Final Outcomes Report (non-confidential)

Project Title: The Conversion of Forestry Residue to Advanced Biofuels in Alberta

Project Leader: Doug Greening
Lead Institution: Steeper Energy
Project Partners: Hatch, Mercer, CanmetENERGY

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Project Description

Steeper Energy has developed a proprietary version of hydrothermal liquefaction (HTL) called Hydrofaction®. It converts biomass waste streams into renewable and sustainable biocrude oil. This in turn can be further refined into renewable fuels compatible with all types of reciprocating and turbine engines. The objective of this ERA supported project was to help advance the core Hydrofaction® process and subsequent biocrude upgrading technology. Ultimately, with a deeper understanding of the challenges and solutions involved in producing finished fuels from Alberta's forestry wastes, the goal was to find commercial partners for a proposed Hydrofaction® plant in Alberta with a capacity of 2000 barrels per day (bpd). To accomplish this work, operational data from Steeper's Hydrofaction® Demonstration and Pilot plants, along with Steeper's Advance Biofuels Center (ABC), was leveraged to better understand the real costs and challenges of building and operating a full-scale plant.

Table Contents

List of tables:

List of figures:

No table of figures entries found.

1 Executive Summary

This document presents the non-confidential results and learnings of the Project, which aimed to demonstrate and commercialize Steeper Energy's Hydrofaction® technology for converting biomass waste streams into renewable and sustainable biocrude. Hydrofaction® biocrude can be refined or co-processed into drop-in fuels that are compatible with existing engines and infrastructure. The Projects' purpose was to advance the commercial viability of the Hydrofaction® biocrude production processes and to subsequently develop upgrade or co-process pathways for its entry into the commercial fuels marketplace. Along with various technical hurdles to get the advanced biofuel technology to market, the project's goal is to develop the world's first Hydrofaction® facility to a contract stage within Alberta, while simultaneously advancing and de-risking the technology for Alberta stakeholders.

The Project achieved its main objectives of advancing towards the technical readiness and commercial viability of the Hydrofaction® technology. During the project the existing pilot and demonstration plants successfully produced biocrude from forestry residues. The biocrude quality was consistent and met the specifications for further refining or co-processing. The Project also identified and evaluated several potential upgrade and co-process partners and pathways, and established relationships with key stakeholders in the biofuels industry. The Project outcomes have enabled Steeper Energy to pursue the development of the world's first commercial-scale Hydrofaction® facility in Alberta, which will provide significant economic and environmental benefits for the province and the country.

The Project will ultimately contribute to the decarbonization of the transportation sector by demonstrating the potential of Hydrofaction® to produce low-carbon fuels from abundant and low-cost biomass waste sources. The life cycle analysis of the biocrude showed that it can reduce greenhouse gas emissions by up to 150% compared to fossil fuels, depending on the feedstock and the upgrade or co-process pathway. The Project also demonstrated the social and environmental benefits of utilizing waste biomass that would otherwise be burned, landfilled, or left to decompose, such as reducing fire hazards, improving air quality, and enhancing soil health.

The Project has generated valuable knowledge and insights that will inform the future development and deployment of the Hydrofaction® technology. The Project has also showcased the innovation and leadership of Steeper Energy and its partners in advancing the bioeconomy and the energy transition in Canada and beyond.

2 Project Description

2.1 Introduction

Steeper Energy has developed a proprietary version of hydrothermal liquefaction (HTL) called Hydrofaction®. It converts biomass waste streams into renewable and sustainable biocrude. This in turn can be further refined into renewable fuels compatible with all types of reciprocating and turbine engines, and energy infrastructure currently in use today. This technology supports decarbonization by dramatically reducing reliance on fossil fuels.

Hydrofaction® achieves an industry-leading 45% biomass-to-oil conversion on a mass basis, and up to 85% of the biomass input energy is recovered in the biocrude. The biocrude has many similarities to fossil crude, which means less refining is required to turn it into a finished fuel, and that the refining can be done using existing petroleum infrastructure. The process is ideally suited for multiple types of wet waste feedstocks. Waste streams from forestry, agriculture, animals, the biogenic portion of municipal solid waste (MSW), and much more, can all be processed using Hydrofaction®.

The basic Hydrofaction® process works by grinding a feedstock down into small chips. These fibers are then mixed with a low-cost catalyst, recycled water from the process, and recycled biocrude from the process. The resultant slurry is then pressurized and heated to approximately ~330 bar and 400C. After approximately 10 to 15 minutes, the thermo-reductive process converts the fibers in the slurry into biocrude and process gases. The resultant stream is primarily a mixture of water, biocrude, gas, catalyst and ash. The resultant converted slurry stream is then reduced in temperature and pressure, so that the converted slurry stream can be separated into its various components. The Hydrofaction® biocrude that comes from this process, while having some similarities to that of bitumen, does have a series of attributes that are unique to the Hydrofaction® process. As shown in Table 2-1, while Hydrofaction® biocrude is superior to that of pyrolysis oil, it is not what most would consider a finished fuel. The engineering and upgrading work done to turn Hydrofaction® biocrude into a finished fuel, is broken down further in section 2 of this report.

Table 2-1 Hydrofaction® Biocrude Derived from Forestry Residues

Test	Method	Result
Water Content	ASTM D4377 (Mod)	0.18 wt.%
Ash	ASTM D482 (Mod)	0.1 wt.%
Micro carbon residue	ASTM D4530	17.08 wt.%
TAN	ASTM D664A	33.19 mg KOH/g oil
High Heating Value - HHV [daf*]	ASTM D240	38.14 MJ/Kg
Density @ 15.6°C	ASTM D4052	1043 kg/m^3
Kinematic Viscosity @ 40°C	ASTM D445	772.6 cSt
Elemental analysis (daf)		
Carbon	ASTM D5291	80.90 wt.%
Hydrogen	ASTM D5291	9.15 wt.%
Nitrogen	ASTM D5291	0.25 wt.%
Sulfur	ASTM D1552	146 ppm
Oxygen	By difference	9.69 wt.%
H/C	Calculated	1.35 molar ratio
Pour point	ASTM D97	-33 °C
Flash Point	ASTM D3828B	74 °C
Fuel fractions		
Naphtha (IBP-190°C)	ASTM D7169	5.9 %
Jet fuel fraction (190–260°C)	ASTM D7169	11.3 %
Heavy middle distillates (260–343°C)	ASTM D7169	23.3 %
Heavy gas oils (343-550°C)	ASTM D7169	39.9 %
Residue (550+)	ASTM D7169	19.5 %

2.2 Background

The basic chemistry behind HTL has been understood since the 1970's or earlier, with Steeper's optimized Hydrofaction® version of HTL being developed over the past 10 plus years. The Hydrofaction® process has been developed and refined at a pilot scale at Steeper's Aalborg University Continuous Bench Scale (CBS) Hydrofaction® pilot plant. The first demonstration scale implementation of the Hydrofaction® process is at the Silva Green Fuels (SGF) 30 bpd (barrel per day) demonstration plant in Tofte, Norway.

While both the CBS and SGF plants have been extremely useful tools in commercializing the Hydrofaction® process, going from a 30 bpd plant up to a commercial plant that is rated for 2000 bpd, is an ambitious step, with risks. At the beginning of this ERA supported project, the SGF demonstration plant was still under construction. Consequently, the risks associated with the scale-up of Hydrofaction®, the upgrading of Hydrofaction® biocrude, and the commercialization of Hydrofaction® have remained relevant. The objectives of this ERA supported project were to help advance both the Hydrofaction® core process and the Hydrofaction® biocrude upgrading development, to lay the groundwork for the eventual building of a 2000 bpd Hydrofaction® plant in Alberta. With a better understanding of the challenges that came from running both the CBS and SGF pilot and demonstration plants, enough basic engineering work was done to better understand the real costs and challenges of building and operating a full-scale plant. Also, with a better understanding of the challenges and solutions for converting

Hydrofaction® biocrude into fuels like Heavy Fuel Oil (HFO), diesel and Sustainable Aviation Fuel (SAF), refining and offtake partners could be found.

2.3 Project Objectives

The project's objectives that were defined in Schedule A, are partially listed here:

Work Package 1 (WP1) - HTL Oil Production: Evaluation of HTL unit operability using Alberta forestry residue as feedstock.

WP2 - Co-processing and Stand Alone Upgrading: Evaluation and optimization of co-processing Hydrofaction® Oil with conventional petroleum feedstocks in Alberta, as well stand-alone upgrading to advanced biofuels.

WP3 - Engineering: Leveraging the participants' experience, investigate areas for further development of the core technologies, and advance those key areas through extensive engineering work. Leveraging the participants' shared experiences and newly developed study data, establish realistic GHG life cycle assessment for the various project options. Feed the appropriate data back to the Engineering Activities teams to allow for corrections in development directions.

WP4 – Alberta Market Deployment Strategy: This work package will generate data that will allow the participants to balance the commercial, technical, and environmental inputs to allow for the best path forward towards a commercial project.

2.4 Performance/success metrics identified in the Contribution Agreement

2.5 Project Performance/success metrics outcomes

Hydrofaction® Oil storage stability:

Storing untreated Hydrofaction oil for extended periods can lead to degradation. In an untreated sample stored for about eight months, the water content increased by 11%, density by 0.2%, and viscosity by 21%, all indicating aging. However, a sample that underwent a single-stage of hydrotreatment demonstrated better stability. After one year, it showed only a minor density increase of 0.03%, with no changes in water content or viscosity. This improvement highlights the effectiveness of hydrotreating in enhancing oil stability during storage.

The stability of the Hydrofaction oil depends not only on pre-treatment but also on storage conditions such as temperature, pressure, and exposure to air. Storing oil above 50◦C atmospheric pressure significantly accelerates its degradation. To mitigate this, nitrogen blankets and pressurized storage are recommended at temperatures exceeding 50◦C. Pre-treatments like hydrotreating or chemical treatment effectively reduce the reactivity of Hydrofaction oil, enabling it to be stored for over a month at temperatures below 110◦C with minimal degradation.

Transient/mixing stability:

Hydrofaction oil demonstrates partial compatibility with vacuum gas oil (VGO), influenced by a combination of factors such as saturated, and aromatic content. In addition to these components, the polar content, such as oxygen, nitrogen, and sulfur, plays a crucial role in compatibility. To prevent issues like phase separation, and catalyst deactivation, pretreatment of Hydrofaction oil is required. Compatibility tests confirmed the stability of a B20 blend (20wt.% partially upgraded Hydrofaction oil with 80wt.% VGO) under storage conditions, showing no phase separation, density increase, or degradation. Microscopy analysis revealed uniform dispersion within the blend, confirming its stable mix.

Following these stability assessments, the pretreated blend was used in a hydrotreating process lasting over 100 hours, during which catalyst performance remained unaffected. Repeated testing further validated the reliability of these findings, demonstrating that Hydrofaction oil and VGO blends, with pretreatment, are suitable for stable integration in refining processes.

Catalyst deactivation:

To evaluate and improve the stability of the catalysts, both stand-alone and co-processing tests were conducted to observe the effects of HTL oil properties and processing conditions. Stand-alone upgrading tests, performed over 700 hours of continuous operation, showed that high water and inorganic content in the HTL oil significantly reduced catalyst activity, leading to increased production of high-boiling-point compounds that deviate from the desired product range. To address these issues, lower space velocities were employed to improve deoxygenation, viscosity reduction, and residue fraction reduction in HTL oil.

Following this, co-processing trials were conducted to test HTL oil in combination with VGO in the hydrotreater, with tests running over 400 hours. These trials revealed that incorporating HTL oil into the VGO hydrotreatment impacted catalyst performance, reducing the removal efficiency of oxygen, nitrogen, and sulfur compared to processing VGO alone. To mitigate these effects, increasing the reaction temperature and adjusting the blend ratio of VGO to HTL oil were shown to help maintain catalyst efficiency and reduce deactivation, providing insights into optimizing processing conditions for mixed feeds.

In recent years, a hydrotreatment run aimed at partially upgrading and HTL oil sample demonstrated stable catalyst activity for approximately 1200 hours without deactivation. This stable performance was confirmed through continuous monitoring of key parameters, ensuring consistent catalyst activity throughout the process.

Hydrogen consumption:

Continuous hydrotreatment experiments have shown that hydrogen consumption in both stand-alone upgrading and coprocessing of HTL oil ranges from 2 to 4 wt.%, with consumption levels varying based on the specific fuel product being targeted. For example, producing diesel in compliance with the EN590 standard results in a hydrogen consumption of approximately 3.7 wt.%. By contrast, when producing marine-like HTL fuel, hydrogen consumption decreases to below 2.5wt.%, reflecting the lower hydrogenation requirements for marine applications.

In trials aimed at producing diesel-quality fuel suitable for blending with commercial diesel, hydrogen consumption was measured at 2wt.%. This level of consumption indicates that the process effectively meets the hydrogenation needs for upgrading HTL-derived oil into a blend-compatible quality. By comparison, fully refined commercial diesel typically requires between 3.0 and 3.5 wt.% hydrogen, due to the more extensive hydrogenation and refining required to meet stringent final fuel standards.

These findings highlight that HTL-derived diesel, especially for blending purposes, demands less hydrogen than fully refined diesel. This lower hydrogen consumption suggests that HTL-derived diesel has the potential to serve as an efficient intermediate feedstock, offering a cost-effective and resource-efficient alternative for partial blending with commercial diesel.

De-nitration:

Efforts were focused on optimizing the hydrodenitrogenation (HDN) process to enhance fuel quality. In stand-alone upgrading and co-processing tests with up to 10wt.% pre-treated HTL oil blended with VGO, nitrogen content was successfully reduced to below 200 ppm, demonstrating the effectiveness of HDN across different processing conditions.

For the diesel produced from HTL oil, HDN achieved a 99% reduction in nitrogen content after multiple hydrotreating stages. The nitrogen level decreased from 0.25wt.% in the raw HTL oil to less than 5 ppm in the final diesel product, ensuring compliance with quality standards and confirming the effectiveness of the optimized HDN process.

Desulfurization:

To meet stringent fuel specifications, hydrodesulfurization (HDS) was evaluated and optimized to improve fuel quality. In initial VGO-co-processing trials, blends containing up to 10wt.% pre-treated HTL oil showed sulfur concentration reduced to below 500ppm. This demonstrated that the process could effectively reduce sulfur under certain conditions, although further optimization was necessary to achieve stricter fuel specifications.

In line with these findings, continuous stand-alone upgrading trials were conducted to refine the process. These trials successfully lowered sulfur levels to below 10 ppm, showing significant progress in reducing sulfur content. The optimization efforts continued with the goal of producing fuel that meets rigorous quality standards, particularly diesel.

For diesel production, HDS achieved a 97% reduction in sulfur content, decreasing it from 146 ppm in the raw HTL oil to just 5 ppm in the final product. This substantial reduction aligns with high-quality diesel specifications, demonstrating the efficiency of the optimized process. These results illustrate successful progression toward refining HTL-derived fuels with minimal sulfur content, ensuring they meet necessary industry standards.

De-oxygenation:

To optimize the deoxygenation process, a series of hydrotreatment stages were employed, resulting in the oxygen content in HTL oil being reduced to below detection limits. This multi-stage approach was critical in improving the process for producing fuels with the desired quality.

For diesel production, hydrodeoxygenation (HDO) was particularly effective, reducing the oxygen content in HTL oil from 9.68wt.% to 0.3wt.%, achieving a 97% reduction. This significant decrease in oxygen is essential for improving the fuel’s stability and combustion properties, ensuring it meets the requirements for high-quality diesel fuel.

In the case of diesel production, hydrodeoxygenation reduced the oxygen content from 9.68 wt.% to 0.3 wt.%, achieving a 97% reduction. This substantial decrease in oxygen is critical for improving the fuel's stability and combustion properties.

Operating cost:

From the work completed in the project higher than expected CAPEX, maintenance, fiber chipping, fiber delivery, and catalyst costs were the major reasons for a final higher than expected opex. It should be noted that at subsequent plants, the plant capex is expected to be significantly lower, which will have the effect of reducing the operating costs. Its also important to note that, the before and after CAPEX and OPEX values were in part defined by before and after the global pandemic pricing. The CAPEX of the plant, which is directly related to the expected maintenance of the plant, jump drastically between 2019 and 2021. The price of many alloy steels, which the plant is made from, increased by 2 or 4 times between these dates.

Carbon Intensity:

With an original target of 15 gCO_2eq/MJ for the project, the final LCA estimate far exceeded Steeper’s expectations. With a plant location identified, several attributes of the location helped reduce the expected Carbon Intensity (CI) for the proposed plant. Nearby behind the meter green power, relatively easy access to the CO_2 sequestration options, and further clarity on how waste forestry fibers should be treated in a LCA calculation, led to an expected fuel carbon intensity of negative 38 gCO_2eq/MJ.

Commercial:

At the beginning of the project, Steeper Energy had no site, commercial partner, or commercial agreements in place to build a first of kind commercial scale Hydrofaction plant. However, by the end of the project, significant progress had been made. We’ve identified an Alberta based commercial partner and selected their site as the proposed location for our plant. This partnership resulted in the signing of a Memorandum of Understanding (MOU), marking a critical milestone in our project's development.

Several factors contributed to the feasibility and attractiveness of the site. The location offered potential behind-the-meter green power options, which are crucial for our sustainability goals. Additionally, the proximity to a proposed CO2 sequestration pipeline, and the possibility of utilizing the Alberta Carbon Trunk Line (ACTL) for CO2 transport by rail, provided viable pathways for reducing our carbon footprint. Lastly, the partner also uses wood products, which creates opportunities for Steeper to utilize some of their waste wood products and could create efficiencies in collecting more woody biomass from the forests.

Throughout the project, we also engaged in several rounds of commercial discussions with potential vertically integrated oil companies. Our conversations with these potential plant offtakers remain active as they continue testing Hydrofaction oil for potential use.

Meanwhile, our collaboration with Hatch, has resulted in their substantial contribution to the latest Hydrofaction plant designs. Hatch is now well-positioned to assist us in the next phases of development.

2.6 Discussion on changes in the Project during the lifecycle of the ERA funded Project scope

As noted above, having picked a location for the proposed plant helped significantly with the GHG estimates for the overall project. The proposed plant location has behind the meter green power options. The location also has the option of shipping any CO_2 to the Alberta Carbon Trunk Line (ACTL). Also, clarity as to how to treat an offset associated with the avoidance of GHG's being released if the plants proposed feedstock was burnt in the forest, helped in reducing the expected resultant fuels CI score. While CO_2 sequestration of the proposed plants process gas stream is not expected early in the plants construction, it appears to be much easier to sequester than originally thought. Taking this all into account Steeper used S&T Squared to review and estimate the proposed plants expected CI score. For a fuel that can be blended with fossil derived HFO, the Hydrofaction® component is expected to have a CI of negative 38 gCO_2eq/MJ.

2.7 Changes to corporate structure of the company or Project consortium since

As is the nature of most commercial arrangements, the Project consortium evolved somewhat over the project's timeline.

2.8 Technology Risks

Generally, almost all of the key risks that were originally identified and categorized at the start of the project have had their Probability, Impact or Risk either moderately or significantly reduced. During the project a small number of new technical risks were identified. Potential solutions for these challenges have already been identified, and work continues to mitigate them.

3 Project Work Scope

3.1 Engineering Core Process Development

Over the scope of this project significant amounts of core Hydrofaction® related testing work was completed at the CBS plant, SGF plant, and at the ABC. These facilities and their test data were used as the foundation information to define much of the engineering work that was performed over the project. Much of this work was specifically related to a FEED study for the Hydrofaction® plant that is being proposed to be built. The new Standard Modular Plant Design (SMPD) that was developed as part of the FEED study, can be loosely defined as a FEL 2 design with multiple deliverables being developed as part of this work, including, but not limited to:

- New SMPD Heat and Mass Balance
- New SMPD PFD's & P&ID's
- New SMPD plant CAPEX and OPEX estimates
- New SMPD General Arrangement
- New SMPD 3D model
- New SMPD water separation system design
- Other typical FEL 2 deliverables

More detail topics development work included:

- Review and selection of critical components for the plant
- Detailed CFD modeling of the slurry flow in the early hot high pressure heat exchangers
- Detailed slurry rheology characterization
- Review of the hot high pressure heat exchangers materials

Beyond the basic SMPD design, several options for the plant were reviewed at a higher level, including

- Optional mild hydrotreating plant
- Optional full hydrotreating plant
- Review of options for how to produce hydrogen at the above noted plants

Ultimately the above work led to the early-stage development of multiple critical components that might be used in the plant like:

- Custom high pressure pumps
- Custom heat exchangers
- Custom slurry preparation systems
- Custom separation systems
- Custom water recovery systems

From the above work, and from the work defined in the next section of this report, the expected Carbon Intensity for the resultant fuels was calculated.

3.2 HTL oil co-processing and stand-alone upgrading

As it relates to co-processing, stand along upgrading and the newly developed Steeper Chemical Treatment processes, the following work was completed.

- Pathways for integrating Hydrofaction® biocrude into the fuels market were designed and tested at a continuous pilot plant scale. The results lead to the possibility of producing various qualities of marine fuel and diesel, as well as the potential production of SAF.

- The stand-alone upgrading pathway studies revealed that the catalyst bed configuration in each hydrotreatment stage and its process conditions should be chosen to maximize the desired fuel product.

- The outcome of this project indicates the feasibility of producing diesel and jet fuel through the use of commercial heterogeneous catalysts at temperatures and pressures similar to the ones used in existing refineries but at a low space velocity.

- Two grades of diesel were achievable: 1) blend component diesel, which possesses properties that are similar to the diesel specifications (EN590 and D975) but must be blended with petroleum diesel to fully meet the specifications, and 2) diesel that meets the specifications without the need for compounding.

- Sustainable aviation fuel (SAF) production from HTL biocrude was also assessed. Based on the outcomes of the upgrading trials, it was determined that the lignocellulosic HTL oil could be utilized to produce particularly aromatic jet fuel. Nevertheless, the potential application of lignocellulosic HTL oil in the production of SAF could be a viable strategy to help meet the considerable demand for SAF. Additionally, certification initiatives for the HTL lignocellulosic jet fuel pathway are required.

- Co-processing of HTL biocrude and VGO was performed in FCC and hydrotreated units. Both approaches indicated promising results that could lead to maximization of biogenic content carbon in the liquid fuels.

4 Commercialization

4.1 Advancements made toward commercialization, commercial deployment or market adoption

Plant Site and Fiber

Over the course of the project several locations, generally in the Northern half of Alberta, were evaluated as potential locations for the proposed first Alberta plant. The best locations had the following attributes:

- Existing rail access
- Exceptional road transport access
- Nearby Green electricity
- Limited competition for feedstock fibers
- At least 300,000 odt per annum of feedstock
- Nearby CO_2 sequestration options

Offtakers

From an offtake perspective, there is significant interest in using the oil from the proposed plant. The commercial and technical due diligence process is still ongoing, but finding a committed offtake partner looks promising.

4.2 Description of technology advancement over the course of the Project

At the beginning of the Project, Steeper's demonstration plant in Tofte, Norway, was not fully assembled. While the construction of the plant was not directly part of the project, the operational data that started to come out of the plant in late 2020 was critical to the Project's success. Throughout the duration of the Project, the operational periods of the SGF plant were progressively extended. The data and biocrude that came from these test runs helped in the development of major parts of the technical work.

Key Engineering / Operational achievements and metrics from the Project included:

- Over 800 hrs of operational time of the SGF plant, as of the completion of the ERA project.
- Adding more accuracy to the SMPD total installed cost estimate, by creating what can be generally defined as a Class 3 costing study.
- A review of typical operational methods of Western Canadian pulp and paper mills, directly led to the review of how the front end of a the SMPD would be built.
- A review of the SGF heat transfer rates from the SGF plant was used to better define the high pressure heat exchanger heat transfer rates. This led to an expected reduction in the number of heat exchangers needed for the ultimate plant.
- A review of the plants hot high pressure equipment's material selection, based on operation data has led to a change in material specifications.

- The GHG calculations performed by a third party were much better than expected. It is reasonable to think that the proposed plant will be able to produce a finished fuel, with a CI score of negative 38 gCO_2e/MJ.

Key Upgrading, Refining and Chemical Treatment metrics included:

- Creation of an advanced laboratory for the upgrading and characterization of HTL oils
- Production of diesel complying with EN590 specification
- Production of Jet fuel like product that could potentially be included in a standardization process.
- Development of an alternative methodology to increase HTL oil thermal stability while reducing its total acid number.
- Proof of concept of co-processing of B5 to B10 blends between HTL oil and VGO.

There are several aspects of development work at various TRL's, but when focused on the highest level of the project, over the course of the project the Technology Readiness Level has shifted from 7 to closer to 8.

As noted above, significant advancements in the total overall technical readiness for the Hydrofaction process have occurred over the course of the project. In particular, Steeper's ability to upgrade the oil from the Hydrofaction process has improved significantly. With a single mild hydrotreating step, there now seems to be a minimum viable product that multiple marine shipping companies are wanting to test. From the core Steeper Hydrofaction (HTL) perspective, the change in TRL is more complicated. While many technical issues were identified and resolved, there do remain a number of issues that need further development work. Almost certainly the TRL of the project has shifted, but to say the project has achieved TRL 8 level, would be a stretch. It is more appropriate to say the TRL has shifted from 7 to something closer to an 8.

5 Lessons Learned

While general engineering work had its own challenges, the commissioning of the SGF plant and the ABC laboratory, right in the middle of the global pandemic was very difficult. With world oil prices dropping to historic levels, material costs skyrocketing, and delivery dates being delayed and then delayed again, completing even small tasks were difficult. Beyond these administrative and commercial setbacks, there were also the following issues:

- The higher-than-expected plant cost estimates was one of the primary reasons to review the costing of the key high installation components. Fortunately, the cost estimate also pin pointed areas of the plant design that needed to be redesigned to reduce cost. While this work is still ongoing, the team has already made significant improvements in the plant's expected Total Installed Cost.
- Raw Hydrofaction oil, that has not been chemically treated or stabilized, can corrode away a marine ship's storage tank. This was key in triggering the development of the Chemical Treatment process which looks to be a very promising commercial pathway.

5.1 Additional Lessons Learned

- Importance of Flexibility and Adaptability: The unexpected global pandemic underscored the necessity for agile project management and the ability to pivot quickly in response to unforeseen circumstances. This adaptability allowed the team to navigate material shortages, cost fluctuations, and logistical delays effectively.

- Collaboration and Communication: The integration of feedback from marine companies interested in testing the minimum viable product ensured that the development remained aligned with market needs and regulatory requirements. This collaborative approach facilitated the refinement of the technology and its readiness for commercial deployment.
- Iterative Approach to Technical Issues: Continuously improving and rigorously testing the processes were vital. Identifying and addressing issues early saved future costs and enhanced the overall reliability and efficiency of the process, paving the way for successful commercialization.
- Effective Resource Management: Efficiently managing resources, including human capital and material supplies, was critical to the project's success. This included implementing measures to optimize supply chain logistics and ensuring the availability of essential components despite global disruptions.
- Regulatory Compliance: Ensuring that all developments complied with relevant regulations and standards was crucial. This involved continuous updates on regulatory changes and integrating these requirements into the project execution plan, ensuring smooth progress and eventual commercialization.
- Stakeholder Engagement: Regularly engaging with stakeholders, including investors, and industry partners, maintained transparency and built trust. This engagement was pivotal in gaining support and addressing concerns promptly, aiding smooth project progression.

These lessons learned underscore the project's complexity and the team's dedication to overcoming challenges, ensuring that Steeper's technology is ready for commercial deployment and can significantly contribute to reducing greenhouse gas emissions and other environmental impacts.

6 Environmental Benefits

6.1 Emissions Reduction Impacts

A table has been provided below to show the annual greenhouse gas (GHG) emissions that Steeper's technology can be expected to reduce. The table assumes that a 2000 bpd plant will be fully commercial and operating in 2028 and that more 2000 bpd plants will quickly come online after that. The initial target market will be roadside residues from the harvesting of commercial forestry. There's enough of these residues in Alberta for about 15 plants. To get more plants in Alberta the waste will need to come from different sources. Additional waste sources are agricultural residues and other organic waste. These other waste streams could provide enough feedstock for another 32 plants. Collectively with roadside residues, agricultural residues, and other organic waste there could be a total of 47 plants in Alberta. The table below only accounts for a total of 20 plants in Alberta by 2050 and after. This represents approximately 43% of the previously identified forestry, agriculture, and organic wastes.

Table 6-1 Annual GHG Reductions

2000BPD Plant Rollout Table								
Year	2025	2026	2027	2028	2029	2030	2040	2050 and after
Total Operating Plants	0	0	0	1	3	5	30	50
Total Operating Plants in Alberta	0	0	0	1	3	5	14	20
Total Annual GHG Reductions (KT)	0	0	-	630	1,502	2,373	13,270	21,988
Alberta Annual GHG Reductions (KT)	0	0	-	630	1,502	2,373	6,296	8,912

The completion of this project is a crucial milestone on the way for Steeper to commercialize its technology. Once Steeper's technology is commercialized Steeper's plant will demonstrate the feasibility and scalability of its innovative technology and provide a low to negative carbon substitute for internal combustion engines or chemicals production. This will reduce the GHG emissions of the transportation and petrochemical sectors, while also creating new revenue streams and jobs for Alberta. Therefore, commercialization of Steeper's technology would contribute significantly to Alberta's success in a GHG-constrained future, as well as to Canada's commitment to achieve net-zero emissions by 2050.

6.2 Other Environmental Impacts

Steeper's project does not have any other environmental impacts, but the completion of the project is an important milestone in Steeper's commercial deployment. Once Steeper is commercial, a commercial plant using forestry material could reduce forest fire risk by providing an economic route for forestry residues and thus lesson the fire risk that they could pose by being left to rot or be burned later. Preventing the burning of wood will help improve the air quality by avoiding the release of particulate matter, carbon monoxide, and other harmful pollutants that can cause respiratory problems. Moreover, wastewater from the biocrude production process could also be used to replace fracking water or other sources that could use Steeper's wastewater instead of fresh water. This would save precious water resources. Lastly, Steeper's biocrude has a reduced sulfur content compared with other fossil fuel oils, which will lessen the harmful environmental effects of burning sulfur-containing fuels. Sulfur dioxide is a major contributor to acid rain, which can damage buildings, soil, and aquatic life.

7 Economic and Social Impacts

The project itself has helped to maintain existing jobs and resulted in some new jobs in Alberta as well. Specifically, one of the ways that Steeper has used the money provided by ERA was to upgrade Steeper's Advanced Biofuel Centre.

Moreover, the effects should the commercial plant go ahead would be much more significant. During the construction phase of a 2000 bpd Hydrofaction® plant, the equivalent of 2500 jobs are expected to be created. When operational, the plant would directly create approximately 30 permanent jobs including operating and administrative staff. It is expected that the chipping, collection, and delivery of forestry slash would create another ~40 permanent jobs. As a rule of thumb, 6 indirect jobs are created for each direct job in the process industry, giving an economic benefit of approximately 420 created jobs per plant.

Following an economically successful first-of-kind commercial plant, subsequent plants could be rolled out in Alberta which would diversify Alberta's economy away from fossil fuels.

8 Scientific Achievements

8.1 Patents and Publications

Articles being release as part of the project:

- Coprocessing Partially Hydrodeoxygenated Hydrothermal Liquefaction Biocrude from Forest Residue in the Vacuum Gas Oil Hydrocracking Process
    - Sandeep Badoga, Anton Alvarez-Majmutov, Julie Katerine Rodriguez, Rafal Gieleciak, and Jinwen Chen Energy & Fuels 2023 37 (17), 13126-13136 DOI: 10.1021/acs.energyfuels.3c01651
- Upgrading of Hydrothermal Liquefaction Biocrude from Forest Residues Using Solvents and Mild Hydrotreating for Use as Co-processing Feed in a Refinery
    - Sandeep Badoga, Anton Alvarez-Majmutov, Julie Katerine Rodriguez, and Jinwen Chen

    - Energy & Fuels 2023 37 (17), 13104-13114
    - DOI: 10.1021/acs.energyfuels.2c03747
- Enhancing Efficiency of Coprocessing Forest Residue Derived HTL Biocrude with Vacuum Gas Oil: An Integrated Pretreatment Approach
    - Sandeep Badoga, Anton Alvarez-Majmutov, Julie Katerine Rodriguez, Rafal Gieleciak, and Jinwen Chen
    - Energy & Fuels 2024 38 (7), 6092-6101
    - DOI: 10.1021/acs.energyfuels.4c00232

8.2 Conference Presentations

Conferences that Steeper either formally presented at, or made private presentations at over the course of the Project included:

- Washington DC, USA - ABLC 2021, 2022, and 2023
- San Francisco CA, USA - ABLC Next 2022 and 2023
- Helsinki Finland – ACI Lignofuels – 2021, 2022, 2023, 2024
- Jasper Alberta, Canada – Alberta Forestry Products Association AGM - 2022 & 2023
- Bologna Italy – EUBCE - 2023
- Ottawa Ontario, Canada – Scaling Up - 2022

9 Overall Conclusions

Upgrading, Refining & Chemical Treatment:

- The new Chemical treatment process helps in creating a potential new pathway to market for HFO marine fuels, that does not require Hydrotreating. This potentially means a Hydrofaction® plant can ship its fuel to most fuel bunkering locations without having to involve a 3rd party refiner, and associated costs.
- The Co-processing tests using oil produced for this ERA project went better than expected. There had been an expectation that the Hydrofaction® oil would need to be either mildly hydrotreated or potentially chemically treated before it could run in an FCC based refinery. It had been feared that for Hydrofaction® oil to run in an existing FCC plant the oil's oxygen content, acidity level, and metals levels would all be too high. However, following a series of co-process tests conducted at a third-party laboratory scale, indications suggest that the Hydrofaction® biocrude can be utilized in its existing state, for at least some FCC based refineries.

Steeper Core Process Development Work:

- The early costing FEED study work preformed by Hatch and in parallel with the Steeper team, generated a range of potential CAPEX and OPEX results that will need to be reviewed as the development work continues.

Commercial:

- The interest level from marine shipping companies and vertically integrated oil and gas companies to be both offtakers and potential plant owners is very encouraging.
- While the CAPEX for the proposed plant was higher than expected, so is the expected CI score for the fuel produced at the plant. The higher reduction in GHG's demand, a higher sales price for the biocrude, and the resultant Internal Rates of Return (IRR) for the proposed Plant seem promising.

GHG Estimates:

- A third party review of the expected CI for the fuels produced at a Steeper Hydrofaction® plant were as low as negative 50 gCO_2e/MJ.
- The expected carbon intensity for the fuel produced at the proposed Hydrofaction® plant is negative 38 gCO_2e/MJ, exceeding the team’s original estimates.

10 Next Steps

As is evident from the above report there are still a few remaining technical challenges. There are also a few upgrading and refining tests that need to be sorted out before large engine testing can be done at scale.

11 Communications Plan

During the project, Steeper’s main knowledge sharing activities included several academic publications, presenting and exhibiting at conferences, and through private presentations to industry connections. These activities aimed to share the non-proprietary knowledge gained through the project with the public and other stakeholders in an accessible and transparent manner. Throughout the project, Steeper attended conferences in Finland, Alberta, Washington, San Francisco, Miami, Ottawa, Amsterdam, Italy and others. Although Steeper did not present at all of these conferences, our attendance facilitated conversations about our Alberta project in our search for partners and potential funding.

Upcoming plans for knowledge sharing include another academic publication relating to the upgrading and coprocessing of Hydrofaction® oil and an upcoming speaking session at Inventures 2024. The project results may also be disseminated through various platforms, such as the Steeper Energy website, social media, and potentially through a press release or newsletter.

12 Literature Reviewed

• List of literature reviewed in an appropriate citation format (if applicable)

N/A

13 Non-Confidential Final Outcomes Report

This report, along with several published articles, is the extent of the Final Outcomes Report.