, with lowest investment and operating costs, focused only converting the organics in the black liquor into an oil-phase or biocrude, and recycle back to the pulp mill, after extraction of the oil phase, of the salts, HTL solids and the aqueous effluent. The biocrude, which contains above 50% of the chemical energy of the black liquor, has a chemical composition that is suitable for further upgrading at conventional refineries and becomes an income to the pulp mill. However, because of the extraction of chemical energy from the black liquor to the biocrude, the net thermal power production of the recovery boiler decreases significantly as the fraction of the black liquor diverted to the HTL plant increases. This, together with the heat and electricity demand by the HTL plant, leads also to a reduction of the thermal power to the Rankine cycle and the net electricity exported by the pulp mill which impact negatively on the revenues of the pulp mill. Use of about 20% bark from the power boiler in the feed to the HTL plant fully compensates the energy losses from the black liquor in the recovery boiler, increases by 10% the energy yield of the biocrude with a slight increase of the evaporation heat demand. Since bark can be replaced by forest residues, this scenario has the lowest impact on the pulp mill operation and leads to the minimum biocrude selling price. Considering a typical commercial Kraft pulp mill with an annual production of 500 kt of bleached pulp, diverting between 20 and 30% of the total weak black liquor with 20% bark to the HTL plant, the total annual biocrude production is in the range of 59.3 and 88.9 kton. Assuming a that gives a 10% return of investment to the pulp mill, the biocrude can be sold to a refinery at a minimum price of 1.16-1.07 €/kg, which provides an annual income to the pulp mill of 68.7-94.7 M€. Increasing the bark content in the feed to the HTL process can result in nitrogen concentrations in the biocrude that can exceed the requirements from conventional refineries. A possible solution is to include de-nitrification of the biocrude in the HTL plant, but this has not been considered in the analysis. Based on the estimated biocrude prices, current oil refineries can produce kerosene and heavy distillates for the aviation and maritime sectors, respectively, with minimum fuel selling prices in the range of roughly 2.3-2.5 €/liter and 1.4-1.5 €/liter, which are high when compared to reference market prices.

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under revision by the European Commission