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From pulp mill side streams to renewable fuels: Process modelling and feasibility of integrated hydrothermal liquefaction

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HTP
Hydrothermale Prozesse

DBFZ

OVERVIEW

- Background & context
- Research objective
- Materials & methods
- Results
- Summary & next steps

Picture reference: IEA Bioenergy, “Direct thermochemical liquefaction,” Bioenergy Review. [Online]. [Accessed: Jun. 5, 2026]

OBJECTIVE

- **Why bark?**
  - Available pulp mill side stream
    - Existing collection & handling infrastructure
    - No additional harvesting required
  - Primarily used for energy generation
  - Rich in lignin and extractives
  - Relatively low N and S content
    - Advantage over some alternative streams
  - Limited studies on bark as a dedicated HTL feedstock

- **Why integration?**
  - Existing feedstock, utility and wastewater infrastructure
  - Potential for heat and steam integration
  - Utilization of HTL side streams within the mill
  - Opportunity to increase value creation from bark

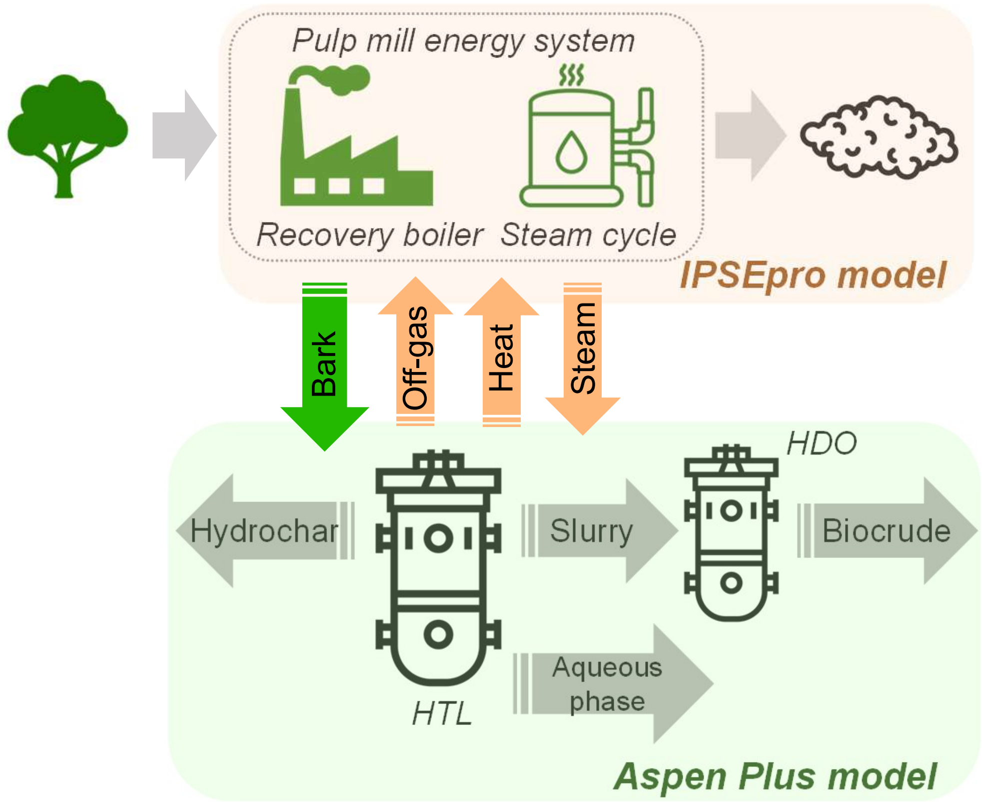
Research question:

Can HTL enable higher-value utilization of bark while maintaining favorable pulp mill energy performance?

MATERIALS & METHODS

Modeling and assumptions

- Simulation of HTL & upgrading steps with *Aspen Plus v14*
  - *Model modified from Master's thesis (*Karolina Małozięć, 2025)
- Pulp mill recovery boiler & steam cycle model with *IPSEpro ver 8.0U*
- Off-gases from HTL and HDO are sent to the recovery boiler
- HTL/HDO heat demand supplied by saturated steam from recovery boiler steam drum; recovery heat and condensate returned back to the pulp mill energy cycle
- Equipment price estimation and biocrude production cost calculation

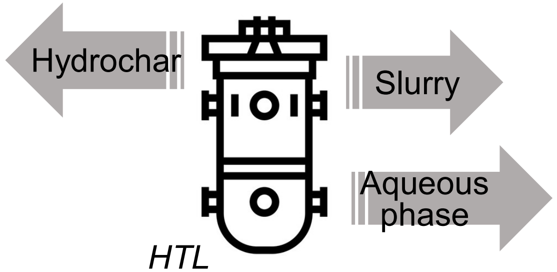


MATERIALS & METHODS

Aspen Plus model: HTL

- Scale: 50,4 kt/a bark (dry basis)
- HTL conditions: 300 °C, 100 bar, 10:1 (water:bark)
- Feedstock properties: Pine bark[1]
- Equation of state: Soave-Redlich-Kwong (SRK)
- HTL reactor modelled with Aspen Plus yield reactor
  - Biocrude represented by model components
    - Component yields adjusted to match desired composition and mass balance

	Pine bark	Biocrude	Hydrochar[3]
C, wt%	52	74	71,9
H, wt%	6,3	8,6	5,1
N, wt%	0,4	0,3	0,3
S, wt%	0,1	0,1	0
O, wt%	41	17	22,8
Ash, wt%	3,1		0
HHV, MJ/kg	19,2	32,9	27,5



HTL yields (excl. water)[1,2]	% (db)
Biocrude	**29,5**
Gas	22,4
Hydrochar	**38,5**
Aqueous phase solubles	9,6

[1] Kalagnanam et al. (2025) Evaluation of Canadian tree barks to produce sustainable biocrude
[2] Ong et al. (2018) Hydrothermal liquefaction of Radiata Pine with Kraft black liquor for integrated biofuel production
[3] Wörner et al. (2025) Focus on hydrochars produced from hydrothermal liquefaction of beech wood, soda lignin and black liquor. European journal of wood and wood products

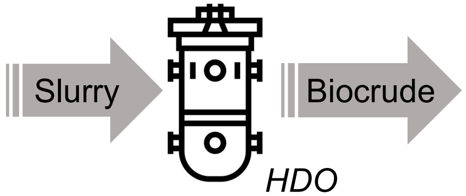
MATERIALS & METHODS

Aspen Plus model: HDO

- Scale: 10 kt/a upgraded biocrude
- HDO conditions: 165 °C, 135 bar[2]
  - Reference used 2-stage fixed bed reactor, LHSV 0,54 (stage 1) and 0,18 (stage 2)
- Treated biocrude modelled using model components
- H_2 consumption 0,05 g/g biocrude
  - Excess recycled back through PSA system

HDO yields (excl. water)[2]	% (db)
Deoxygenated biocrude	**81,7**
Gas	2,5
Water	15,7

Treated biocrude[1]	wt%
C	88,1
H	11,4
N	0,02
S	0,1
O	**0,2**
HHV, MJ/kg (Duolong)	46



Biocrude product distribution[2]	wt%
Light (C4)	0,5
Gasoline (C5-C10)	41,5
Diesel (C10-400C boil)	39,6
Heavy oil >400C boil	18,4

[1] Magdeldin et al. (2017) Techno-economic assessment of the by-products contribution from non-catalytic hydrothermal liquefaction of lignocellulose residues

[2] Zhu, Y. et al. (2014) Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading

MATERIALS & METHODS

IPSEpro model. Pulp mill and steam cycle

- A realistic Nordic kraft pulp mill was modelled, with HTL/HDO integrated as additional steam users with heat recovery back to the mill energy cycle
  - Simplified pulping line, recovery boiler and steam cycle
  - No biomass/bark boiler
- HTL/HDO heat demands were supplied entirely by saturated steam from the recovery boiler steam drum
  - The condensate from HTL is used to cover heat demand of the HDO process
  - Condensate from HDO heating flashed to produce steam for MP & LP steam users; remaining flow sent to deaerator
- HTL/HDO power demand not included in net electricity production calculations

Pulp mill scale

- 1,6 M ADt/a,
- 350 d/a

Recovery boiler

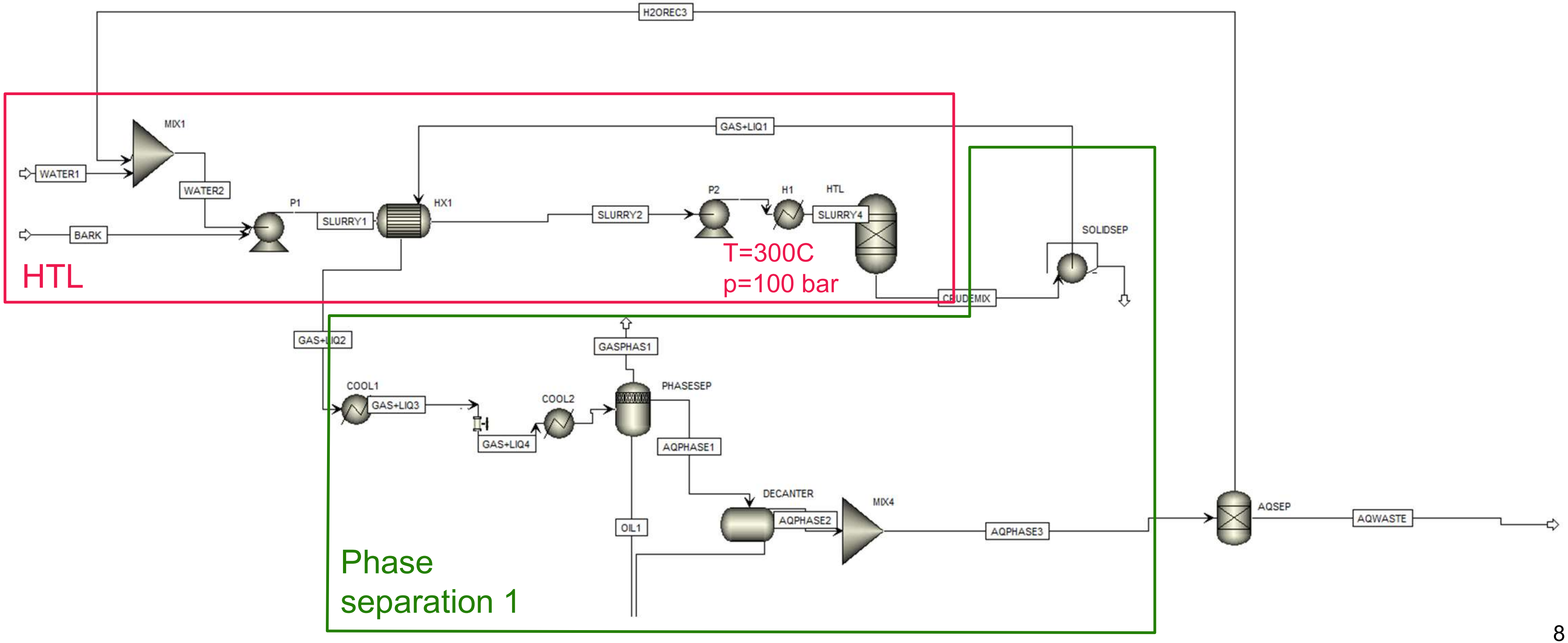
- Capacity 1086 MW (LHV)
- 1,5 t_{BL}/ADt
- Black liquor solids 83%

Live steam

- 333,5 kg/s steam
- 100 bar / 510 °C

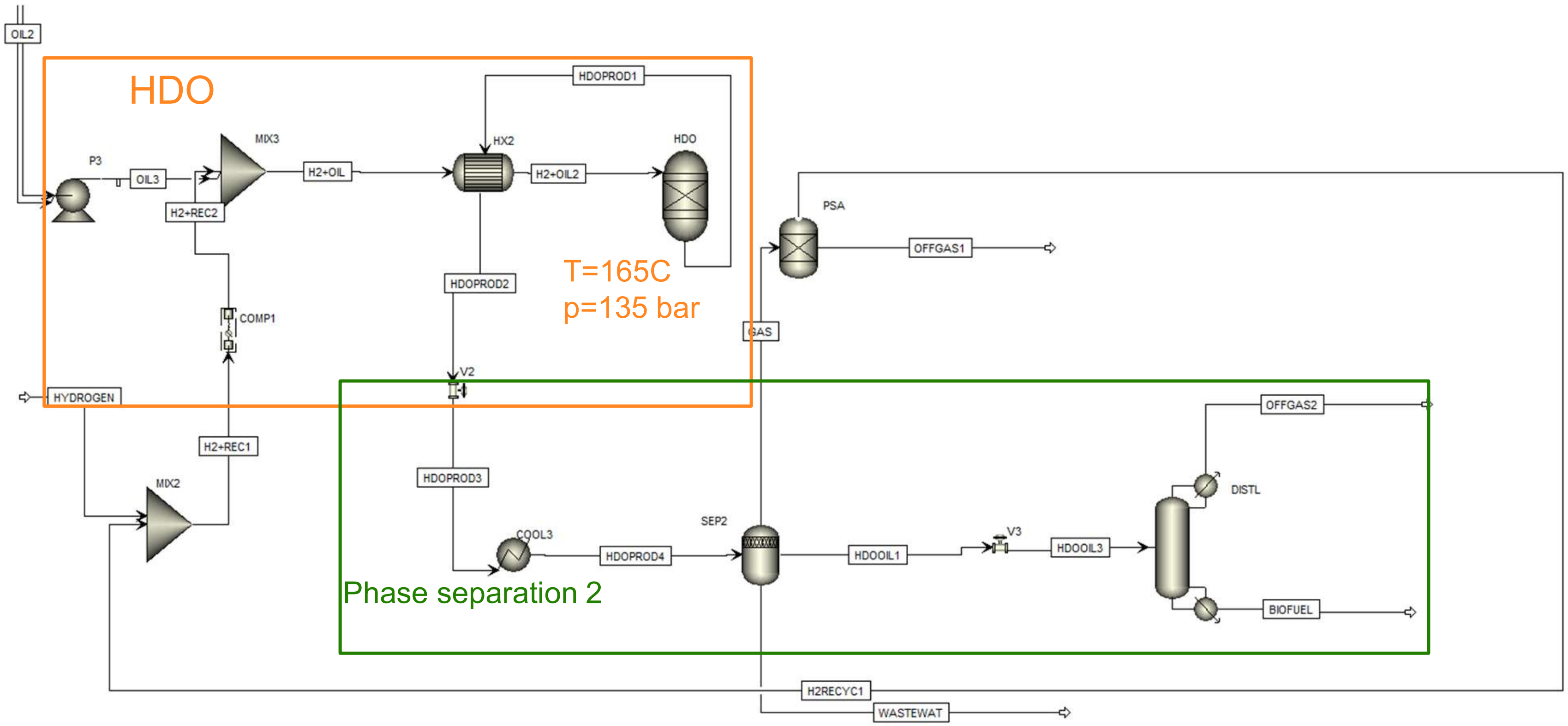
MATERIALS & METHODS

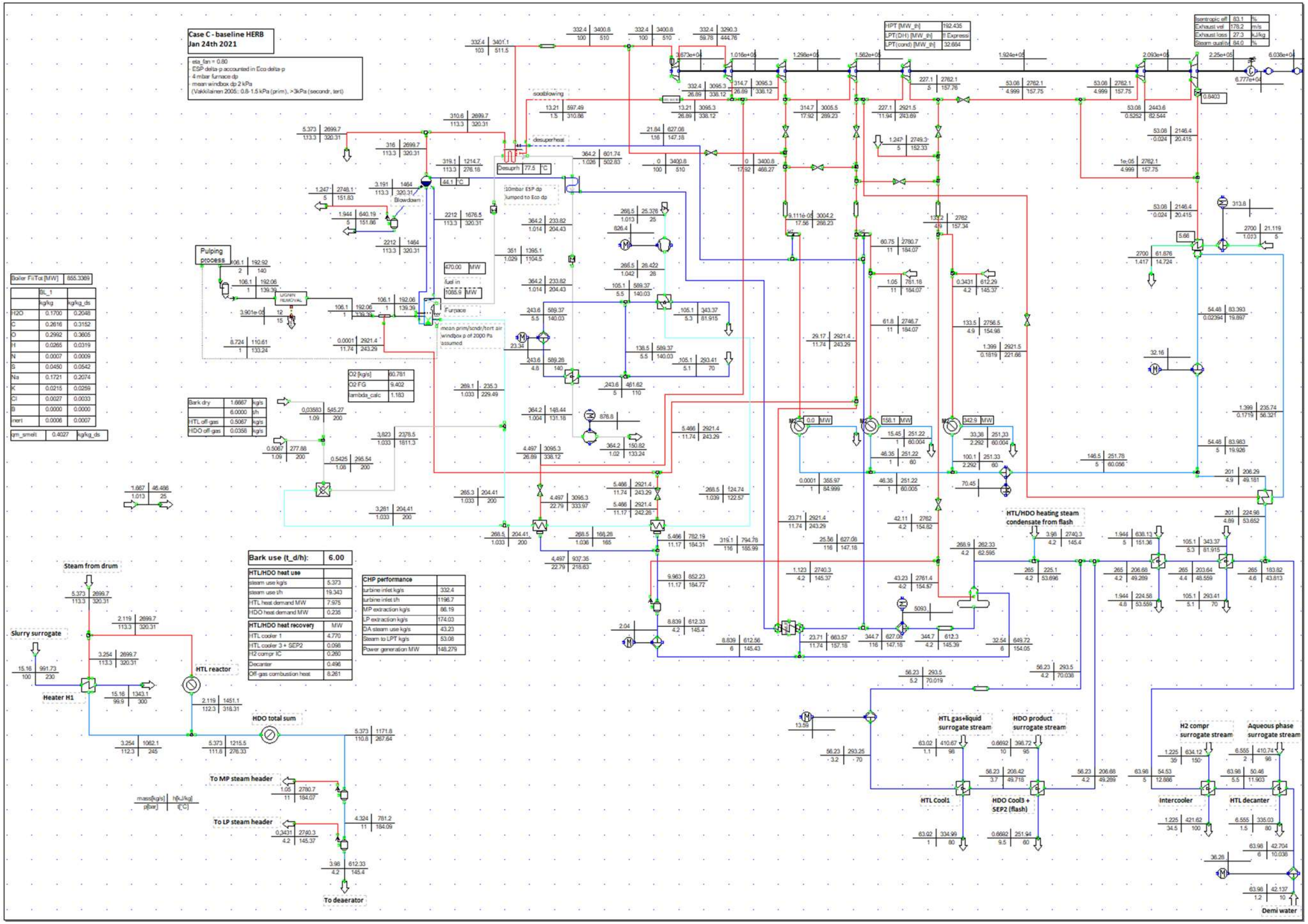
Aspen Plus flowsheet: HTL and phase separation



MATERIALS & METHODS

Aspen Plus flowsheet: HDO and phase separation





Pulp mill and steam cycle. IPSEpro model

MATERIALS & METHODS

Assumptions for techno-economic calculations

- Drying and final separation of biofuel not included in system
- Heat integration with pulp mill recovery boiler and steam cycle
- Access to pulp mill wastewater treatment and recycling water circulating through pulp mill evaporators
- Capital cost estimates represent early-stage screening accuracy (±30–50%)

Production cost assumptions	**€/unit**
Bark feedstock (internal side stream), MWh	**25**
Makeup and cooling water, m^3	3,4
H_2, kg	**7,5**
HDO catalyst price (CoMo/F-Al_2O_3), kg	35
Electricity (consumed and generated), MWh	50
Char selling price, MWh	40
Steam price, MWh	25

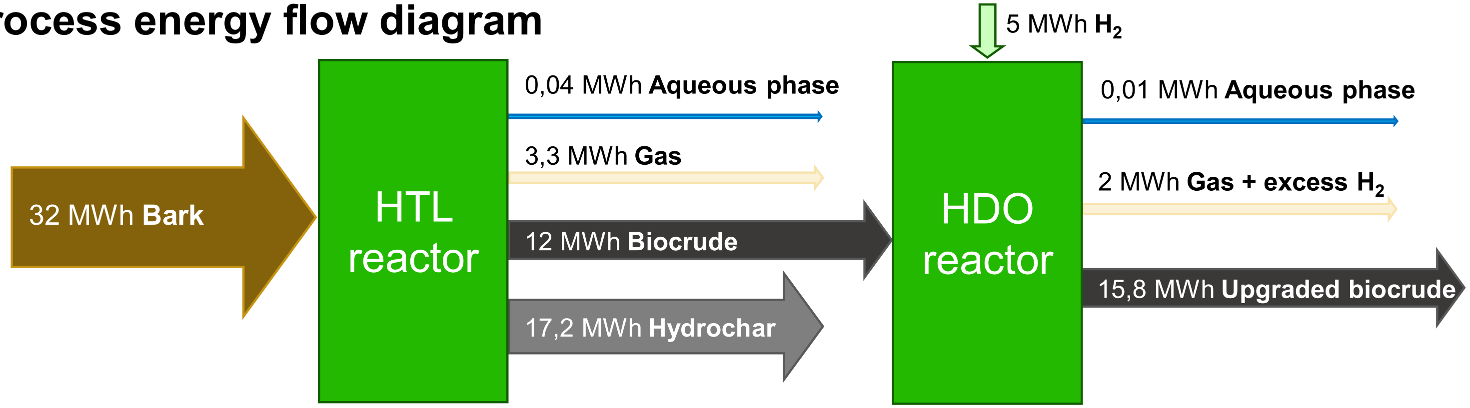
Capital charge interest rate, %	15
Plant life, a	20

Fixed cost assumptions	
ISBL x equipment cost	3,2
OSBL	40% of ISBL
Design and engineering	25% of ISBL + OSBL
Contingency	15% of ISBL + OSBL
Material factor	1,3

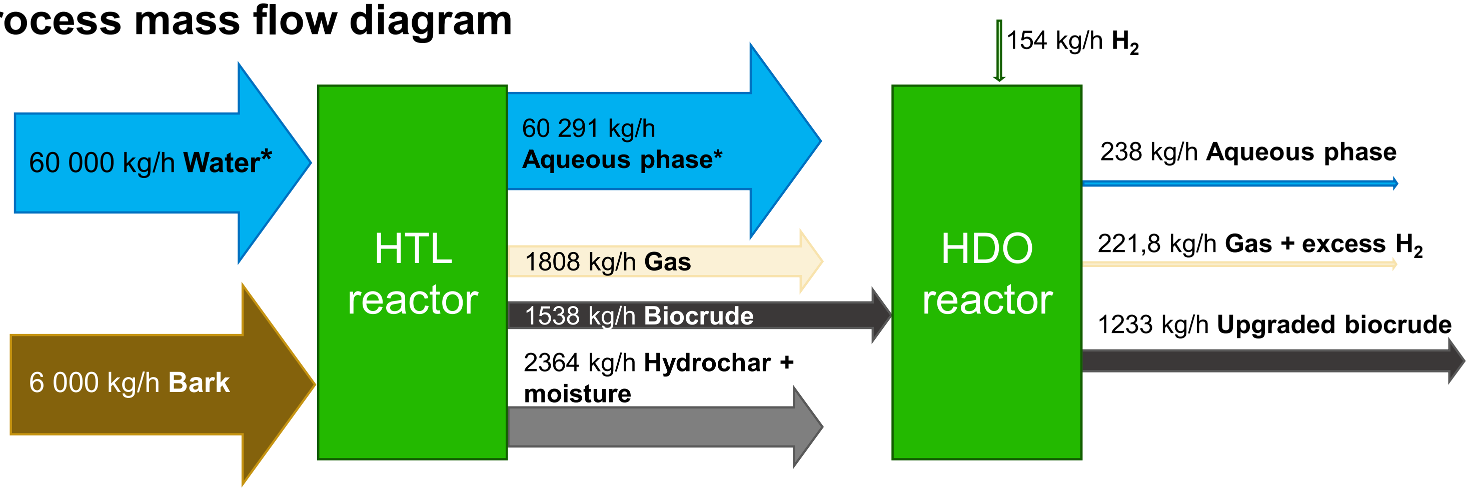
Fixed operating costs	
Labor/hourly wage	10/26,9 €/h
Supervision	25% of operating labor
Overheads, % of FCI	2 % of FCI
Maintenance, % of FCI	5% of FCI
Tax and insurance, % of FCI	2% of FCI

RESULTS

Process energy flow diagram



Process mass flow diagram



*Arrow widths are proportional to mass flow, except water streams, which are truncated for visualization purposes.

RESULTS

Utility demands: 6 dry t/h of bark (main equipment only)

Process step	Heating utilities, MW	Cooling utilities, MW	Electricity requirement, MW
HTL*	10,1	0	0,3
Phase separation 1	0,0	4,9	0,03
HDO	0,1	0,1	0,0
Phase separation 2**	0,1	0,3	0,3
Total	**10,3**	**5,2**	**0,6**

** Bark drying or pre-treatment was not included in the process*
*** Biofuel was not separated into different fuel fractions*

RESULTS

Process techno-economics

- Bark processing 50,4 kt/a
- Treated biocrude 10,3 kt/a
- Plant operating hours 8400 h, 350 d

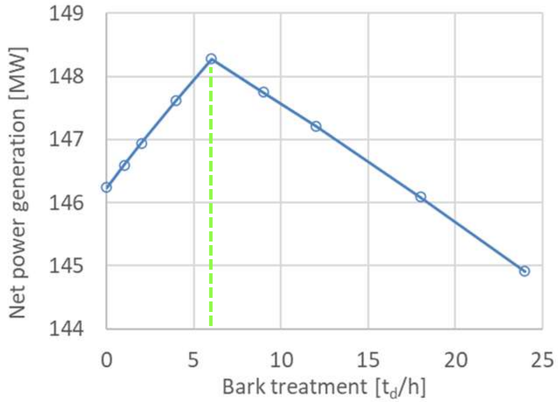
Main equipment cost, M€	6,9
ISBL cost, M€	21,9
OSBL cost, M€	8,8
Design and engineering, M€	7,7
Contingency, M€	4,6
Total Fixed costs	43,0
Total cost of production, M€/a	22,7
Production cost €/L of biofuel	**1,6**

RESULTS

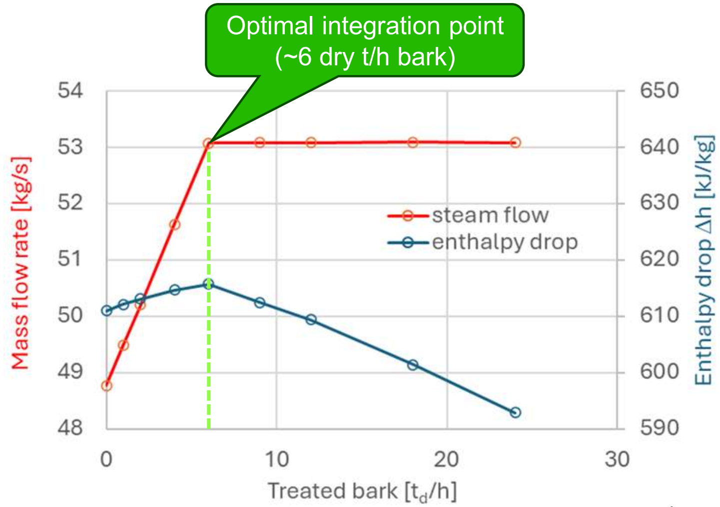
Impact of HTL integration on pulp mill power generation

- HTL/HDO require **high-temperature steam** from the recovery cycle but also return recoverable **low-grade heat**, reducing condensate/feedwater heating demand.
- In the studied steam cycle, this integration benefit peaks at **~6 dry t/h** bark. Above this scale, the low pressure (LP) turbine reaches its swallowing capacity, so additional steam cannot be efficiently converted to power.

The optimal HTL scale is highly mill-specific
→ it depends on the site-specific steam cycle, turbine capacity and heat recovery possibilities.



Net power generation before HTL/HDO electricity demand

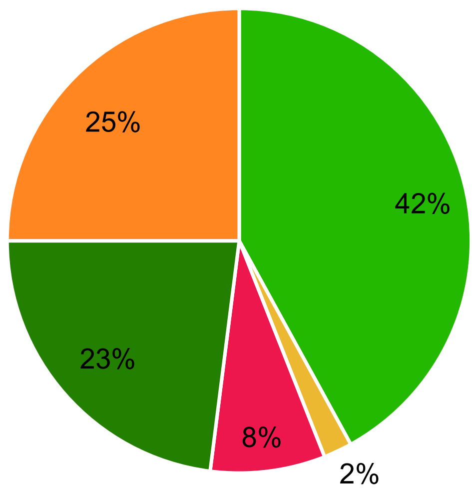


Low pressure turbine performance

CONCLUSIONS

- For the studied pulp mill configuration, the maximum feasible integration level was achieved at **6 dry t/h bark** inlet
  - At this integration level, approximately **1 MW net power surplus** was generated
- The estimated production cost of upgraded biocrude was **1,6 €/L** for a scale of 50,4 dry kt/a (**144 t/d**) bark and **10,2 kt/a treated biocrude (~30 t/d)**
  - **1,5 €/GGE (~9 kWh/L)**
- Final biocrude pricing depends greatly on process and plant configuration, feedstock and production scale
- Literature values range from **1,7 to 6,5 €/L** depending on process configuration and assumptions[1]
- In PNNL document on wet waste HTL and upgrading the minimum selling price was estimated at **4,2 to 4,2 €/GGE** for a case of 110 dry short t/d of feedstock[2]

Annual production cost division, %



Annual value of bark for energy use (40 €/MWh)	**10,8 M€**
Equivalent annual upgraded biocrude sales at 1,5 €/L	**22,3 M€**

HTL-HDO integration can approximately **double** the value generated from bark compared with direct energy use, but the achievable integration level is highly site-specific.

[1] del Alamo and Indlekofer (2023) Scale-up, risks and costing of integrating the production of HTL biofuels in conventional pulp mills. BL2F WP 4.2
[2] Li et al. (2024) Site-specific Design Case Study for Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels

FUTURE STEPS

- **Broader pulp mill integration cases**
  - Mill configurations with/without biomass boiler
  - Inclusion of district heating demand
  - Pure pulp vs. integrated pulp & paper mill
  - Identification of mill-specific steam-cycle limitations

- **Aqueous phase management**
  - Direct routing to pulp mill evaporators or wastewater treatment
  - Partial recycle after treatment
  - Utilization for H_2 production, e.g., SCWG or reforming routes
  - Comparison of environmental and economic impacts

- **Hydrogen and product upgrading**
  - External H_2 purchase vs. integrated H_2 production
  - Sensitivity to H_2 and electricity prices
  - Optimization of HDO severity and fuel product distribution
  - Hydrochar valorization alternatives

Thanks for listening!

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(project data not utilized in the work)