

Final report

1. Project details

Project title	Sludge2Fuel
File no.	[64021-1076]
Name of the funding scheme	EUDP
Project managing company / institution	Crossbridge Energy A/S
CVR number (central business register)	3716 3810
Project partners	Circlia Nordic, Fredericia Spildevand og Energi, Crossbridge Energy A/S, Krüger-Veolia, Aarhus Universitet
Submission date	26 June 2025

2. Summary

Project summary

The purpose of the project:

Sludge2Fuel was a demonstration project to demonstrate direct conversion of wet wastewater sludge to sustainable fuels using an innovative hydrothermal conversion technology (HTL) and subsequent upgrading. The technology can prevent harmful substances such as microplastics, pathogens and residual pharmaceutical compounds entering the environment while at the same time reducing our dependence on fossil fuels.

Results, conclusions and perspective

The project was intended to demonstrate integration of the HTL technology developed by Circlia Nordic (CN) at a municipal wastewater treatment plant – Fredericia Spildevand og Energi (FRSE) – and upgrading of the produced biocrude oil to transport fuel at Crossbridge (CBE) with strong support from Krüger Veolia (KV) on wastewater integration and Aarhus University (AU) who was a key knowledge partner in the whole process.

Results include:

- Establishing optimal HTL process conditions for both primary and secondary wastewater sludge and pilot scale samples of oil, process water and solids produced (AU)
- Comprehensive validation that the HTL process can be integrated in the wastewater treatment plant without reducing the plants overall biological cleaning efficiency (AU, KV)
- New sensitive analytic tools to quantify trace-components in biologically treated HTL process water validated (AU)
- Upgrading of oil validated in lab/pilot scale (CBE)
- Design of a modular HTL plant adapted for the condition at FRSE established (CN) and hazard and operability (HAZOP) study completed (CBE, CN, FRSE, AU)
- Full scale HTL plant detailed design completed, subcontractors selected, and build completed including comprehensive documentation and 3rd party validations. (CN)
- Plant specifications validated via full scale at an industrial site on industrial waste sludge and 15 t of biocrude produced (CN)
- Comprehensive techno-economic and lifecycle analysis as well as early design studies of refinery integration completed. (AU, CBE)

Unfortunately, the overall goal of showing full scale demonstration at the FRSE site was not possible due to delays and budget excesses. The later primary due to price hikes after the Ukraine crises.

CN will continue to develop and market the HTL technology and experiences strong international interest, which is expected to result in commercial scale of products based on the results already during 2025.

The HTL technology combined with upgrading is the most efficient method of converting waste biomass into transportation fuel and, when fully implemented, will strengthen security of supply and reduce CO₂ emissions by millions of tons.

Projektesumé:

Formålet med projektet:

Sludge2Fuel var et demonstrationsprojekt, der skulle demonstrere direkte omdannelse af vådt spildevandsslam til bæredygtige brændstoffer ved hjælp af en innovativ Hydro termisk omdannelses-teknologi (HTL) og efterfølgende opgradering. Teknologien kan forhindre skadelige stoffer som mikroplast og medicinrester i at komme ind i miljøet, samtidig med at vi reducerer vores afhængighed af fossile brændstoffer

Resultater, konklusioner og perspektiv:

Projektet havde til formål at demonstrere integration af HTL-teknologien udviklet af Circlia Nordic (CN) på et kommunalt spildevandsrensingsanlæg – Fredericia Spildevand og Energi (FRSE) – og opgradering af den producerede bioråolie til transportbrændstof på Crossbridge (CBE) med stærk støtte fra Krüger Veolia (KV) om spildevandsintegration og Aarhus Universitet (AU), som var en central videnspartner i hele processen. Resultaterne omfatter:

- Etablering af optimale HTL-procesforhold for både primært og sekundært spildevandsslam og pilotskalaprøver af olie, procesvand og producerede faste stoffer (AU)
- Omfattende validering af, at HTL-processen kan integreres i spildevandsrensningsanlægget uden at reducere anlæggets samlede biologiske rengøringseffektivitet (AU, KV)
- Nye følsomme analytiske værktøjer til kvantificering af sporkomponenter i biologisk behandlet HTL-procesvand valideret (AU)
- Opgradering af HTL-olie valideret i laboratorie-/pilotskala (CB)
- Design af et modulært HTL-anlæg tilpasset forholdene ved FRSE etableret (CN) og fare- og driftsundersøgelse (HAZOP) afsluttet (CB, CN, FRSE, AU)
- Detaljeret design af fuldskala HTL-anlæg afsluttet, underleverandører valgt og byggeri afsluttet inklusive omfattende dokumentation og tredjepartsvalidering (CN)
- HTL-anlægget demonstreret i fuld skala på et industrianlæg med industrielt affaldsslam og 15 t produceret bioråolie produceret (CN)
- Omfattende teknøkonomisk og livscyklusanalyse samt tidlige designstudier af raffinaderiintegration afsluttet. (AU, CB)

Desværre var det overordnede mål om at vise fuldskala demonstration hos FRSE ikke muligt på grund af forsinkelser og budgetoverskridelser. Den senere primært på grund af prisstigninger efter Ukraine krisen.

CN vil fortsætte med at udvikle og markedsføre HTL-teknologien og oplever stærk international interesse, hvilket forventes at resultere i kommercielt salg af produkter baseret på resultaterne allerede inden 2025.

HTL-teknologien kombineret med opgradering er den mest effektive metode til at omdanne affaldsbiomasse til transportbrændstof og vil fuld implementeret styrke forsyningssikkerheden og reducere CO₂ udledningen med millioner af ton.

3. Project objectives

The objective of the Project is a full-scale demonstration Project of conversion of Wastewater sludge by Hydrothermal Liquefaction to produce HTL-Oil which can be used to produce Sustainable transportation Fuels integrated with the Wastewater Treatment Plant at Fredericia.

4. Project implementation

The project kick-off meeting was held on the 1st of September 2021. The project is closed on the 19th of June 2025 after almost 4 years of work.

Shortly after the project kick-off the project faced challenges during the Corona and Energy crisis that developed at the same time. This led to challenges on critical materials supply and delays affecting the time plan and the economy.

During the project it became clear that the original plan could not be carried out due to the BioCrude could not be upgraded without further pre-treatment. As the pre-treatment was not a part of the scope a change request was submitted to reduce the length of the integrated upgrading of wastewater sludge to 6 month allowing enough time to demonstrate proof of concept without jeopardising the impact on the Fredericia Wastewater Treatment plant and at the same time produce enough HTL BioCrude to perform laboratory test to upgrade enough fuel to perform a small motor test at Alfa-laval.

In the middle of the implementation the project faced another challenge as the planned integration with Fredericia Wastewater & Energy the wastewater required a separate permit for discharge of wastewater. An agreement with Fredericia Kommune, the permitting authority agreed to commence the permitting process under the umbrella of existing permit of the Fredericia Wastewater & Energy plant permit. Additional work on investigating the HTL wastewater impact on the Fredericia Wastewater Treatment plant, including both short- and long-term effect on the biological process as well as evidence of reduction of toxic and highly non-degradable substances. The work had to be extended to include a wide range of substances where limited evidence was described in literature. The work was completed, and a permit could be submitted and reviewed by Fredericia Kommune resulting in a permit proposal.



Initially the project followed the project plan where in parallel the HTL plant was built and the integration of the plant at FRSE prepared. Pilot scale HTL tests were conducted at AU to produce and evaluate the different fractions: HTL wastewater, solids and bio-crude.

Pilot scale tests were then performed on these separate fractions. It became apparent that the integration of the HTL process water into the WWTP at FRSE was more challenging than expected due to nitrification inhibition initially and then due to the presence of some residual compounds that may not be broken down biologically.

Based on the pilot test a Mass & Energy balance has been delivered as a Basis of Design. Further the different fraction has been described

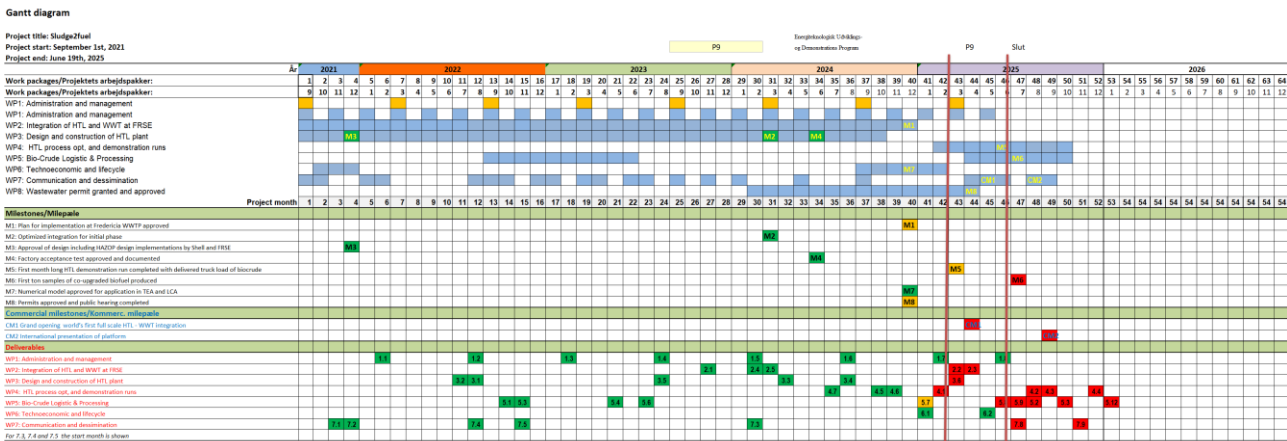
- Off-gas
- HTL BioCrude
- HTL wastewater
- Solids fraction

The project has delivered below milestones:

Text	Status
<p>Milestone 1: Plan for implementation of the HTL-process water stream at the Fredericia WWTP approved. <i>A preliminary Plan has been developed in accordance with the original milestone plan. Implementation has been delayed due to permitting taking longer than anticipated and finally stopped as it was agreed to stop the project before execution of the erection of the HTL plant at the wastewater plant.</i></p>	
<p>Milestone 2: Optimised integration for initial phase.</p>	

Short- and Long-term testing of HTL wastewater with FRSE type wastewater. Testing of inhibition and impact on FRSE outlet performance. Substantial investigation into PNEC values of toxic and environmental impact.	
Milestone 3: Approval of design including HAZOP design implementations by Shell and FRSE.	✓
Milestone 4: Factory acceptance test approved and documented	✓
Milestone 5: First month long HTL demonstration run completed with delivered truck load of biocrude. One month run on industrial waste stream demonstrated. No biocrude delivered as biocrude belonged to industrial customer.	✓
Milestone 6: First ton samples of co-upgraded biofuel produced. Milestone deleted in change of program. A first ton has been produced on industrial waste but no co-processing as oil belonged to industrial customer.	Not done
Milestone 7: Numerical model approved for application in TEA and LCA.	✓
Milestone 8: Wastewater permit granted. Draft permit submitted by Fredericia commune for comments. Project stopped and therefor permitting process stopped.	✓
CM1: Grand Opening of world first full scale HTL – WWT integration	Not done
CM2: International presentation of platform	Not done

Project Plan – Gantt Chart



4.1 Describe the risks associated with conducting the project.

Technology Risks.

Risk	Probability (1 = smallest, 5 = largest)	Impact (1 = smallest, 5 = largest)	Preventive measures
Lack of timely approval of location of treatment plant at FRSE site at Røde Banke 16, 7000 Fredericia	1	3	Dialogue with local authorities already initiated, and plan for approval process outlined. Backup locations at Shell or municipal sites identified both in short distance from FRSE. Truck sludge from FRSE and process water back to FRSE acceptable during test demonstration period.

Novel pressure exchanger design not to specifications	1	3	Technology has been validated at 1/3 of full-scale dimensions at pilot site. Timeline allows for mitigation corrections. Backup solution is to utilize a standard high pressure feedpump and only use the pressure exchanger for the take-off system. Will increase power consumption and thus reduce process efficiency by about 10%
High temperature particle separation system inefficient	2	2	Based on design and test experience from AU Fouling and PNNL. Back-up is to improve ordinary three-phase post separator and if needed add a centrifugal step on the hot oil outlet from the separator, relevant models identified in collaboration with GEA/Alfa Laval. A special amount in the budget is set aside for renting such equipment for the project period but will only be used if needed.
Inhibition of biological processes in the WWT plant due to contaminants in HTL process water	2	2	HTL process water diluted by a factor of 300 by main feed stream. Inhibition studies of nitrification system indicate manageable inhibition levels. Risk mitigation: Apply a dedicated pretreatment of the process water to reduce contaminants before returning to primary or secondary stage of WWT
Processing route for upgrading do not meet product quality – Fit for Purpose Requirements	2	3	Develop biocrude pre-treatment test facilities to remove contaminants before hydrotreatment. Use fuel for less demanding segments and ensure product quality long term storage stability of Low Sulphur Bunker Fuel.
Limited lifetime of hydrotreatment catalyst	2	3	Apply guard bed in HT Add extra purification step before HT; Take in experience from ongoing innovation programs including innovation fund project. PNNL has demonstrated 2000 hour continued upgrading on biocrude applying high temperature filtration.

Technology Readiness Level (TRL).

Technology and subcomponents	TRL at start of project	TRL at completion of project
Integration of HTL technology in WWT plant	5	8
HTL demo-plant	6	8
Biocrude upgrading with green hydrogen	5	7
Technology for use of recovered solids as P fertiliser	4	6

Did the project implementation develop as foreseen and according to milestones agreed upon?

- Milestones 1-3 delivered according to plan.
- Milestone 4-6 partly delivered through the 1-month test period at the external industrial site.
- Milestone 7-8 delivered according to plan.

Did the project experience problems not expected?

- In the first year (P1-P2) investigations by FRSE led to changed location of HTL unit to a more optimal location of HTL plant. Original location difficult due to soil conditions and nearby residential area.
- During the 2nd year (P3-P4) Corona and Energy crisis leading to difficulties in meeting and supply of critical parts and services delayed the construction of the HTL unit. At the same

time the Energy crisis led to high prices on equipment and instruments/control systems to the unit. The double ownership of the unit and the agreed materials purchase process was ineffective and led to delays of materials. It was decided to transfer budget to Circlia Nordic from Crossbridge to reduce inefficiency and further delays.

- In the 3rd (P6-7) year two issues were identified: 1) Unforeseen issues with processing raw HTL-oil at the Refinery and 2) prolonged time to get wastewater permit. Both these issues led to a change in the project to reduce the test period to 6 months minimising the production time of HTL-oil and wastewater but still get enough production time to get data to get to Proof of Concept for the integrated Wastewater Treatment and HTL-oil upgrading.
- In the 4th year (P8-P9) after rejection of wastewater permit due to inhibition guidelines, the permitting was resumed and a draft permit issued. At this time the steering committee decided to stop the project because of the original objective of upgrading of HTL-oil, budget and time spend was not worth while continuing.

5. Project results

5.1 Results vs objectives and technical results

One of the main project objectives, to demonstrate the full-scale integration of HTL at the WWTP, was not obtained, while several other objectives were indeed met.

The main reason for not achieving the full-scale implementation was due to

- Delay in delivery of components for the HTL Plant
- Delay in obtaining a wastewater permission at the FRSE plant
- Not possible to receive HTL-oil at Refinery for Co-Processing to transportation fuels due to lack of pre-treatment to meet acceptance matrix (unforeseen additional scope).

The cause for the delay in components was due to the war on Ukraine but eventually this delay was not a major obstacle as the wastewater permit was delayed anyway. The reason for the wastewater permit being delayed, was partially that the consortium underestimated the complexity in obtaining such a permit. Laboratory results at AU showed high nitrification inhibition when the HTL wastewater was tested in the wastewater cleaning process of FRSE. These results were obtained from an industry standard "shock test", where the maximum allowed nitrification inhibition was exceeded. This meant many additional tests had to be performed at AU at the request of Fredericia Kommune. Eventually the nitrification inhibition issue was solved at AU, by demonstrating long-term (several months) wastewater cleaning operation in a continuous reactor where nitrification inhibition was acceptable. It was also shown that overall wastewater treatment performance was not affected negatively by integration of HTL wastewater (COD, P, N removal). AU also developed new analytical methods to detect very low concentrations of compounds in the HTL wastewater before and after cleaning. Although many compounds were successfully removed there were around 10 compounds that were poorly removed in the laboratory setting and gave rise to concern as they could end up in the final water bodies. Extensive work was carried out to quantify these, assess their degradation and potential environmental effects. Probable No Effect Concentration (PNEC) values were chosen

to assess their potential impact. Many of the compounds in question did not have experimental PNEC values published in literature so that computational derived PNEC values were used as a baseline. In close collaboration with Fredericia Kommune a detailed plan for monitoring the wastewater during operation of the HTL plant was derived as well as a mitigation plan where the wastewater could be diverted to a secondary holding tank for additional cleaning if necessary. This entire work took around 1.5 years and eventually the permit had still not been obtained in Spring 2025.

Despite the challenges with regard to delivery delays and significantly increased costs for producing the full scale demonstration HTL unit, it was completed with a factory acceptance test in August 2024.



As the FRSE site could not be completed due to lack of local permits, it was decided to test the unit at an industrial site in Rostock Germany (with full support from the consortium and EUDP). At this site the demonstration unit where it was used to test conversion of an industrial waste sludge.

Partially the original objective was met by producing a fully functioning commercial scale HTL plant at TRL 7-8 which was demonstrated successfully for two weeks at an industrial site using an industrial waste feedstock. Over 10 m³ of HTL bio-crude were successfully produced and the HTL plant performance validated.

The plant was packed and transported as a single unit, and completed, installed, connected and commissioned within the month of October:



During the month of November 2025, processing conditions were optimized and several production runs were completed including a 48 hr and a 24 hr run, during which more than 16 tons of biocrude were produced.



Overall, the test was a great success, and it provided valuable information on how to design a full scale production unit. Also it validated the design principles and the overall efficiency of the demonstration unit including the pressure exchanger with reduced power consumption and the heat exchanger with over 87% heat recovery.

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Overall, the results from AU, showed that reintegration of HTL wastewater in a conventional WWTP is feasible, overall COD, P and N removal are not negatively affected. However, attention should be paid to specific compounds that could be recalcitrant to the biological treatment processes in a WWTP. Their environmental effects should be investigated further. Finally, it should be noted that, the detailed mass balances produced by Kruger, showed that the reintegration of HTL wastewater, adds an additional ~20% COD to the inlet of the wastewater treatment plant, which requires that the plant has this additional capacity.

The HTL solid fraction was also investigated by AU for final disposal/application. The overall findings of this investigation confirmed high P content (61,750 mg/kg) in hydrochar, low toxicity, PAH and PFAS content but elevated heavy metal content. It was concluded that the hydrochar could be applied to land but if heavy metal contents should be too high in certain circumstances, that the P could be extracted and precipitated with NH_4 in the water to produce struvite. This struvite had acceptable heavy metal contents.

HTL bio-crude was produced using the HTL pilot plant at AU and subsequently upgraded using conventional refinery technology (catalytic hydrotreatment) at the University of Prague. The results were overall encouraging. A high-quality biofuel was obtained with a good fuel cut distribution, high in kerosene. It was however also observed that the HTL bio-crude needs significant cleaning before it can be introduced into a refinery. This concerns especially solid particles, metals and some residual water. This could be done by hot centrifugation, solvent extractions and filtering and acid washing. A large-scale test of such pre-treatments was not performed during the project due to lack of sample availability as the HTL plant was not run at FRSE.

A techno-economic analysis of the integrated process was carried out at AU. The results revealed a commercially attractive process especially when the avoided cost of current sludge disposal is included in the assessment. The minimum biocrude selling price without feedstock credit ranged from 0.9-1.8€/kg, depending on WWTP size between 100k and 1000k population equivalent. Using a typical feedstock credit cost, a competitive or lower biocrude production price was obtained compared to fossil crude.

In parallel a life cycle analysis was carried out which revealed a preliminary overall GHG saving potential using the HTL concept compared to fossil baseline of 9-119% (85 to -18 gCO₂-eq./MJ). For the estimation of the carbon footprint, the upgrading of biocrude and the relevant energy and hydrogen requirements for hydrotreatment and downstream distillation to drop-in fuels have been considered. The wide range of GHG saving potential is due to different assumptions of the electricity mix (grid, wind), hydrogen source, solids handling (incineration or as fertilizer), etc. For the base case where electricity is provided by the current Danish grid, also to produce hydrogen, and solids are incinerated, the GHG saving potential is 29% (67 gCO₂-eq./MJ). However, if it is assumed that biocrude can directly be used as fuel, without the need for upgrading or any other downstream processing, the resultant GHG saving potential for the base case is 88.4% (10.9 gCO₂-eq./MJ). For upgraded bio-crude using green hydrogen would equally improve the GHG saving potential.

5.1.1 HTL pilot scale Unit production runs

HTL pilot runs were performed using the pilot plant at Aarhus University Foulum (Figure 1). Primary and secondary sludge were provided by FRSE in the same proportions as they are produced in the wastewater treatment plant, 30 wt.% primary sludge and 70% secondary sludge on a dry basis. A total of 600 kg of sludge mixture was processed in two separate campaigns, conducted at 325°C, 20 minutes residence time and a flow rate of around 60 kg/h. There were some issues observed in separating the product mixture at this scale as an emulsion of the three phases had formed (char, oil, water). This is because the pilot scale reactor, in contrast to CN's demos scale HTL plant, does not have a reliable inline solid separation device that separates the solids from the HTL reaction mixture. The existing solid separator was however able to recover a portion of the hydrochar at conditions relevant to the CN plant which showed low contamination with organic material (1-2%).

The hydrochar could hence be used for further evaluation, as a surrogate for future samples produced using the demo scale plant. The bio-crude had to be manually separated from the HTL product emulsion by filtration and solvent extraction using acetone. This was performed satisfactorily so that a portion of biocrude could be sent for analysis and upgrading. Due to the issues with the product emulsion, no reliable mass balance could be performed so instead batch reactors were used to mimic the conditions of the pilot and future demo plant. These released a bio-crude yield of 29.3 %, 23.2% hydrochar, 12.5% gas yield and 34.9% of the sludge material fractionating into the process water. In terms of carbon distribution around 65% of the incoming carbon was recovered in the bio-crude, 20% in the process water, 15% in the gas and 5 % in the hydrochar. These numbers were used for the mass, carbon and nitrogen balance estimations for the full-scale integration.



Figure 1: HTL pilot plant at AU

Mass and Energy Balances at WWTP Scale

A mass balance model was developed for the Fredericia WWTP (average flow 17,344 m³·d⁻¹), comparing a baseline scenario using anaerobic digestion for sludge stabilization with an alternative scenario using HTL (Figure 2). In the HTL scenario, approximately 50% of the incoming chemical oxygen demand (COD) from sludge was recovered as energy-rich biocrude, compared to about 20% recovery as methane in the anaerobic digestion baseline. Phosphorus recovery was also enhanced through HTL, as most of the phosphorus concentrated into the solid hydrochar, suitable for fertilizer production. However, the shift to HTL increased oxygen demand for the mainstream biological treatment due to the high levels of soluble carbon and nitrogen in HTL-PW. Overall, the net energy output of a WWTP in the HTL scenario was estimated to be ~20% higher than the anaerobic digestion scenario, despite the increased oxygen demand (i.e. increased aeration requirements) for the biological treatment at the WWTP.

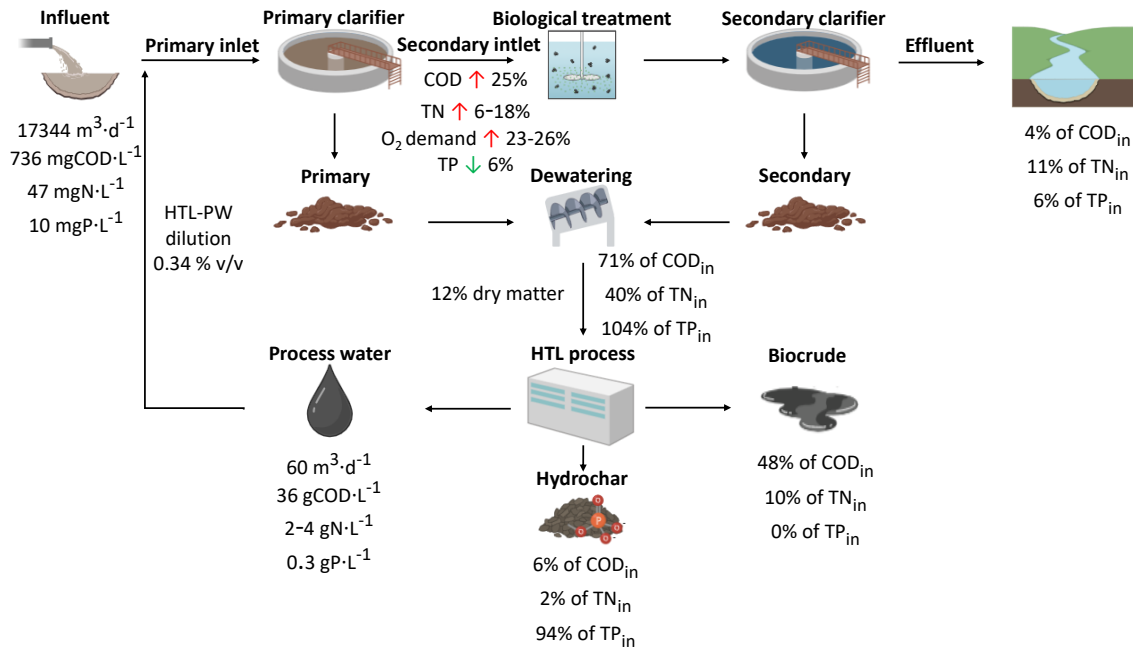


Figure 2: Diagram illustrating the mass balances when sludge is treated by HTL at the WWTP of Fredericia, highlighting the estimated changes of the loads of chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) as well as oxygen requirements for the biological treatment.

5.1.2 Wastewater testing program and results

Aerobic Biological Treatment of HTL Process Water

Continuous laboratory-scale sequencing batch reactors (10 L) were operated for over six months to simulate the aerobic treatment of HTL-PW at realistic concentrations (up to 145 mgCOD·L⁻¹ from HTL-PW) and conditions relevant to full-scale systems (HRT: 20 h; SRT: 15 d; temperature: 15 °C) (Figure 3). The reactors were inoculated with activated sludge from Fredericia WWTP and fed with synthetic wastewater supplemented with HTL-PW in increasing volumetric loads (up to 0.3% v/v).



Figure 3: Sequencing batch bioreactor used for investigating the aerobic treatment of HTL process water.

The characterise and analyse the chemical composition of HTL-PW, a new analytical method based on solid-phase extraction (SPE) and GC-MS was developed. Chemical analyses identified and quantified 40 organic compounds produced by HTL. Over 90% removal efficiency was achieved by the aerobic treatment for most compounds, including amines, linear and cyclic amides, cyclic ketones, and hydroxy aromatics (Figure 4).

Although initial batch assays showed significant inhibition of nitrification (up to 44%), continuous operation demonstrated microbial adaptation. Nitrification inhibition in the effluent was reduced by 63–69% due to microbial degradation of pollutants. Community sequencing revealed that nitrifying bacteria composition remained stable, suggesting that heterotrophic degradation protected nitrifiers from direct toxic effects. However, certain N-heterocyclic compounds, particularly pyrazines and methylquinoline, showed limited biodegradability, with effluent concentrations (1–50 µg·L⁻¹) approaching or exceeding predicted no-effect concentrations (PNECs) for aquatic organisms, indicating residual ecotoxicological risks for the receiving environment (Figure 4). It should be noted that for these critical compounds, PNEC values are based on QSAR models, hence have a high uncertainty. Therefore, more ecotoxicological research is needed to understand the risks associated with the discharge of these critical compounds into the environment.

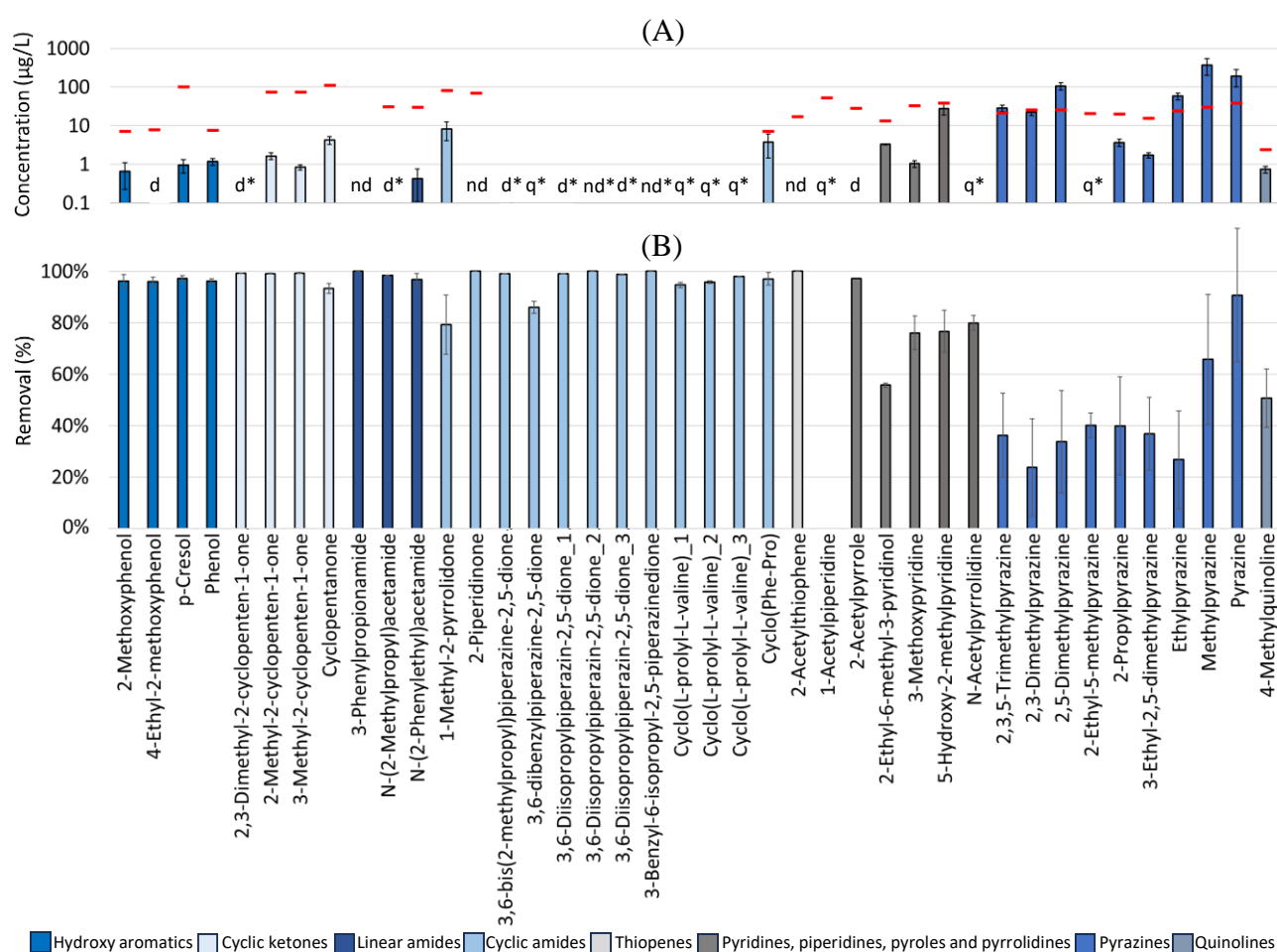


Figure 4: (A) Effluent concentrations (n = 3) compared to PNEC values (red dash). Compounds marked with (*) indicate no available standard. Compounds are classified based on signal-to-noise ratio as quantifiable (q, SN>10), detectable (d, 3<SN<10), or non-detectable (nd, SN<3). (B) Removal efficiency (%; n = 3) based on influent and effluent concentrations. For compounds without available standards (*), removal efficiency was estimated from the difference in peak area in influent and effluent. Error bars indicate standard deviation.

Anaerobic Digestion of HTL Process Water

As an alternative treatment and to evaluate energy recovery potential via biogas, HTL-PW from sewage sludge was co-digested with cattle manure in semi-continuous anaerobic reactors (1.8 L, 40 °C, 15–30 day HRT) over a three-month period. Organic loading rates (OLR) ranged from 2 to 4.3 gCOD·L⁻¹·d⁻¹. Methane yields were severely inhibited when HTL-PW concentrations exceeded 12.8 gCOD·L⁻¹, with complete inhibition at 17 gCOD·L⁻¹. Microbial community analysis using full-length 16S rRNA and mcrA gene sequencing showed strong suppression of methanogenic archaea, while fermentative bacteria remained functionally redundant. The inhibition potentially caused by the high levels of nitrogenous heterocyclic compounds in the HTL-PW from sewage sludge. These findings highlight the limited applicability of anaerobic digestion for treating HTL-PW from protein-rich feedstocks unless pre-treatment or detoxification is applied.

Micropollutant Destruction and PFAS Degradation

HTL was also shown to contribute to the destruction of micropollutants in sewage sludge. Pharmaceuticals, biocides, and a range of per- and polyfluoroalkyl substances (PFAS) were either destroyed or transformed during the HTL process. At 350 °C, complete degradation of several PFAS, including perfluoroalkyl carboxylic acids, was observed with significant defluorination (30–60%), although the transformation of PFAS into volatile hydroperfluoroalkanes raised concerns about emissions to the atmosphere. This dual benefit of energy recovery and contaminant destruction enhances the appeal of HTL as a sustainable sludge treatment method.

Conclusion

Integrating HTL into WWTPs provides a promising route for enhanced energy and resource recovery, with significant benefits in terms of biocrude yield and phosphorus concentration in solids. However, HTL-PW from sewage sludge presents substantial challenges for downstream biological treatment due to its high-strength, inhibitory composition. Aerobic treatment showed good potential with adapted microbial communities, but certain persistent compounds remained problematic. Anaerobic digestion offered limited feasibility without further treatment of HTL-PW. Future work should focus on pre-treatment strategies, pollutant degradation pathways, and optimizing biological systems for long-term integration of HTL in wastewater management.

5.1.3 Solids fraction upgrading

We investigated the potential of hydrochar, the solid residue from HTL, as a phosphorus (P) resource for struvite (NH₄MgPO₄·6H₂O) fertilizer production. We produced the hydrochar using the continuous pilot-scale HTL reactor and characterized its composition before subjecting it to acid leaching with sulfuric acid, hydrochloric acid, and citric acid. Using response surface methodology, we optimized the extraction process and found that 0.7 M sulfuric acid for 6.5 hours yielded up to 94% P recovery. We then precipitated struvite from the extracted P using HTL process water as an ammonium source, with and without the addition of citric acid. The addition of citric acid increased struvite purity from 36.6% to 53.8% and significantly reduced heavy metal content, although it decreased overall P recovery from 67% to 40%. We confirmed the composition and morphology of the resulting struvite using ICP-OES, FTIR, XRD, SEM-EDS, and TGA. While the raw hydrochar exceeded regulatory limits for some heavy metals, the citric-acid-treated struvite met EU fertilizer standards. We evaluated the toxicity of the hydrochar and found that it was relatively low even in its native form. Our results demonstrate that hydrochar could potentially be used as a fertiliser directly in certain cases when the heavy metal content is not too high but converting it into purified struvite is a viable approach for sustainable phosphorus recovery and improved sludge management.

5.1.4 HTL-oil characterisation & Upgrading

Value creation and technical upgrading have been key to the success of the project.

The HTL oil produced is a viscous heavy oil. The oil is not miscible with fossil oils, due to polarity and contains significant amounts of contaminants, metals, salts, unsaturated, aromatics and oxygen. Further the HTL-oil is not stable as it forms 'sludge' overtime.

Analysis of the HTL oil by Prague University is reported below:

Table 1: Measured properties of "Sludge2Fuel" bio-crude and used methods

Density at 15 °C (kg.m ⁻³)	997.0	EN ISO 12185
Kinematic viscosity at 40 °C (mm ² .s ⁻¹)	124	ASTM D445
Water content (wt.%)	24.7	ASTM D6304
Total acid number (mg _{KOH} .g ⁻¹)	45.2	ASTM D664
C/H/O content (wt.%)	60.9/10.1/24.9	ASTM D5291 ¹
Sulphur content (wt.%)	0.9	EN ISO 20846
Nitrogen content (wt.%)	3.1	ASTM D4629
HHV from EA (MJ.kg ⁻¹)	33.2	Equation 1
MCR (wt.%)	13.1	ASTM D4530
Basic N (mg.kg ⁻¹)	9640	UOP 269
Carbonyls content (mmol C=O.g ⁻¹)	3.7	ASTM E3146
Phenols content (wt.% eq. guaiacol)	5.7	[1]
Insolubles (wt.%)	0.26	ASTM D7579
Na/Ca/Zn/Fe content (mg.kg ⁻¹)	38/81/31/979	[2]

¹ oxygen content computed by difference

² sample burning, mineralization and AAS analysis

Based on the characterization it can be concluded that pre-treatment is necessary to use this as feedstock for further treatment. The pathway for upgrading has been reviewed.

Direct processing together with fossil crude is not possible as the two phases do not mix. Further pre-treatment in the fossil refinery through desalting is also not considered possible as the polarity will not work, but probably a stable emulsion phase will be generated.

Two other options have been reviewed:

- Outside fence upgrading and the pre-treated fuel used as drop-in fuel to Marine Gasoil or Marine Fuel oil
- Pre-Treatment by acid wash and filtering will remove water, solids, salt and contaminant to < 100 ppm.

Co-Processing into existing HDT 2-5% is possible but will result in reduced throughput as the feedstock content of oxygen and nitrogen will require more severe conditions than fossil feedstock.

Further pre-treatment to remove organic acids, phenols, unsaturated and asphaltenes could reduce operating limits in existing HDT units and potentially increase co-processing capability.

Deep HDT by 2-stage high pressure low LHSV at Prague University shows significant upgrading to distillate products. This can be achieved by modifying the existing HDT to a 2-stage unit or installing a 2-stage high pressure unit to process the HTL oil separately. The upgraded HTL oil from these tests are shown in Table 4 and 5. A picture of the fractional cuts are shown in Figure

The HTL oil has been characterized and key pre-treatment steps identified for acceptance matrix into a Refinery processing route into Co-Process to Marine Fuels

Table 4: Selected properties of organic phase from bio-crude hydrotreated at 400 °C

Density at 15 °C (kg.m ⁻³)	807.4
Kinematic viscosity at 40 °C (mm ² .s ⁻¹)	2.01
Water content (mg.kg ⁻¹)	96
Total acid number (mg _{KOH} .g ⁻¹)	0.04
C/H/O content (wt.%)	85.8/13.9/0.0
Sulfur content (mg.kg ⁻¹)	93
Nitrogen content (wt.%)	0.27
HHV from EA (MJ.kg ⁻¹)	46.4
MCR (wt.%)	<0.01
Basic N (mg.kg ⁻¹)	800
Carbonyls content (mmol C=O.g ⁻¹)	0.0
Phenols content (wt.% eq. guaiacol)	1.4

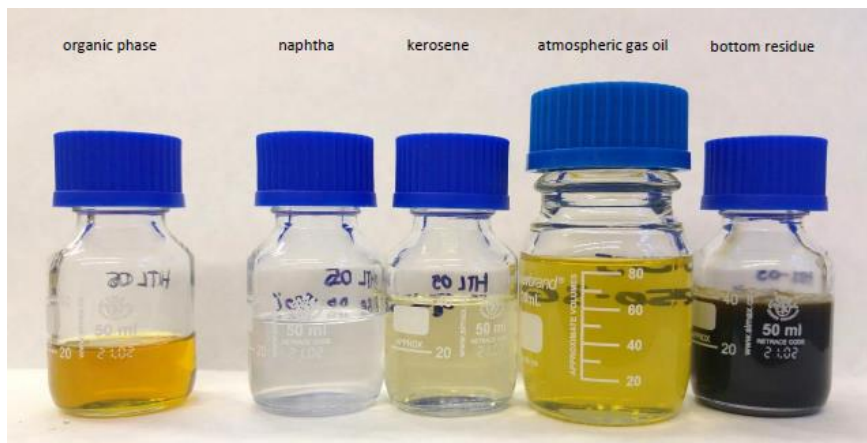
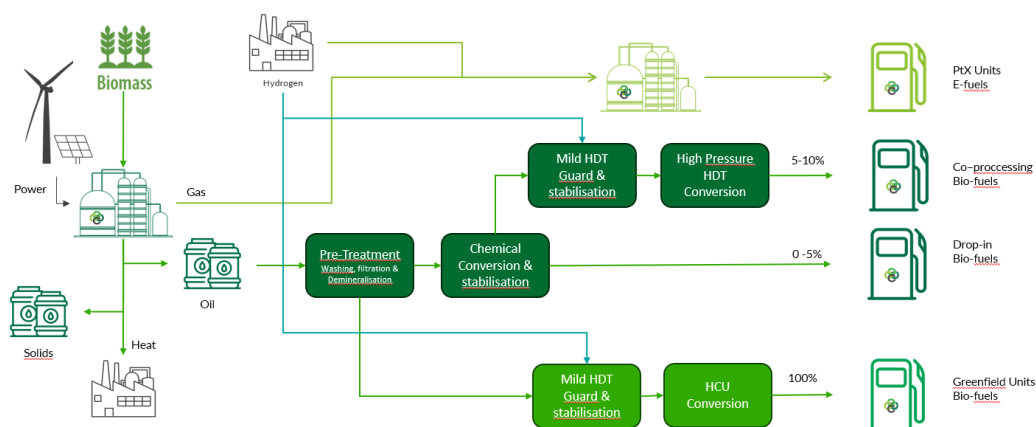


Figure 4: Organic phase from primary liquid product (on left) and distilled fractions

Table 5: Yield of distillates and bottom residue from organic liquid phase obtained at temperature 400 °C (related to the bio-crude)

Fraction	Yield (wt.%)
Naphtha	8.6
Kerosene	10.8
Atmospheric gas oil	24.1
Bottom residue	11.6

Pathway for Biomass to Bio-Fuels



Design, construction and demonstration run of pre-treatment is not part of the funded project and therefore this option has not been pursued. Further demonstration runs of storage and handling of pre-treated HTL oil have also not been pursued.

The test runs of 2-5% Co-Processing for marine fuels and successful Motor performance and handling/storage of the finished fuel are also outstanding.

5.1.5 Life Cycle Assessment and Technical & Economical Assessment

The focus of the techno-economic and life cycle assessments (TEA and LCA) has been in smaller decentralized HTL plants, integrated in typical sizes of wastewater treatment plants (WWTP) at the feedstock source. Fredericia WWTP (FRSE), with the 2021 annual sludge production of 25,950 m³ of primary sludge (5% DM) and 168,910 m³ of secondary sludge (1% DM), corresponding to approximately 150k PE, was used as the base case. The minimum biocrude selling price (MBSP) was determined by minimizing the net present value (NPV) in the project's lifetime and including overall CapEx and OpEx. Sensitivity analyses were conducted to identify the parameters with the bigger impact on economics. The TEA was further expanded to include typical European WWTPs sizes ranging from 0.1 to 1 million PE, to evaluate the influence of size in MBSP. In addition, different sludge handling credits, to enhance biocrude competitiveness with petroleum-derived fuels were proposed.

For the LCA the system boundaries were expanded to include transportation of biocrude to the refinery and subsequent upgrading via hydrogenation, to remove heteroatoms, and distillation of the upgraded oil to drop-in fuels. This was necessary for the calculation of emission reductions of final fuels relative to the fossil baseline. All necessary models for the calculation of the mass and energy balances of the upgradation process were developed. Furthermore, different scenarios for hydrogen provision (SMR, electrolysis with grid or wind electricity), solids fate (incineration, land application for fertilizer substitution and carbon sequestration), etc. were analysed.

TEA of the base case (Fredericia) revealed a MBSP of 1.4 €/kg, which is significantly higher than petroleum crude oil price. The findings emphasize the critical role of operational expenditure (OPEX), where utilities, plant maintenance, and salaries form a substantial portion of costs. However, there are certain key parameters that can improve the MBSP, as shown in figure 5.1.5.1. Sludge handling fee (feedstock credit) has the stronger positive impact (lower MBSP) followed by reduced electricity prices and increased biocrude yield. On the other hand, the desired internal rate of return (IRR), depending if the plant is operated by the WWTP for low to no profit or by an external company aiming at profit, lower biocrude yields, lower slurry DM content, and increased number of required operators (labour) have the stronger negative impact (higher MBSP).

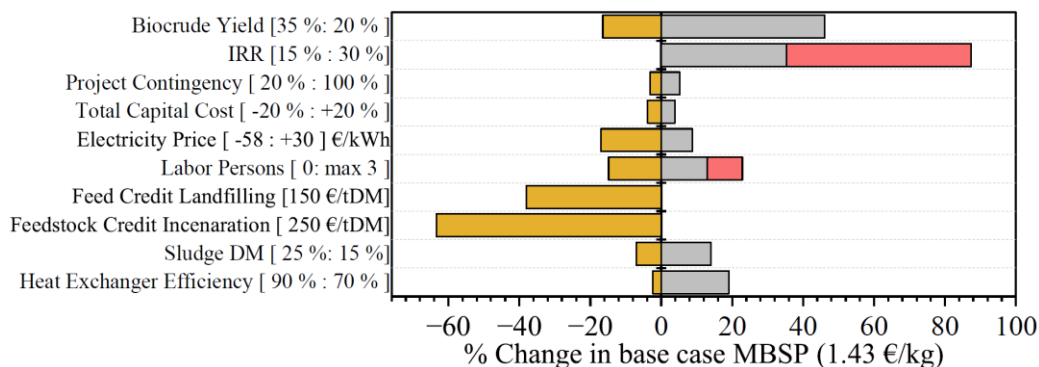


Figure 5.1.5.1. Sensitivity analysis of key parameters on MBSP

Integration of HTL in larger WWTPs can emerge as a significant factor influencing the production costs of sludge biocrude, thereby facilitating its competitiveness against fossil crude counterparts. With WWTP capacities varying between 0.1 and 1.0 million P. E., the MBSP ranges from 0.9 € to 1.8 € per kilogram of biocrude (Figure 5.1.5.2). MBSP can be further reduced if a sludge handling fee, like the current financial burden for sludge or digestate disposal, is considered as a credit. As shown in the analysis is Figure 5.1.5.2, for a sludge handling credit of 200 €/ton, the MBSP becomes competitive to petroleum crude price for WWTP capacity of 300k PE, typical for many European cities.

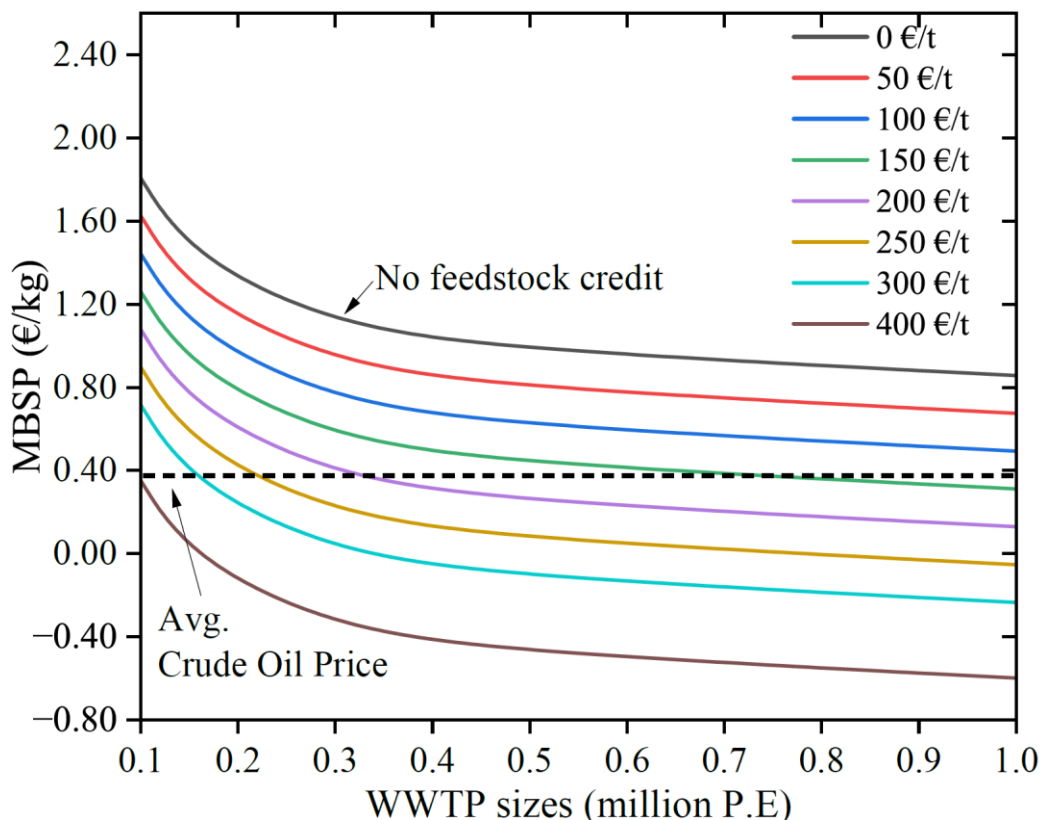


Figure 5.1.5.2. Effect of plant size and sludge credit on biocrude selling price (Dashed line shows the average crude oil price adjusted for lower bio-crude quality)

Preliminary LCA results revealed overall GHG saving potential, using the HTL concept, compared to fossil baseline of 9-119% (85 to -18 gCO₂-eq./MJ). The wide range of GHG saving potential is due to different assumptions of the electricity mix (grid, wind), hydrogen source, solids handling (incineration or land application), etc. The main part of the emissions is attributed to hydrogen production for the cases where non-renewable energy is used for its production (either from natural gas or through electrolysis using electricity from current Danish grid). For the base case where electricity is provided by the current Danish grid to produce hydrogen and to cover all other energy requirements (HTL, PW treatment, hydrotreatment, distillation, etc) and solids are incinerated, the GHG saving potential is 29% (67 gCO₂-eq./MJ). However, if it is assumed that biocrude can directly be used as fuel, without the need for upgrading or any other downstream processing, the resultant GHG saving potential for the base case is 88.4% (10.9 gCO₂-eq./MJ). Lastly, in case solids can be applied to land, significant emission savings can be achieved by considering replacement of fossil fertilizers and carbon sequestration.

5.2 Commercial results

Many of the technical results outlined above also have commercial value. Commercial implementation of HTL at WWTP is now well documented at pilot scale and the effect on the WWTP biology well known. This is crucial information for commercial implementation. A full scale HTL plant demonstra-

tion plant was commissioned and employed in an industrial setting which can be exploited commercially. The utilisation of the bio-crude in a refinery or directly as a fuel was not documented and is a remaining barrier towards commercialisation.

A successful 1-month demonstration run has been carried out on an industrial organic waste stream as a first step to demonstrate proof of Concept.

5.3 Dissemination

The project results were disseminated through the following peer reviewed publications in international journals:

1. Hussain, A. and K. Anastasakis (2025). "Technoeconomic evaluation of integrating hydrothermal liquefaction in wastewater treatment plants." *Bioresource Technology* 419: 132030.
2. Macêdo, W. V., R. D. Harpøth, J. S. Poulsen, N. de Jonge, C. H. Fischer, L. M. Agneessens, J. L. Nielsen, P. Biller, C. K. Rickers and L. Vergeynst (2024). "Anaerobic digestion of wastewater from hydrothermal liquefaction of sewage sludge and combined wheat straw-manure." *Bioresource Technology* 399: 130559.
3. Macêdo, W. V., J. S. Madsen, P. Schacksen, R. Sandeep, J. L. Nielsen, P. Biller and L. Vergeynst (2025). "Aerobic biological treatment of hydrothermal liquefaction process water of sewage sludge: Nitrification inhibition and removal of hazardous pollutants." *Water Research* 277: 123351.
4. Macêdo, W. V., J. S. Schmidt, S. B. Jensen, P. Biller and L. Vergeynst (2023). "Is nitrification inhibition the bottleneck of integrating hydrothermal liquefaction in wastewater treatment plants?" *Journal of Environmental Management* 348: 119046.
5. Maqbool, W., P. Biller and K. Anastasakis (2024). "A kinetic process model for sewage sludge hydrothermal liquefaction in Aspen Plus: Model validation with pilot-plant data and scale up." *Energy Conversion and Management* 302: 118136.
6. Neha, S., M. Nguyen, L. Vergeynst and P. Biller (2025). "PFAS destruction through catalyzed hydrothermal liquefaction using modified hydrochar." *Journal of Water Process Engineering* 72: 107606.
7. Neha, S., L. Vergeynst and P. Biller (2024). "Evaluating hydrothermal liquefaction hydrochar from sewage sludge as a phosphorus resource through struvite production." *Journal of Environmental Chemical Engineering* 12(3): 113014.
8. Wen, J., S. Neha, P. Biller, K. Kristensen and L. Vergeynst (2024). "Detection of volatile hydroperfluoroalkanes during hydrothermal liquefaction of perfluoroalkyl carboxylic acids at circumneutral pH." *Journal of Hazardous Materials* 476: 134955.

Conferences:

- First Conference with Reference Group has been held in June 2022.
- Delegation 1 at Circlia Nordic. Reference Group Meeting. Sludge2Fuel Project Group
- Energi og ressourceudnyttelse I Vandsektoren, DANVA – Temadag. 19. januar 2022. Sludge2Fuel – Bedre udnyttelse af slam. Peter Daugbjerg, FRSE
- Slam håndtering – teknologier (pyrolyse og HTL) og miljøforhold – del 1. 21. marts 2022. Overvejelser om omlægning til HTL. Peter Daugbjerg, FRSE

- Slamhåndtering – teknologier (Pyrolyse og HTL) og miljøforhold – del 1. 21. Marts 2022. Slamhåndtering ved HTL. Ib Johanssen, Circlia Nordic
- Åbent hus hos Crossbridge. 20. August 2022. Informations stand. Peter Daugbjerg, FRSE og Ib Johanssen, Circlia Nordic
- Åbent hus Crossbridge. 20 august 2022. Roll-up, Gitte Lyager, FRSE
- IWA World Water Congress & Exhibition, Copenhagen. 11-15. September 2022. Hydrothermal Liquefaction as a technology for carbon and nutrient recovery from sewage sludge. Patrick Biller, AU
- IWA World Water Congress & Exhibition, Copenhagen. 11-15. September 2022. Continuous Wet Oxidation of Aqueous Phase from Hydrothermal Liquefaction of sewage sludge. Patrick Biller and Lars Bjørn Silva Thomsen, AU
- IWA World Water Congress & Exhibition, Copenhagen. 11-15. September 2022. Integrating Hydrothermal Liquefaction for Sewage Sludge Management with Resource Recovery. Williane Vierira Macedo, Jennie Spicker Schmidt and Leendert Vergeynst, AU
- IWA World Water Congress & Exhibition, Copenhagen. 11-15. September 2022. Commercial application of Hydrothermal Liquefaction for Sewage Sludge Management with Resource Recovery. Ib Johanssen, Circlia Nordic
- Driftens dag Samforsyning. 14. September 2022. Sludge2Fuel, oplysning om ny teknologi. Kristian Philipsen, FRSE
- Nordic Hydrogen Workshop, 14. September 2022. Oplæg for erhvervsdelegation under Nordic Hydrogen Workshop. Peter Daugbjerg, FRSE
- Fachforum Hydrothermale Prozesse, Leipzig Germany. 27-28. Januar 2023. Patrick Biller, AU

6. Utilisation of project results

Technological Results:

- Design and use of modular HTL-unit is ready for use in converting biomass to HTL oil, 'water' and solids. The unit is fit for converting Biogas digestate, industrial organic waste etc. in the Danish and European market by Circlia Nordic.
- Laboratory testing of Fredericia Wastewater in simulated test of integration of HTL-technology and Wastewater Treatment facility demonstrating impact on biological processes and effluent changes. Test method of toxic and difficult substances, including conversion (PFAS, LAS etc.) in Wastewater Treatment demonstrated.
- Development of Solids extraction of phosphorous into fertilizer fraction.

Commercial results:

- Industrial sludge conversion in modular HTL-unit to BioCrude.
- Design and use of modular HTL-unit is ready for use in converting biomass to HTL oil, 'water' and solids. The unit is fit for converting Biogas digestate, industrial organic waste etc. in the Danish and European market by Circlia Nordic
- The results on the upgrading of the HTL-oil have led to further work on the pre-treatment and is continued in a new EUDP project – UpBio where Topsoe and Alfa-Laval will develop the

upgrading scheme to amongst others will fit the Crossbridge Energy A/S refinery configuration. The primary focus is co-processing of Marine Gasoil and Fuel oil. This project will derisk and clarify the commercialisation of HTL and other thermochemical bio-mass processes.

Competitive situation in the market:

- The competitive situation in the market is unchanged. The development of sustainable fuels is delayed and mainly driven by legislation. The Marine fuel market is very competitive as the fuel is primarily seen as a cost.
- The sustainable Marine bio-fuels market is waiting for the IMO standards. Until now the market is preparing for additional commitment into both energy improvements and change of fuels by introduction of 'legal' minimum requirements. The Marine market is moving towards LNG/LPG and some e-fuels as Methanol and Ammonia. The bio-fuels marine fuel is mainly biodiesel (FAME/HVO) for smaller coasters. The market is still waiting for larger volumes of biofuels for Heavy Fuel Oils, including supply chain and logistics.
- HTL and other pyrolysis oils manufacture is emerging as processes but still have some way to go to commercial fuels. These fuels however are cheaper and therefore have promising outlook.

7. Project conclusion and perspective

Conclusions from the project.

- Integrated HTL and wastewater treatment is potentially a solution to avoid landfilling of wastewater sludge. The technology has clear environmental benefits on PFAS/PFOS, FAS and other patogene or toxic substances. Upgrading of the produced oil to Marine Fuel needs further development before the combined solution is investment ready.

Next steps:

- Improve the upgrading of the HTL-oil pathway through demonstration projects on pre-treatment for allowing co-processing at industrial Hydrotreatment to marine fuels.
- The HTL technology has potential to be used in other organic waste areas such as biogas digestate and organic waste disposal / reuse
- What are the next steps for the developed technology?
- Put into perspective how the project results may influence future development

8. Appendices

- No appendices.