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A Techno-Economic Appraisal of Green Diesel Generation through Hydrothermal Liquefaction, Leveraging Residual Resources from Seaweed and Fishing Sectors

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Abstract: This study examines the economic viability of an emerging technology for potential up-scaling and commercialization in a specific location: the village of New Stuyahok, Alaska. The proposed technology is hydrothermal liquefaction, which utilizes kelp macroalgae and fishing waste as feedstock. These materials were chosen due to their easy availability in the village and their alignment with the local economy. The economic evaluation is based on the net present value (NPV) and sensitivity models. Different feedstock ratios (on a dry basis), such as 100:0, 50:50, and 30:70 of kelp and fishing waste, respectively, were evaluated to determine the optimal combination. The results indicated that the process is economically viable only when a high proportion of fishing waste is used. This can be ascribed to the constrained output yield of the kelp biomass and the relatively negligible influence exerted by alginate production on the NPV. However, the ratio 50:50 appears to be economically promising if the costs can be reduced by at least 13.5% or the benefits can be increased by 12.1%. Nevertheless, government support could play a crucial role in expediting the implementation of this technology once it becomes market-ready. This means being practical, scalable, and economically viable, enabling reduced investments or increased benefits that signify its readiness. Utilizing such a tool offers valuable insights into the framework of the proposed technology and the use of local natural resources.

Keywords: economic viability; seaweed; fishing industry; kelp macroalgae; local natural resources

Citation: Rosales-Asensio, E.; Segredo-Morales, E.; Gómez-Marín, N.; Pulido-Alonso, A.; Sierra, C. A Techno-Economic Appraisal of Green Diesel Generation through Hydrothermal Liquefaction, Leveraging Residual Resources from Seaweed and Fishing Sectors. *Water* **2023**, *15*, 3061. https://doi.org/10.3390/w15173061

Academic Editor: Helena M. Ramos

Received: 8 August 2023
Revised: 22 August 2023
Accepted: 24 August 2023
Published: 27 August 2023

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1. Introduction

Alaska's sparse population is a challenge to the overall service sector of the residents, meaning high costs of transportation, staffing, and infrastructure [1]. Alaska has plenty of oil, but the price is currently relatively high, which necessitates looking for new and more sustainable resources to be used as fuels [2]. In addition, most of the transportation depends on weather conditions, given the maritime character of a significant part of the state, which increases associated costs and affects remote areas more.

Renewable fuels are currently considered a sustainable alternative, especially those coming from residues. Seaweed biomass has been considered an up-and-coming possible source of biofuels due to its higher production yields and higher carbon dioxide fixation rate than terrestrial crops [3]. It is a renewable material with great potential [4] that does not compete for land space as it grows in oceans, which is an advantage over other potential biofuels [5].

The production system of seaweed is relatively simple, but it is also a costly activity given the disadvantages of offshore operations [6] and transplantation [7]. Nonetheless, Alaska's most significant economic and employment drivers are based on the seafood industry [8], which contributed, for example, USD 5.7 billion to Alaska's economy in 2019 [9]. Accordingly, the option to utilize seaweed is suited to Alaska's economy, and an added benefit is that its infrastructure is already focused on the maritime sector.

The production from seaweed of biofuel with the necessary characteristics is still under investigation in order to achieve commercialization [10] because there are still significant knowledge gaps [11]. The fact that about 85% of the algae content is water [12–17], as well as the transportation cost from retrieval to the processing plant, are two of the bottlenecks of some technologies that might hinder their sustainable use [18,19]. Conventional processing technologies (e.g., direct combustion, pyrolysis, and gasification) require drying the algae biomass to a low moisture content [20]. This results in elevated energy demands that restrict the efficient operation of these processes. To circumvent this limitation, hydrothermal liquefaction (HTL) has been suggested as a means of valorizing moist feedstocks. This approach enables the avoidance of energy-intensive pre-drying procedures [21]. Therefore, HTL exhibits a likely profitable capability for the manufacturing of crude bio-oil from wet biomass [22,23] and is a promising technology for its fast development [24]. Many studies have already explored the application of seaweed biomass via the hydrothermal liquefaction process. Among the most notable may be those carried out by Morales et al. (2022), who focused on a description of the relevance, application, and engineering platforms of hydrothermal systems [25]; Anastasakis and Ross (2015), who made energy output comparisons between the products from hydrothermal liquefaction and products from anaerobic digestion and fermentation [26]; and He et al. (2016), who studied the use of organic co-solvents in the hydrothermal liquefaction of macroalgae [27].

Seaweed farming is in its early stages in Alaska [28], and there is a growing interest in commercial seaweed algae farming [29]. If a coordinated public–private partnership with a comprehensive statewide plan is used, this industry will generate USD 1 billion over 30 years [30]. Alaska has a thriving aquaculture industry; the largest seaweed farm in North America is located in Southeast Alaska [31]. By 2027, the worldwide kelp market is expected to be worth USD 95 billion, up from USD 40 billion in 2020 [32], with kelp farming being the fastest-expanding aquaculture sector in Alaska [33].

On the other hand, fisheries products are the largest private sector industry in Southeast Alaska, both in terms of human resources capacity and labor revenues [9,34]. It is the US's most productive commercial fishing state and produces more volume than all other US states [9]. Therefore, the Alaskan fishing industry produces more than one million metric tons of waste annually [21,35,36]. Currently, the solid waste program allows three methods for managing commercial fish waste on land: landfill disposal, land application, and composting. In this sense, fish processing waste can be a promising renewable biomass for biorefineries [37], and its use can especially help manage a high number of residues.

Laminaria sp. is the most complex and extensive genus of brown seaweed, holding paramount importance in the scientific community due to its high diversity of species, ecological dominance, and noteworthy economic significance [38]. The annual yield from ocean seaweed farms is in the order of 1 kg dry wt./m^2 [39]. Depending on the species and growing conditions, *Laminaria* sp. contains different biochemical compositions (%), typically in the range of 11–14% w/w of proteins, 1–3% w/w of lipids, 17–39% w/w of carbohydrates, and 11–12% w/w of ashes [40]. This fact indicates a higher biochemical composition in carbohydrates, which are typically composed of four main types: alginate (10–40% w/w), laminarin (2–34% w/w), mannitol (5–25% w/w), and fucoidan (5–20% w/w) [41]. The ultimate composition of *Laminaria* changes in the range of 26–37 C (% w/w), 4–6 H (% w/w), 1–4 N (% w/w), 30–35 O (% w/w), and 0.6–0.9 S (% w/w). Its HHV ranges between 10 and 15 MJ/kg [42].

Previous HTL studies with *Laminaria* sp. recommended an earlier recovery of proteins and carbohydrates to improve bio-oil quality [43]. That is in line with other studies that propose an excellent path for the positive economic balance of seaweed HTL by obtaining value from other subproducts [44].

The presence of protein and carbohydrates in biocrude can harm bio-oil quality due to the introduction of significant amounts of oxygen and nitrogen [45]. Under hydrothermal conditions, these components can degrade and produce toxic substances such as furfural, hydroxymethyl furfural, and complex aromatic compounds [46]. Notably, carbohydrates exhibit a negative energy balance and can act as emulsifiers, posing challenges in separating desired end products from the aqueous and organic phases [43].

In addition, carbohydrates lead to a higher production of water-soluble products under hydrothermal conditions compared to other biochemical fractions [47]. Extracting and recovering specific carbohydrate compounds is advisable to tackle these concerns and streamline the process. This approach improves the overall product quality, reduces the production of water-soluble products, and facilitates the development of an algal biorefinery [43].

Alginate is a gelling agent found and extracted from brown seaweed (e.g., *Ascophyllum* sp., *Laminaria* sp., *Lessonia* sp., and *Macrocystis* sp.). It is the most abundant marine biopolymer and, next to cellulose, the most abundant biopolymer in the world [48]. Furthermore, it is used as a stabilizer in many food products. It is also used in the food industry as a thickener and emulsifier for sauces, dressings, and jams, and it needs no heat to gel [48]. Furthermore, alginic acid decreases cholesterol concentration, exerts an antihypertension effect, can prevent the absorption of toxic chemical substances, and plays a significant role as dietary fiber [49]. In addition, commercial sodium alginate also inhibits putrefactive compounds and has antibacterial, anti-inflammatory, and anticancer properties [50].

Among the innovative techniques currently being researched for alginate production, sub-critical water extraction (SWE) stands out for its distinctive ability to harness the adjustable solvent properties of water. This enables the extraction process to achieve peak efficiency while avoiding employing aggressive organic solvents [51].

Furthermore, due to the considerable potential of the solid waste produced by the fish processing industry to deliver a satisfactory bio-oil quality [52], a co-liquefaction of kelp and fishing wastes can enhance the bio-oil yield. From the whole fish, the fish processing industry can separate the fillets, the head, the frame, the viscera, and the skin. The four components that participate in their composition are moisture, proteins, fat, and ashes. For example, for the pollock species (with 8% moisture content), the whole fish has 66% w/w of proteins, 16% w/w of fat, and 11% w/w of ashes. In more detail, the fillets and the skin have the highest protein content (85–88%), the viscera have the highest fat content (48% w/w), and the head and bones have the highest ash content (14–20% w/w) [53]. Those values should be considered when evaluating the yields in the HTL process according to the final product composition.

This study assesses the economic viability of producing bio-oil using seaweed through a hydrothermal liquefaction (HTL) process in the community of New Stuyahok. The average load of the town is 237 kW, with a peak of 432 kW and an average daily load demand of 5686 kWh [54]. The community's dependence on fuel means it has to be transported over extensive distances, including sea and air transport. Aside from Alaska's rising seaweed market, the state is notorious for its significant ocean fisheries. Therefore, this study explores the integration of byproducts from the fishing industry to address potential constraints associated with utilizing kelp biomass, an aspect that has not been previously investigated.

2. Methods

2.1. Sequential Hydrothermal Liquefaction (SEQHTL) Process

Figure 1 presents a flow diagram of the proposed process. A kelp biochemical composition (on a dry basis) of 40%, 12%, and 1% for carbohydrates, proteins, and lipids, respectively, is assumed. The kelp biomass is milled and slurried. The first step uses low-temperature hydrothermal retreatment (at 120 °C, 4 MPa, and 5 min), in which water extraction of alginate is performed to recover 15% of the yield, following [51]. Although mannitol and other carbohydrates can be recovered, more experimental data are needed to consider their extraction in this first step. Then, residual kelp biomass is mixed with fish waste slurry and co-liquefied at 240–250 °C and 22 MPa for 15 min to produce bio-oil, syngas, biochar, and an aqueous phase [43]. Finally, the bio-oil is upgraded by hydrotreating to market-ready renewable diesel [55]. This study assumed a bio-oil yield of 21% w/w for kelp biomass. Related to fishing waste, a biochemical composition (on a dry basis) of 32%, 38%, 10%, and 20% for carbohydrates, proteins, lipids, and ashes, respectively, is assumed. A yield of 55% w/w is considered, following the results found by Conti et al. (2020) [56], where better results were found in supercritical conditions in comparison with subcritical conditions.

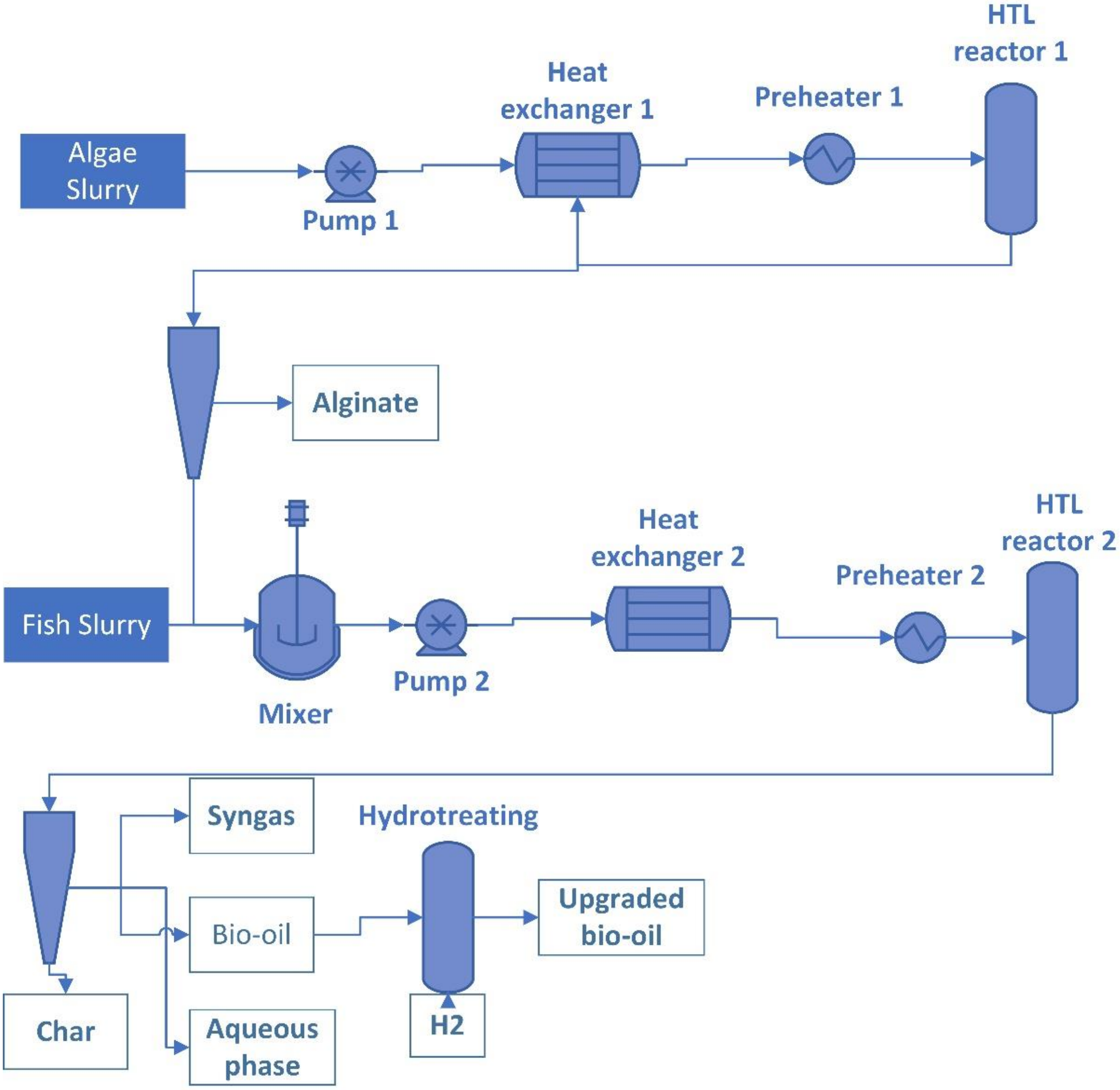

Figure 1. Sequential hydrothermal liquefaction (SEQHTL) process with kelp and fish slurries as feedstock.

2.2. Cost–Benefit Data Inputs and Assumptions

This section presents technical and economic data for a financial assessment of bio-oil production in New Stuyahok (Alaska) via the HTL process using debris flows, considering seaweed and fish waste biomass as feedstock. It was performed based on estimations and assumptions from the literature, the state of the art of the HTL process, and the use of these two feedstocks. Table 1 shows the allocation of diesel expenses for electricity production and the average cost of this energy vector in Alaska's market.

Table 1. Energy rates by fuel type in New Stuyahok [57].

Description	Average Energy Cost
Electricity	0.61 USD/kWh
Diesel	1.722 USD/L

In addition, Kouhgardi et al. (2023) [58] established that according to the end use, the price of the seaweed subproducts might vary, considering here the cost as 236 USD/t in the case of chemical uses.

New Stuyahok is a remote rural environment [59,60], accessible only by boat or plane [61], where the main economic base is salmon fishing [61]. New Stuyahok is almost 500 km from Anchorage and entirely off the road network [62].

The conceptual configuration of the required equipment involves the co-location of the seaweed processing facilities with the existent fish processing equipment so that transport and offloading can be carried out utilizing the same harbor installations employed by the fish processors, reducing those costs.

The introduced costs are inherently uncertain due to the absence of specific processes in the market. We have made several assumptions to determine their impact on the resulting parameters to address these uncertain values and enhance our analysis. Table 2 displays the primary data utilized during the evaluation.

Table 2. Inputs and suppositions for the techno-economic analysis of a hydrothermal liquefaction process.

Assumption	Value	Source
Size of plant	50,000 kg per day	[63–67]
Annual days of operation	250 days per year	[68–72]
Cost of hydrothermal liquefaction capital	USD 13,250,000	[73,74]
Labor cost	USD 200,000 per year	[75–77]
Maintenance cost	USD 420,000 per year	[78–80]
Energy cost per kWh	0.61 USD/kWh	[57,81]
Energy amount required per kg raw material	0.35 kWh/kg	[82]
Discount rate(s)	9%	12% is the minimum internal rate of return typically used for any private infrastructure project subject to formal economic evaluation [83,84]; and 6% is conventionally used for publicly funded projects [85].
Federal tax rate	21%	In the US, corporate taxable income is subject to a flat rate of 21% [86].
Alaska State tax rate	9.4%	Alaska imposes a corporate income tax on business income, with rates of 9.4% for taxable income brackets at or above USD 222,000 [87].
Tax depreciation system	7-year MACRS	The 7-year modified accelerated cost recovery system (MACRS) depreciation is a federal income tax convention that benefits businesses by helping them plan for the decline in value of, among others, agricultural machinery and equipment over a given period [88,89].
Lifetime	30 years	[90–93]

Table 2. *Cont.*

Assumption	Value	Source
Kelp		
Kelp cost per unit	200 USD/dry t	[39]
Yield of alginate	15%	[51]
Yield from kelp (% ash-free dry weight)	21%	[94]
Fishing Waste		
Fishing waste cost per unit	0 USD/kg	
Yield from seafood waste (% ash-free dry weight)	55%	[56]
Upgrading		
Yield from hydrotreating	98%	[95,96]
Hydrogen consumption	0.043 kg H_2/kg biocrude	[95,96]
Cost of hydrogen gas	5 USD/kg	[97]
Price of alginate	236 USD/t	[58]

2.3. Simulation Method

The NPV of the investment is the difference between the present value of the benefits and the costs resulting from the investment. More specifically, the NPV is defined as the present value equivalent of all cash inflows less all cash outlays associated with a project. If the NPV is positive, the project is economically worthwhile. If the NPV is negative, it indicates a financial loss. If the NPV is zero, the present value of all the benefits over the useful lifetime equals the present value of all the costs. The NPV method converts payments in the future to present values and makes them comparable. The NPV method can be expressed mathematically according to Equation (1):

$$NPV = -I + \sum_{i=1}^{i=n} \frac{B_i - C_i}{(1+r)^i} \tag{1}$$

where “I” is the initial outlay (investment), “i” is the actual year, “B_i” is the annual benefits, “C_i” is the yearly costs of the period “i”, “n” is the useful life of the project, and “r” is the discount rate.

When computing the NPV, the underlying assumption is that across all years, the benefits primarily comprise the revenue generated from fuel sales (1322 USD/kg). The costs are the operating expenses, including labor, maintenance, energy, chemical products, raw materials, and taxes paid. A discount rate of 9% is used.

The net present value calculation has certain disadvantages. One is that it does not consider future cash flows’ risk or uncertainty. On the other hand, cash flows can be unpredictable and subject to unforeseen changes depending on external factors beyond our control. For this reason, an NPV sensitivity analysis has been carried out, which will indicate the variables that most affect the economic result of a project and those that have little impact on the outcome. The sensitivity must be determined with respect to the most uncertain parameter. In this study, the possibility of changes in benefits, costs, and investments was considered. Therefore, it was determined how sensitive the NPV is with respect to benefits, costs, and the necessary investments. The NPV and sensitivity analysis were calculated in a Microsoft Excel spreadsheet.

For the SWOT analysis, a large variety of economic, social, sustainability, and environmental aspects were addressed.

3. Results and Discussion

This section assesses the financial feasibility of utilizing seaweeds for fuel manufacturing and consumption in a sea-dependent community such as New Stuyahok, Alaska. Alaskan seaweed varieties are being cultivated to supply inputs to food production companies. When these markets expand, the Alaskan seaweed trade will increase. Alaska's economy and its sea-dependent local society would benefit from gaining proper knowledge of the seaweed processing industry instead of merely growing and harvesting seaweed and transporting it to another place for food purposes. This research work is targeted individually at the village of New Stuyahok, Alaska.

Literature values were adapted and used for the techno-economic analysis. This paper acknowledges that achieving a positive outcome in modular fuel product manufacturing, conducting thorough feedstock characterization of residual products, and pursuing further advancements are essential prerequisites to successfully introducing these products to the market.

The production of bio-oil and renewable diesel, according to the flow diagram from Figure 1, was calculated in three different scenarios based on the feedstock ratios of kelp and fishing waste (on a dry basis): (1) using only kelp as raw material, (2) using a 50:50 fishing waste/kelp mass ratio as raw material, and (c) using a 70:30 fishing waste/kelp mass ratio as raw material. If 12,500 t of raw material is treated annually, a mass flow of bio-oil and the corresponding renewable diesel would be obtained, as shown in Table 3 for each of the scenarios under study.

Table 3. Results of the techno-economic analysis.

	Kelp Only	**Fishing Waste and Kelp (50:50)**	**Fishing Waste and Kelp (70:30)**
Bio-oil (t/year)	2625	4750	5600
Diesel equivalent produced (t/year)	2573	4655	5488
Alginate (t/year)	1875	938	563
Net present value, NPV (M USD)	−23.6	−5.5	+1.71

The analysis shows that the net present value (NPV) exhibits a positive magnitude only when increasing the fishing waste/kelp mass ratio up to 70/30. This can be ascribed to the constrained output yield of the kelp biomass and the relatively negligible influence exerted by alginate production on NPV.

Figure 2 shows a sensitivity analysis of the three scenarios. The benefits, costs, and investment variables have been modified in the range between −20% and +20%. As stated, the NPV values become positive at a 70:30 ratio of fishing waste and mixed kelp (Figure 2c). In addition, there are two zero values at the 50:50 ratio (Figure 2b): if benefits are increased by 12.1% or if costs are reduced by 13.5%. No positive values were found when using solely kelp biomass (Figure 2a).

It has been detected that in many cases, the cash flows are positive, but the initial investment to be made is so high that, in principle, the projects are not considered profitable. High initial investment costs are a significant barrier to implementing HTL technology. Despite rising oil prices, the initial investment is relatively high, which may discourage the implementation of the technology. Therefore, investment grants or technology transfer tax credits, low-interest loans, or subsidies could be a practical policy approach to promoting the adoption of this technology. Energy transition policies, exemplified by the paths taken by Finland and various other European nations in favor of advancing biomass usage over fossil fuels, possess the potential to alleviate existing limitations that impede growth within this sector. Carbon taxes and investment subsidies are proven policy instruments that could facilitate the quick adoption of HTL technology. It will provide regional energy security and community vulnerability protection while at the same time yielding demonstrable environmental benefits by displacing oil. HTL technology has very low commercial maturity, and therefore further research will be required from the technical side.

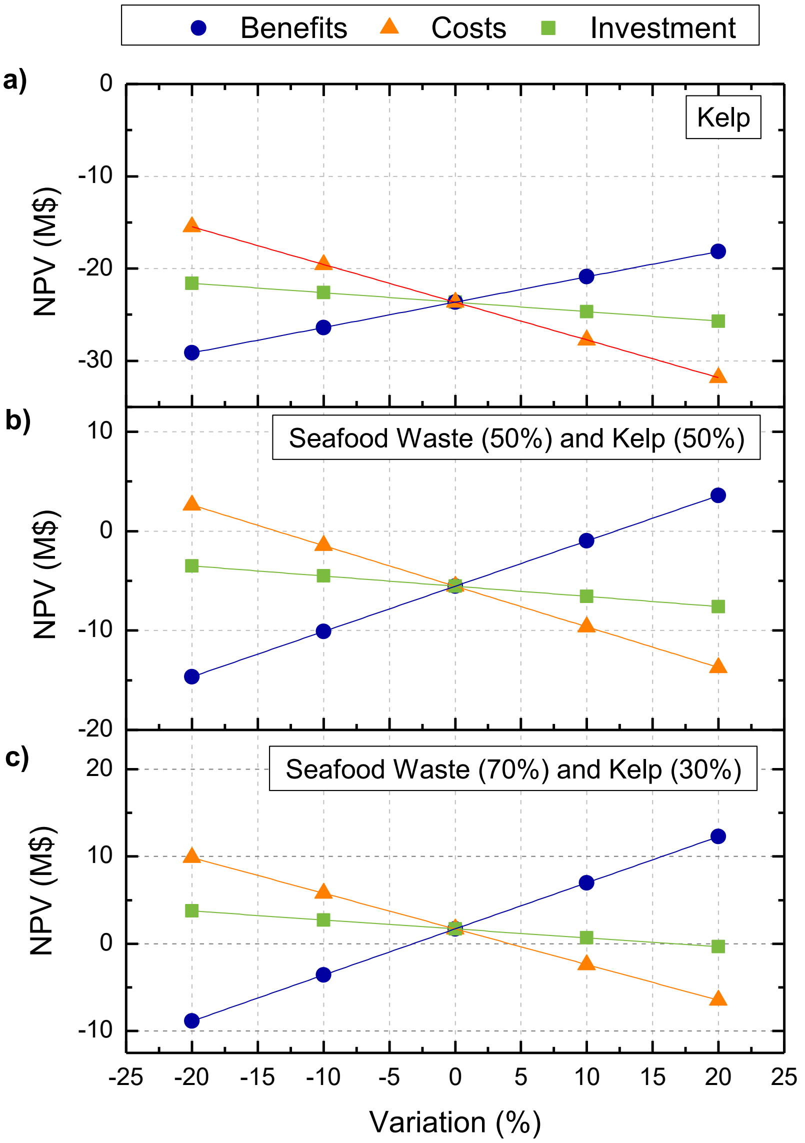

Figure 2. Sensitivity analysis for the net present value concerning benefits, costs, and investment using as feedstock: (**a**) kelp (100%), (**b**) combined seafood waste and kelp (50:50), and (**c**) combined seafood waste and kelp (70:30).

Moreover, to increase the benefits of a plant producing diesel from hydrothermal liquefaction, it is crucial to improve the efficiency of the plant, increase production, and find ways to maximize the value of the final product. This can be achieved by optimizing plant processes, such as adjusting temperature, pressure, and residence times in hydrothermal liquefaction. It is also essential to explore pretreatment technologies to improve product quality and diversify products such as light fuels, lubricating oils, and chemical products. Additionally, researching market opportunities, such as demand for renewable diesel and business collaborations, can help maximize revenue. Lastly, improving waste management through recycling and power generation measures can reduce associated costs and generate additional revenue.

Table 4 shows a SWOT analysis of the hydrothermal liquefaction of fishing waste and kelp as a promising technology for valuable products and biofuel production. This analysis evaluates this innovative process's strengths, weaknesses, opportunities, and threats. By understanding these factors, stakeholders can make informed decisions and develop strategies to maximize the potential of hydrothermal liquefaction in the context of fishing waste and kelp utilization in Alaska.

Table 4. SWOT analysis.

Strengths	Weaknesses
• Turning waste into a source. • Using locally available materials for energy. • Scalable solutions form communities of different sizes and rural/urban. • Solutions can be combined to amplify benefits (wood, food). • It can extend the lifespan of landfills. • Seaweed biofuel can fix greenhouse gas (CO_2) by photosynthesis and does not compete with food production.	• High capital investment in equipment. • High transportation cost forces a trade-off between more infrastructure (more facilities) and longer transport to a central location. • Lack of infrastructure for waste collection system.
Opportunities	**Threats**
• Capturing value from waste products like fish waste, food scraps, and wood chips. • Additional jobs are created as more complex waste recovery systems are implemented. • Climate benefits. • Simultaneous processing of heterogeneous organic material.	• The temporal discrepancy between waste availability and its utilization, considering the associated storage expenses. • Lack of technical support and training to operate complex equipment and systems. • Sensitize the population for the separation of waste. • Technological maturity and demonstration scales.

4. Conclusions

The present study investigates the prospective utilization of kelp biomass and fishing waste via HTL in a region with considerable production capabilities, namely the village of New Stuyahok in Alaska. This region boasts accessible kelp from aquaculture, albeit still in the developmental stages, alongside byproducts from local fishing industries. Incorporating this waste material into the process ensures a minimal cost for the fishing waste component. Using New Stuyahok's natural resources for biomass helps overcome fuel availability limitations. The HTL process, coupled with refining techniques, has been chosen as the technology of interest because of its ability to handle biomass with varying water content. This adaptability paves the way for leveraging these specific biomasses. While the technology is undergoing technical refinement, this study aimed to assess whether the proposed approach presents favorable prospects for the local community. Using a 30:70 kelp-to-fishing-waste ratio creates a positive NPV in a simple model. Positive NPV outcomes can be achieved with a 50:50 ratio under conditions where production costs decrease by 13.5% or benefits increase by 12.1% compared to the baseline scenario. It is important to acknowledge the study's limitations, originating from the technology's current level of maturity and the absence of real-scale data. Nevertheless, this study functions as a guiding reference that identifies challenges and vulnerabilities that the technology and feedstock combination must overcome to ensure successful implementation in the immediate future.

Author Contributions: Conceptualization, E.R.-A.; Methodology, E.R.-A.; Validation, E.S.-M., N.G.-M. and C.S.; Formal Analysis, E.S.-M.; Investigation, E.S.-M. and N.G.-M.; Data Curation, E.S.-M.; Writing—Original Draft Preparation, E.R.-A. and E.S.-M.; Writing—Review & Editing, E.S.-M. and N.G.-M.; Visualization, N.G.-M., A.P.-A. and C.S.; Supervision, N.G.-M., A.P.-A. and C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflict of interest.

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