PNNL-31092

Kelp Energy Products and Marine Renewable Energy for Coastal Alaska Communities

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Abstract

This document summarizes the results of a U.S. Department of Energy (DOE)-sponsored project conducted to understand, evaluate, and address the challenges related to kelp processing and alternative off-season use of the seafood industry capacity in Alaska, and address the potential use of marine renewable energy (MRE) systems to provide the necessary power for potential unit operations associated with kelp processing.

The report describes potential energy conversion processes for kelp and fish waste followed by a techno-economic and life cycle analyses for these processes. An initial aquatic ecological assessment for Southwest Alaska that outlines location-specific aquatic ecologic assessments that will be required to address the influence of kelp farming on the marine ecosystem. A kelp compositional analysis was conducted on samples of several commercial food-grade kelp as well as local samples of Alaskan kelp. A world survey of kelp cultivation was included to provide information regarding the kelp industry around the world. Finally, an initial assessment of the co-development of marine renewable energy and kelp processing capabilities in Southwest Alaska.

Summary

This document summarizes the results of a U.S. Department of Energy (DOE)-sponsored project conducted to understand, evaluate, and address the challenges related to kelp processing and alternative off-season use of the seafood industry capacity in Alaska, and address the potential use of marine renewable energy (MRE) systems to provide the necessary power for potential unit operations associated with kelp processing.

It is viewed quite widely, and this report assumes, that Alaska will have a thriving kelp industry within the next 5 to 10 years that has the potential to not only lead the United States in kelp production for food (initially), but also become a significant leader in world kelp production with additional non-food products, including fertilizers, biochemical and food additives, as well as rare-earth elements. However, this report provides another view of how the Alaska kelp industry could additionally capitalize on the use of fish waste, existing fish processing facilities, and MRE concepts to provide additional value and benefit for energy and other products for coastal Southwest Alaska communities. While additional study is needed, Alaska communities in the Southwest Alaska Municipal Conference (SWAMC) region, and others, could derive significant economic benefits from such a symbiotic relationship.

A SWAMC needs assessment, based on a questionnaire sent to project Steering Committee members early during the project, identified needs and outcomes of interest to the communities, as listed below. They are followed by key project findings and recommendations.

Key Needs and Outcomes for SWAMC Communities

- Identify processes and products that sustainably unlock economic activity for new kelp farming and processing that benefit the isolated coastal communities in the SWAMC region.
- Identify species of kelp whose characteristics have the greatest market value to Alaska and associated production processes that have the lowest environmental impacts.
- Identify synergies with existing fisheries and community infrastructure, including waste streams (e.g., fish processing waste, solid municipal waste) along with kelp coproducts as a potential local viable energy source.
- Identify new products and processes appropriate for small-scale and entry-level kelp farmers to develop and bring to market, emphasizing the need for opportunity for community input for mariculture development.
- Create an educational system to grow the awareness and skills to expand the industry.

These needs and stakeholder outcomes helped to focus the work of this effort. Although the last two items are highly important, the scope of this project effort was limited to the first three items.

Key Findings

The co-processing of kelp waste from food processing along with fish waste appears to be viable from a technological, economic, and life cycle perspective and could provide significant economic benefit to remote coastal communities in Alaska.

- **Energy Conversion Processes** – It is feasible for fish processing facilities idle during the off-season to be used for kelp processing, which would leverage facility and equipment infrastructure. It may be reasonable to repurpose fish processing equipment to be used also

for kelp processing. However, hurdles to be overcome include adapting equipment for a different feed material and managing risks, such as the contamination of food-handling equipment. Alternatively, mobile modular kelp processing equipment could be installed and removed from the facility or co-located at the same site, thereby enabling the use of facility infrastructure including power, water, logistics, and waste handling.

- **Techno-Economic Analysis** – The financial metrics of Alaska biodiesel production via a modular hydrothermal liquefaction (HTL) process using kelp improve with the addition of seafood processing waste from well-established seafood processors in Alaska. Configuring existing or new processing plants to capture and use the seafood waste along with processing the kelp waste stream appears to have economic potential. Depending on the opportunity cost of the capital used, the break-even price of biodiesel using a modular Alaska HTL process would range from $3.18–$3.64 per gallon.
- **Life Cycle Assessment (LCA)** – A cursory assessment indicated that bioenergy produced via anaerobic digestion (AD) and HTL using combined feedstocks from kelp waste, from food processing, and fish waste results in reduced greenhouse gas emissions compared to conventional fossil fuel use in Alaska coastal communities. Bioenergy production using only kelp cultivated specifically for energy is not environmentally preferable.
- **Aquatic Ecology Assessment in Southwest Alaska** – Location-specific aquatic ecologic assessments will need to be performed in Southwest Alaska to assess the potential influence of kelp farming on the marine ecosystem. Species that are federally listed, as well as critical and essential fish habitats in Southwest Alaska are well-known. A suggested framework could be used to determine the aquatic species and habitat that may be affected by kelp harvesting.
- **Kelp Compositional Analysis** – Compositional analysis of commercial food-grade kelp and Alaska kelp was conducted. Additional analysis was hampered by the COVID-19 pandemic, and additional site-specific analyses at different times of the season should be conducted.
- **Kelp Asset World Survey** – Kelp cultivation is concentrated in eastern Asia—particularly China, North and South Korea, and Japan—and accounts for more than 99 percent of all the kelp grown in the world. However, efforts elsewhere in the world are growing. Several European countries are looking to grow a few species of kelp. All this indicates the viability of a robust kelp market.
- **Co-Development of Marine Renewable Energy and Kelp Processing Capabilities** – While significant marine energy resource is available at the scale needed for kelp processing, transmission remains a large barrier to production of marine energy in coastal Alaska. To take full advantage of marine energy, processing facilities need to be as near as possible to renewable energy resources.

Recommendations

Based upon the research that was conducted and discussions of results with the SWAMC Steering Committee, several recommendations have been agreed upon and are listed below.

- Additional work should be conducted by choosing several specific coastal communities in Alaska for which to provide more detailed analyses of carefully considered use cases that would reduce the uncertainties of site-specific potential demonstration costs.
- Because of the COVID-19 pandemic, the project team had limited ability to engage in discussions directly with the fish processing companies to begin to understand their views

about co-processing of kelp and fish waste. Processing facilities are different and unique, so conducting detailed discussion with several processors would be of tremendous benefit.

- Additional characterization and compositional analysis of Alaska kelp should be conducted. Because of COVID-19 pandemic challenges, the number of samples was greatly reduced from what was originally hoped for at project outset.
- Other remote communities in Alaska, including several in Southeast Alaska, should be considered for future study. This could include similar efforts for energy processing.
- Additional study for other potential new and diverse kelp products should include recent interest in replacement of manufactured plastics for packaging and traditional uses.
- The Alaska kelp supply chain gaps should be assessed to determine the overall cost and other key parameters, including logistics, energy, and labor implications.
- Technical roadmapping should be conducted to establish the goals and potential technology solutions related to the development of a thriving kelp industry in Alaska.

Acknowledgments

First and foremost, the authors of this report acknowledge the U.S. Department of Energy—in particular, the Energy Efficiency and Renewable Energy's Advanced Manufacturing Office and the Water Power Technologies Office—for providing the necessary funding for this effort.

The stakeholder organization, represented by the Southwest Alaska Municipal Conference (SWAMC), was well engaged throughout the entire project, even after the COVID-19 pandemic created several roadblocks most of which the Pacific Northwest National Laboratory (PNNL) research team was able to eventually overcome. In particular, thanks go to SWAMC Executive Director Shirley Marquardt and Economic Development Specialist Laura Vaught.

The PNNL research team received Alaska kelp samples from Blue Evolution, who also provided a significant cost share to the project. Chief Executive Officer Beau Perry was instrumental in ensuring that their samples were shipped. This was especially challenging during the pandemic.

Additional kelp samples were received from Seagrove Kelp. Chief Scientist and Research Director Dr. Tiffany Stephens was instrumental in providing their samples.

One portion of the research project was focused world kelp asset mapping, and thanks go Melissa Good, the University of Alaska Sea Grant Marine Advisory Program leader who provided guidance for that effort.

Thanks also go to several PNNL staff, as well as students and former staff members who supported the overall effort: Grace Pennell, Andrew White, Madison Moore, Hayley Farr, Mikaela Freeman, Li-Jung Kuo, Angelica Bautista, Scott Edmondson, Brady Anderson, and Ian Leavy.

Special thanks especially go to Erik O'Brien, a program manager for the Denali Commission, and one of the primary motivators for this effort. His support in the original proposal effort and his unending energy to support Alaska economic development is truly amazing.

Acronyms and Abbreviations

ACS	American Chemical Society
AD	anaerobic digestion
ACEP	Alaska Center for Energy and Power
ADFG	Alaska Department of Fish and Game
AMO	Advanced Manufacturing Office
AMPP	Alaska Manufacturers Business Pilot Project
ANRE	Agency for Natural Resources and Energy
BCR	benefit-to-cost ratio
CA	cellulose acetate
CAPEX	capital expenditure(s)
CCV	Continuing calibration verification
CHP	combined heat and power
CO	carbon monoxide
CO2eq	carbon dioxide equivalent
DGE	gallon of diesel equivalent
DOE	U.S. Department of Energy
DPS	distinct population segment
EERE	Energy Efficiency and Renewable Energy
EFH	essential fish habitat
EIO	Economic Input-Output
ESA	Endangered Species Act
EU	European Union
FAO	Food and Agricultural Organization
GHG	greenhouse gas
GWP	global warming potential
HAB	harmful algal bloom
HAPC	Habitat Areas of Particular Concern
HASQARD	Hanford Analytical Quality Assurance Requirements Document
HDPE	high density polyethylene
HHV	higher heating value
HTL	hydrothermal liquefaction
ICV	initial calibration verification
IDL	Instrument Detection Limit
IEA	International Energy Agency
KEEI	Korea Energy Economics Institute
KNREC	Korea New and Renewable Energy Center

LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
MACR	Macroalgae Cultivation Rig
MACRS	Modified Accelerated Cost Recovery System
MBTU	million British thermal units
MDL	Method Detection Limit
MEC	Marine Energy Conversion
MFSP	Minimum Fuel Selling Price
MHK	marine and hydrokinetic
MMPA	Marine Mammal Protection Act
MPE	Ministry of Petroleum and Energy
MRE	marine renewable energy
MSA	Magnuson-Stevens Fishery Conservation and Management Act
MT	metric tonne(s)
NH_3	ammonia
NOAA	National Oceanic and Atmospheric Administration
NOx	oxides of nitrogen
NPV	net present value
NREL	National Renewable Energy Laboratory
OPEX	operating expenditure(s)
PCE	Power Cost Equalization (Program)
PCF	product carbon footprint
$PM_{2.5}$	particulate matter less than 2.5 microns in diameter
PM_{10}	particulate matter less than 10 microns in diameter
PNNL	Pacific Northwest National Laboratory
PSA	Pressure Swing Absorption
rpm	revolutions per minute
SME	subject matter expert
SO_2	sulfur dioxide
SWAMC	Southwest Alaska Municipal Conference
SC	Steering Committee
TEA	techno-economic analysis
USDA	United States Department of Agriculture
VOC	volatile organic compound
VS	volatile solid
WPTO	Water Power Technologies Office

Contents

Figures

Tables

1.0 Introduction

This document summarizes coordinated projects sponsored by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE's) Advanced Manufacturing Office (AMO) and a seedling project sponsored by DOE's Water Power Technologies Office (WPTO). The research team is led by Pacific Northwest National Laboratory (PNNL) and includes expertise in advanced processing technologies, techno-economic analysis, life cycle assessments, environmental sciences, and characterization of various biological materials. In addition, a Post Bachelor from the University of Alaska was contracted to survey kelp processing activities worldwide, and the Ohio State University provided additional support in the characterization of kelp. Guidance and understanding of specific Alaska coastal community economic challenges was provided by a Steering Committee (SC). The SC is led by the Southwest Alaska Municipal Conference (SWAMC) and includes 12 stakeholders representing Alaska State and local economic development interests, native Alaskans, fish processors, and kelp production interests. The team worked closely with the SC to conduct the two-pronged study of kelp production possibilities in Southwest Alaska from manufacturing and marine renewable energy perspectives.

1.1 Project Purpose and Scope

The EERE AMO portion of the project has the specific aim to understand, evaluate, and address the challenges related to alternative off-season utilization of the massive seafood industry capacity in Alaska to support the processing of kelp for potential value-added products. Such dual-use activities are assessed for their feasibility and potential to decrease downtime, increase productivity, create year-round Alaska jobs, improve environmental performance, and develop new products for the Alaska ecosystem and economy.

The EERE WPTO portion of the project has the specific aim to address the potential use of marine renewable energy (MRE) systems to provide the necessary power for the off-premises unit operations associated with kelp processing. This could be very attractive for several reasons. First, MRE could provide independently integrated power to kelp processing systems that would minimize the impact on the fish processing plants by eliminating the need to modify the existing power infrastructure. Additionally, MRE could provide excess power to the local coastal community grid during the off-kelp season.

To achieve these aims, PNNL technical staff conducted research on modular manufacturing to address the potential need for modular systems for kelp pre-processing as well as additions that may be necessary for intermediate or final processing. PNNL performed a techno-economic analysis to determine the economic efficacy of harvesting and processing Alaska kelp for various use cases. Cursory comparative greenhouse gas life cycle assessments of the proposed infrastructure dual-use options were completed as an indicator of environmental impacts, tradeoffs, and benefits. Marine environmental biologists worked with the SC to understand the unique Alaska coastal environment and describe the challenges to be overcome to ensure that a sustainable parallel kelp industry can improve Alaska's economy. Ongoing kelp characterization efforts and MRE considerations are expected to further inform processing decision-making.

1.2 Report Organization

Each chapter of this report was developed to be a self-contained source of information, so the chapters do not need to be read in sequential order. Because this work was an initial study, the information and analysis are presented to provide stakeholders and other readers with a first look at the co-development of an Alaska kelp industry for energy and other products in conjunction with the existing mature fish processing industry. The ensuing chapters are organized to address some of the challenges and opportunities.

Chapter 2 focuses on the early phase of the project to engage the SWAMC SC and understand the Alaska stakeholder needs that established the basis for much of what the project focused on. Although there were several needs outside the scope of this limited activity, the project focused on the needs that were of highest priority. Appendix B provides details of the SC questionnaire that was used to engage and assess stakeholder needs.

Chapter 3 provides a summary of the types of processes considered for kelp processing for energy and other projects. Three basic processes—anerobic digestion, hydrothermal liquefaction, and fermentation—were considered. The chapter also discusses the use of fish processing facilities for various activities and the use of fish waste as a co-feed for processing. Because of challenges associated with the COVID-19 pandemic, the project team was unable to meet with fish processors to fully discuss the opportunities for fish waste utilization and the use of some of the fish processing infrastructure for processing kelp. However, these aspects were incorporated in the associated techno-economic analysis and the life cycle assessment.

Chapter 4 provides the assumptions underlying the techno-economic analysis including costs, benefits, calculations, and sensitivities. While there is significant uncertainty, the ability to co-process kelp and fish waste has the potential to provide biocrude at a market price in several of the remote coastal communities.

Chapter 5 provides a life cycle assessment that included scenarios of the use of combinations of kelp, kelp waste, and fish waste for processing, using either hydrothermal liquefaction or anaerobic digestion as pathways to a diesel-like fuel or to methane for combined heat and power for local infrastructure, respectively. Additional details of the life -assessment are found in Appendix A.

Chapter 6 provides an ecology assessment of the region of Southwest Alaska. Because seafood and the associated fisheries are such an important cultural and economic value to all Alaskans, it was important to provide an initial assessment of the endangered species along the southwest coast of Alaska as well as their critical habitat that must be considered prior to conducting kelp farming activities. There are both potentially positive aspects and challenges of mass kelp farming in Alaska, so a framework for assessing aquatic resources is presented for use in future studies.

Chapter 7 provides a kelp asset world survey to provide the SC with information about kelp growing, harvesting, and usage worldwide. While many countries publish significant information about kelp, others have minimal information publicly available. Most of the kelp around the world is harvested for human consumption. The cultivation, growing, and harvesting of kelp has increased significantly over the past 50–60 years, especially in Asia, particularly China, South Korea, North Korea, and Japan.

Chapter 8 contains characterization and compositional data derived from work performed at PNNL and Ohio State University on commercial samples (dried) as well as specific Alaska samples that were harvested in 2020 and shipped to PNNL for analysis. Measurements were obtained on several samples from Blue Evolution, a commercial kelp-growing and product development company, which included alginate and fucoidan percentages. In addition, various trace metals and rare-earth element concentrations were measured to see whether additional extraction would be potentially viable for Alaska kelp. Appendix C includes the details from work performed at Ohio State University.

Chapter 9 provides an initial assessment of the co-development of marine renewable energy, fish processing, and kelp processing in remote coastal communities in Alaska. The assessment addressed current energy costs and energy requirements for kelp processing (for food or high-value chemicals) and for biofuel processing. The assessment then addressed both tidal and wave resource assessments and determined how close these resources were to the communities of interest. An initial estimated cost of providing the MRE as well as the cost of transmission infrastructure was derived.

2.0 Kelp Processing and Stakeholder Needs

This chapter summarizes the Alaska stakeholder needs associated with the Alaska Manufacturers Business Pilot Project – Kelp Processing and Product Forms. To effectively provide potential recommendations for kelp processing, it was vital to obtain an assessment of need directly from the stakeholder community. A stakeholder needs assessment was conducted in two primary steps.

The first step was to request information from each of the SWAMC SC members to determine their thoughts pertaining to the needs and the outcomes of kelp processing and economic development. Those needs are summarized as follows:

- Identify processes and products that sustainably unlock economic activity for new kelp farming and processing that benefit the isolated coastal communities in the SWAMC region.
- Identify species of kelp whose characteristics have the greatest market value to Alaska and associated production processes that have the lowest environmental impacts.
- Identify synergies with existing fisheries and community infrastructure, including waste streams (e.g., fish processing waste, solid municipal waste) along with kelp coproducts as a potential local viable energy source.
- Identify new products and processes appropriate for small-scale and entry-level kelp farmers to develop and bring to market, emphasizing the need for opportunity for community input for mariculture development.
- Create an educational system to grow the awareness and skills to expand the industry.

This overall effort focused on the first three SC-identified needs. The last two items are outside of the current scope of the project but are important for the overall success of the Alaska kelp industry.

To address the primary needs identified by the SC, the project team conducted research activities to understand how kelp grown in Alaska near fish processing facilities could be processed efficiently and sustainably to help determine the potential gains in local community economic and labor force development. Furthermore, the project team has undertaken activities to characterize several Alaska kelp species to determine their energy content, as well as other materials of interest such as alginates and rare-earth elements that the kelp uptake from the local marine ecosystem. As the project continues, additional efforts are addressing the integration of kelp processing facilities near fish processing facilities, either as co-processors or to use fish processing waste, or both. The project team is also assessing the possibility of processing a third feedstock of local solid municipal waste streams to address local energy needs as well as local community waste disposal needs.

The second step in the assessment was to understand the population and energy information associated with many of the southwestern Alaska coastal communities so that several use cases and potential processing schemes can be identified for future economic and environmental analyses and feasibility studies. The project team looked at population, energy prices, energy use, and where nearby tidal energy could be integrated into the kelp processing operations, as well as providing communities with an additional source of renewable energy.

A down-selection of communities for potential use cases would be a decision for the SC. The most promising SWAMC communities based upon their diversity of population, energy cost/use, fish processing facilities, and distances from potential tidal energy sources are Adak, Dillingham, Egegik, False Pass, Kodiak, Naknek, and Unalaska (also known as Dutch Harbor).

2.1 Stakeholder Description

As a nonprofit regional economic development organization for Southwest Alaska, SWAMC (https://swamc.org) serves three subregions of Southwest Alaska: the Aleutian/Pribilofs, Bristol Bay, and Kodiak. SWAMC was formed to serve the common interests of the region encompassing the Aleutians East Borough, the Aleutians West Census Area, the Bristol Bay Borough, the Dillingham Census Area, the Kodiak Island Borough, and the Lake & Peninsula Borough. In 1988, municipal leaders from the region forged a partnership to advocate for the needs of rural communities and the responsible development of the region's core economic sector—commercial seafood harvesting and processing. Figure 2.1 depicts the geographical location of SWAMC member communities.

Figure 2.1. Southwest Alaska Municipal Conference Communities.

The large expanse of the Southwest Alaska region relative to its small population increases costs for all aspects of life. At the top of that list is energy, which is expensive due to the cost of developing and maintaining infrastructure and the low population density, which result in the inability to achieve the economies of scale necessary to reduce costs. Use of renewable energy from kelp coproducts and MRE has the potential to offset the high costs of energy, but resources remain largely stranded given current technology and the costs of harnessing and delivering renewable energy. The region has substantial infrastructure devoted to ports, airfields, communities, and fisheries, thereby providing support for transportation, homes, businesses, energy, and, primarily, the fishing industry. The SC for this effort was organized by SWAMC and includes the organizations listed in Table 2.1.

Table 2.1. SWAMC Steering Committee organizations.

Organization	Interest/Expertise
State of Alaska, Alaska Energy Authority	Energy Development, Biomass
Alaska Manufacturing Extension Partnership	Value-Added Economics
Aleutians East Borough	Economic Development, Planning, Mariculture
Kodiak Island Borough	Local Economic Development and Planning
Alaska Oceans Cluster	New Business Formation

Organization	Interest/Expertise
Wild Source, Sun’aq Tribe of Kodiak	Processing Technology
Alaska Marine Conservation Council	Community Development, Fish Processing
OptimERA Inc	Technology Development
Kodiak Kelp Company	Kelp Production
Ecotrust	Regional Distribution Systems
Blue Evolution	Kelp Hatchery and Product Development

Stakeholder needs were gathered using a focused questionnaire from SWAMC to the SC and through continued interactions with the project team. SWAMC provided the questionnaire to all SC members to assess their needs by answering a set of questions focused on outcomes. Appendix B, Section B.1, includes the details of the questions and responses from each of the SC members.

2.2 Evaluation of Energy Needs for SWAMC Coastal Communities

The project team used several sources of information from Alaska to understand the energy costs, uses, needs, locations of fish processors, and sources of marine resources (primarily tidal and wave). This information was evaluated to select three to four representative communities as potential “use cases” for future specific processing and energy options that would benefit the isolated communities in the SWAMC region.

More than 50 communities were evaluated, using data from several sources (AEA 2019; ADFG 2021; Haas et al. 2011) that provided information about each of the communities in the SWAMC region. The information included population, costs of electricity per kilowatt-hour, the total community kilowatt-hours consumed, and the number of registered fish processing facilities, according to the Alaska Department of Fish and Game (ADFG). In addition, the distances of communities/fish processors from significant tidal resources, in terms of currents between 0.8 m/s and 1.0 m/s and those that were greater than 1.0 m/s. It should be noted that the Alaska Power Cost Equalization (PCE) Program Statistical Report (AEA 2019) does not include Kodiak because parts of the island, including the community of Kodiak and Port Lions have access to hydropower and wind energy sources and do not rely on fossil fuel. While the PCE report provides information about communities across Alaska, the project team selected approximately 50 communities that were within the SWAMC region and were considered small isolated coastal communities. The overall results of the analysis are provided in Appendix B.

The results from the community analysis were then reviewed and analyzed for further reduction of potential isolated coastal communities based upon the data that were gathered. The motivation for down-selection was to allow the project team to have three to four examples for which use cases could be generated to allow for the study of diverse communities from a perspective of relative high and low populations and a range of costs per kilowatt-hour as well the amount of energy consumed, while also ensuring that there are one or more fish processing facilities in or near the communities, and addressing the high tidal resources that may be relatively close to the communities. The project team also included Kodiak because it is part of the SWAMC region, and it has a relatively large population. The results of the down-selection are shown in Table 2.2.

Table 2.2.SWAMC community initial analysis and down-selection.

Borough/ Census Area	SWAMC Community	PCE Community Population	PCE Cost per kWh	PCE Total kWh Consumed	AFDG Registered Processor Facilities	Distance (km) to mean tidal current > 1	Distance (km) to mean tidal current > .8
Aleutians West	Adak	308	$1.25	2,138,300	2	28.03	18.37
Dillingham	Dillingham	2572	$0.40	19,143,177	2	0.59	0.93
Lake & Peninsula	Egegik	76	$0.50	621,249	4	84.97	5.35
Aleutians East	False Pass	73	$0.41	722,482	2	3.48	3.11
Kodiak	Kodiak	- Not included in PCE Report -			9	26.12	25.64
Bristol Bay	Naknek	887	$0.32	26,290,460	12	25.41	1.63
Aleutians West	Unalaska	4341	$0.27	53,379,409	6	21.42	20.84

Each of the communities under consideration for further study has a diversity of population, energy costs, as well as energy consumption rates. They also have a diversity of fish processing facilities and distances to potential tidal power resources. All these factors will be addressed such that the use cases and subsequent results will be inclusive of these and other communities.

2.3 References

ADFG (Alaska Department of Fish and Game). 2021. “Commercial Permit and License Holders Listing, https://www.adfg.alaska.gov/index.cfm?adfg=fishlicense.holders.

AEA (Alaska Energy Authority). 2019. “Power Cost Equalization Program – Statistical Report” http://www.akenergyauthority.org/LinkClick.aspx?fileticket=qgKDRJywe2M%3d&portalid=0.

Haas K, H Fritz, S French, B Smith, and V Neary. 2011. *Assessment of Energy Production Potential from Tidal Streams in the United States*, Final Project Report. Georgia Tech Research Corporation, Atlanta, Georgia. DE-FG36-08GO18174.

3.0 Waste-to-Energy Products

Considerable effort has been expended evaluating the potential to convert algae, including macroalgae (kelp) to renewable fuel products. There are two primary challenges with making this an economic proposition. The first challenge is the cost of acquiring the raw material from the ocean, either by harvesting wild kelp or by growing and harvesting kelp from farms. Kelp energy content is 11 to 12 MJ/kg on a dry basis versus 17 to 18 MJ/kg for terrestrial biomass (Roesijadi et al. 2010) and about 42 MJ/kg for crude oil. Kelp has 85–90% water content, so the heating value of raw kelp is only about 1 MJ/kg, which is over an order of magnitude lower than that of crude oil. The relatively low energy content of raw kelp implies that the costs of recovering, transporting, and handling the raw feedstock will be significant.

The second related challenge is the amount of water contained in the raw kelp—85–90% by weight. Producing dry biomass from raw kelp requires more energy than the starting energy content of the kelp. Therefore, the most feasible processes for producing renewable energy are the ones that can take a wet feed stream. Three viable alternative technologies are anaerobic digestion, hydrothermal liquefaction, and fermentation, which produce a methane rich biogas, a bio-oil, and alcohols, respectively. All three require additional processing to produce a drop-in fuel replacement for natural gas or liquid fuels. More is provided on these alternatives below.

Many organizations have proposed a biorefinery concepts for kelp, which may overcome the economic challenges of producing renewable fuels from kelp by producing higher value coproducts. The coproducts help to amortize the costs of acquiring the raw materials and front-end processing, such as cleaning and sorting. Globally, products produced from seaweed include human food, agar, alginate, carrageenan, fertilizers and conditioners, and animal feed that totaled $5.5–6 billion in 2003 (DOE-EERE-BETO 2016). Other possibilities include precious metals, pharmaceuticals, and nutraceuticals. Kelp mariculture is currently nascent in Southwest Alaska and there is significant private and public interest in growing these commercial activities. Consequently, a more tractable scenario for producing biofuels from kelp is to use the waste materials after higher value products are recovered.

Fish products are the largest industry in Southwest Alaska, so there is a commensurate opportunity to use fish processing waste in a waste-to-energy scheme. The concept of waste-to-energy products is illustrated in the diagram in Figure 3.1. The red boxes refer to existing fishing and fish processing operations, while the green boxes refer to parallel operations in harvesting and processing kelp. Both produce waste streams containing substantial organic materials that could be fed to a waste-to-energy process. As mentioned above, the preferred technologies do not produce a drop-in replacement for existing energy products, so additional upgrading is needed to make a saleable product. Alternatively, the product streams could be burned to provide process heat or to generate electric power within the fish or kelp processing plants or provided to the local community for district heating. These alternatives would not necessarily require upgrading, thereby saving upgrading costs. It is beyond the scope of this project to consider the full range of opportunities here and would need to be considered case by case.

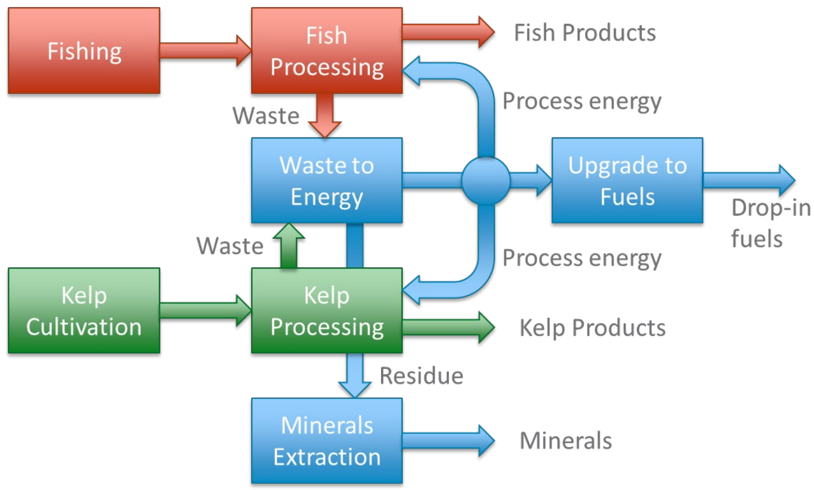

Figure 3.1. Flow diagram of kelp and fish waste-to-fuel scenarios.

The residue from the waste-to-energy process consists principally of inorganic minerals that is a source of other marketable products, including fertilizer and precious metals.

3.1 Energy Conversion Processes

There are many technologies for converting biomass to energy products that are at various stages of development for various feedstocks. Most of them have at least laboratory test data for one or more varieties of kelp, but there is a scarcity of data at the industrial or commercial scale. Furthermore, kelp species vary widely in their composition, so preliminary and pilot-scale testing and development will be needed before deploying any of the technologies.

Kelp has a higher water content than other biomass feedstocks, including microalgae. Kelp also has a high ash content, which is inorganic constituents that cannot be converted to fuels. Examples of ash content of *Macrocystis* (brown), *Laminaria* (brown), and *Gracilaria* (red) are 41%, 26%, and 38%, by weight on a dry basis, respectively. The remainder is referred to as volatile solids (VSs) that consist of primarily proteins and carbohydrates, with relatively little lipids (fats) or lignocellulosics (fiber).

Factors involved in selecting a conversion process include the allowable water content of the feed, the carbon conversion efficiency, and the conversion rate. Because of the high-water content of kelp, processes that can accept higher water content in the feed are preferred. Carbon conversion efficiency—how much carbon content is converted to fuel—determines how much fuel can be produced, which depends on the form of the carbon for a given process. Conversion rate determines the size of the equipment because slower rates mean longer residence time in the process, which is an important consideration for modular systems.

Conversion processes that require dry feeds such as gasification, pyrolysis, and combustion are not considered because of the high cost of drying kelp. Instead, three processes that can accommodate wet feeds are explored further. Anaerobic digestion (AD) produces methane, hydrothermal liquefaction (HTL) produces a bio-oil, and fermentation produces alcohols.

3.1.1 Anerobic Digestion

AD is a process by which bacteria break down organic matter in the absence of oxygen to produce methane in the biogas product. Biogas from AD contains 50–75% methane and most of the remainder is carbon dioxide (CO_2), making it unsuitable as a replacement for natural gas that contains less than 1% CO_2. Nevertheless, biogas can be combusted in a boiler to produce steam for process heat, community district heating, or producing electricity in a turbine.

Biogas can be upgraded to natural gas pipeline grade using commercial gas separation processes. Gas absorption using amines is the dominant process for this separation in the petrochemical industry. Another commercial process is pressure swing adsorption (PSA) using solid sorbents (Chen et al. 2020). Membranes are an attractive technology because of their energy efficiency, compactness, and passive operation, and cellulose acetate (CA) membranes are the most used commercially. However, energy is expended in the separation process, reducing the net energy produced. Gas absorption is a thermal process requiring process heat, while PSA and membranes require a compressor to generate the required pressure. Therefore, it would be more beneficial to use the biogas locally than to absorb the added capital and operating expenditures (CAPEX and OPEX) to make a saleable energy product. Whether to consume the biogas locally or to upgrade it to saleable natural gas is a case-by-case decision.

Yields of methane from kelp and fish vary considerably in the literature. One example provided a conversion rate of 13 kg CH_4/MT wet kelp (Gunaseelan 1997). Values from multiple sources ranged from about 10 to 27 kg CH_4/MT wet kelp. If the kelp contains 30% carbon on a dry basis, 13 kg CH_4/MT wet kelp represents about 22% carbon efficiency. The fuel value of the methane translates to about 5 equivalent gallons of diesel per metric tonne (MT) of wet kelp. At an average value of $2.53/gal diesel in Southwest Alaska, the value of the methane in displacing diesel fuel consumption is about $12/MT wet kelp. This estimate assumes a rate of methane production from kelp, which will be lower after coproducts are recovered, thereby reducing the remaining carbon available for converting to methane. Nevertheless, it provides an upper limit on the energy value that can be expected from AD of kelp.

AD is a relatively slow process that requires from several days up to 2 weeks to process biomass. Consequently, the process requires large tanks to process aqueous slurries of ground kelp and fish waste, and biogas is recovered as it bubbles out of the slurry. Modular AD systems are available commercially. Figure 3.2 shows the HORSE AD25-1 modular system from Impact Bioenergy that is capable of processing 40 T/yr of food waste producing 570 ft^3/d of biogas. Impact Bioenergy also markets a larger-scale system that processes 1,500 T/yr of food waste generating 21,500 ft^3/d of biogas. As with any specific technology, testing with the actual feed stream is necessary to characterize productivity.

Figure 3.2. Impact Bioenergy modular anaerobic digestion system.

3.1.2 Hydrothermal Liquefaction

HTL is a high-temperature (>300°C), high-pressure (200 atm) process for direct conversion of biomass to liquid biocrude. A schematic of a lab-scale HTL system is shown in Figure 3.3 (Elliott et al. 2014). The wet-mill slurry of kelp is fed at about 5–20% by weight to a 1 L reactor, and the reaction occurs in less than an hour of residence time. After cooling, the product stream separates into three phases: a gas phase, an oil-rich phase, and an aqueous phase. Carbon yields of over 50% in the bio-oil have been accomplished.

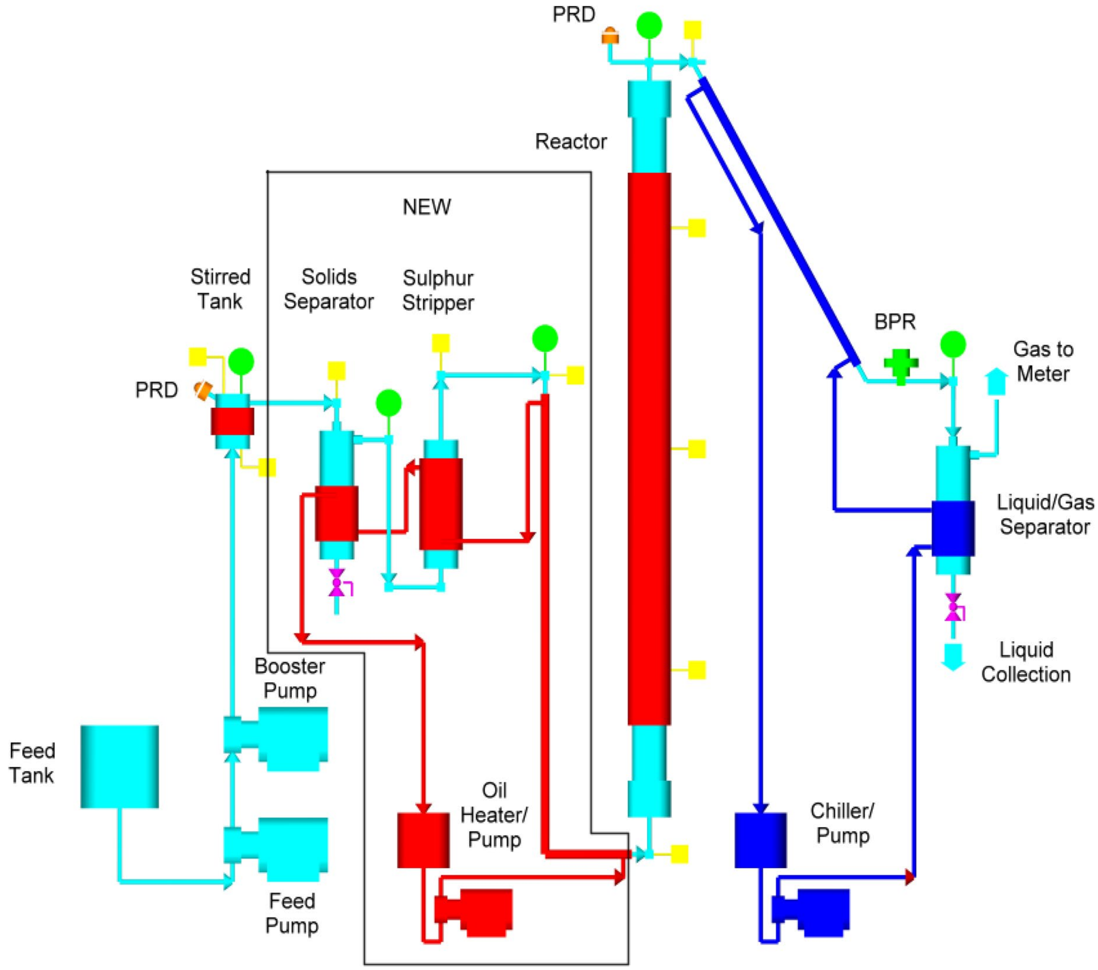

Figure 3.3. Schematic of a bench-scale continuous-flow reactor system. PRD is pressure relief device, BPR is back pressure regulator, yellow squares represent thermocouples, and green circles are pressure sensors.

HTL bio-oil is typically high in oxygen and nitrogen compounds and is not stable. In the case of processing *Saccharina*, the biocrude was a deoxygenated viscous oil. When the carbon compounds in the aqueous phase were added, carbon conversion was over 90%.

HTL biocrude typically requires further refining to make a replacement liquid fuel, like biodiesel, and a process such as solvent extraction is needed to recovery aqueous phase carbon. Oil refinery processes are typically required, such as hydrotreating to remove oxygen and sulfur. Upgrading HTL biocrude adds significant complexity to the overall plant, making it more challenging for smaller plants to be economical. Alternatively, the research (Elliott et al. 2014) demonstrated catalytic hydrothermal gasification of the product to make a fuel gas containing about 60% methane and 40% CO_2, percentages similar to AD, which then could be upgraded to natural gas, as before. This may be the most tractable route to a commercial fuel product. Alternatively, the HTL biocrude or biogas can be combusted in a boiler to produce steam for process heat, community district heating, or producing electricity in a turbine.

The HTL residual solids were high in nutrients, particularly nitrogen and phosphorus that could be recovered and marketed as fertilizer.

The reasonable processing times and relatively simple overall process make HTL amenable to modularization, although commercial systems are not yet available off-the-shelf. One Danish company, bio2oil, is intent on providing decentralized HTL technology. Currently, deploying HTL technology for kelp requires test and process development for a given kelp species and pilot-scale demonstration.

3.1.3 Fermentation

Fermentation is a third alternative for converting kelp biomass to fuel products, most commonly ethanol. The low lignan content of kelp makes it a good feed material for fermentation, but pretreatment is important to break down complex carbohydrates into fermentable sugars in order to obtain a high yield (Ghadiryanfar et al. 2016). Pretreatment methods include acid hydrolysis, saccharification, or enzymatic hydrolysis. Some sugars are not easily fermented, and pretreatment can create inhibitor compounds that lower yields. The appropriate combination of pretreatment and yeast selection must be selected to maximize yield. Obtaining 50% of the theoretical yield of ethanol from biomass is considered ambitious (Milledge et al. 2014), although higher yields have been obtained in the laboratory.

A significant challenge to obtaining an ethanol product from fermentation is the separation of dilute ethanol from the fermentation broth. This is commonly accomplished with distillation, an energy-intensive process. Furthermore, ethanol forms an azeotrope with water, which limits the ethanol concentration to less than 96% ethanol with conventional distillation. Extractive distillation is commonly used to break the azeotrope to produce higher concentrations, but this adds another solvent and additional process steps. Nevertheless, ethanol is successfully produced commercially from land-based biomass, such as corn.

Another option is to produce higher alcohols, such as butanol, which has a higher energy density and is more readily recovered from the fermentation broth. So far, butanol yields from kelp are low and significant improvements are needed to make butanol production economically feasible (Milledge et al. 2014).

Industrial-scale fermenters are readily available, such as the Solida Biotech equipment shown in Figure 3.4. Residence times are similar to those needed for AD, typically multiple days. Consequently, fermentation is a process that can be modular, but the equipment tends to be relatively large.

Figure 3.4. Solida Biotech industrial-scale fermenters.

3.2 Co-use of Fish Processing Facilities

It has been proposed that fish processing facilities that are idle during the off-season could be used for kelp processing, which would leverage facility and equipment infrastructure and save on capital expenditures for establishing independent kelp processing facilities. This is envisioned to occur in one of several ways. It may be possible to repurpose fishing processing equipment to be used also for kelp processing. However, hurdles to be overcome include adapting equipment for a different feed material and managing risks, such as contamination of food-handling equipment. Alternatively, mobile modular kelp processing equipment could be installed and removed from the facility or co-located at the same site, enabling the use of facility infrastructure such as power, water, and waste handling. The feasibility of this approach depends on the scale of the kelp processing systems. For example, the Impact Bioenergy system shown in Figure 3.2 could reasonably be moved in and out of a facility or positioned outside, but a larger-scale AD system would not be amenable to portability and would need a fixed location.

This proposition has been explored in a demonstration project that used a fish processing facility to perform cleaning and sorting of harvested kelp that was then freeze-dried for shipment. Co-use of equipment was achieved for cleaning and sorting, but new equipment was brought in for freeze-drying the kelp. In addition, the power to the facility required upgrading. The proposition tested was to ship an “unrefined” product to other communities, such as in the lower 48 states, where value-added products would be produced. A better proposition for Southwest Alaska communities is to produce final products locally, thereby capturing the additional value for the local economy and stimulating more job growth. Nevertheless, this was a successful demonstration of co-use of facilities for upstream processing of the raw feedstock.

3.3 References

Chen X, G Liu, and W Jin. 2020. Natural Gas Purification by Asymmetric Membranes: An Overview. Green Energy & Environment. pre-proof GEE 299.

DOE-EERE-BETO (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office). 2016. *National Algal Biofuels Technology Review*. Washington, D.C.

Elliott DC, TR Hart, GG Neuenschwander, LJ Rotness, G Roesijadi, AH Zacher, and JK Magnuson. 2014. "Hydrothermal Processing of Macroalgal Feedstocks in Continuous-Flow Reactors." *ACS Sustainable Chem. & Eng.* 2: 207-15.

Ghadiryanfar M, KA Rosentrater, A Keyhani, and M Omid. 2016. "A review of macroalgae production, with potential applications in biofuels and bioenergy." *Renew. Sustain. Energy Rev*. 54: 473-81.

Gunaseelan VN. 1997. "Anaerobic Digestion of Biomass for Methane Production: A Review." *Biomass and Bioenergy* 13: 83-114.

Milledge JJ, B Smith, PW Dyer, and P Harvey. 2014. "Macroalgae-derived biofuel: a review of methods of energy extraction from seaweed biomass." *Energies* 7: 7194-222.

Roesijadi G, SB Jones, LJ Snowden-Swan, and Y Zhu. 2010. *Macroalgae as a Biomass Feedstock: A Preliminary Analysis.*PNNL-19944, Pacific Northwest National Laboratory, Richland, Washington.

4.0 Techno-Economic Analysis

This chapter develops the financial metrics of Alaska biodiesel production via a modular hydrothermal liquefaction (HTL) process using waste streams from the emerging Alaska kelp processing industry and from the seafood processing industry. Configuring existing or new processing plants to capture and use the seafood waste along with processing the kelp waste stream appears to have economic potential. Depending on the opportunity cost of capital used, the break-even price of biodiesel using a modular Alaska HTL process would range from $3.18–$3.64/gal.

These initial estimates are highly uncertain and rely on important assumptions. The costs of the HTL process are adapted from literature values and may not adequately reflect what would be experienced in Alaska. Also, some important costs may not have been fully addressed at this stage, including fuel transportation to remote locations. Similarly, this chapter discusses federal and state economic incentives or subsidies that could be used to defray costs by initial investors in these ventures, but these incentives or subsidies have not been fully analyzed. To the degree that the available incentives and the estimated costs would offset each other, the economic metrics in this report would be valid, subject to further analysis and confirmation.

These findings suggest that there is an economically viable role for a local biodiesel production industry in southwestern Alaska. Such an industry can create an environmental win-win by converting two Alaska food processing waste streams into a fuel resource needed by Alaska's marine-dependent communities. The biodiesel would offset a portion of the fossil-based diesel now being used to meet these demands.

4.1 Techno-Economic Analysis Overview

This chapter provides initial estimates of the economic viability of non-food kelp utilization for fuel production and consumption in southwestern Alaska's marine-dependent communities. Alaska kelp species are being farmed to provide inputs to food product manufacturing ventures. Bull, ribbon, and sugar kelp may prove economically viable for many potential food products. As these markets grow, the demand for Alaska kelp will grow. It is in the interest of the economy of Alaska to capture as much of the kelp processing industry as possible within local marine-dependent communities, rather than simply growing and harvesting the kelp for shipment elsewhere for processing into food products. This study focused specifically on communities covered by the Southwest Alaska Municipal Conference including towns and villages within the Boroughs of Aleutians East, Bristol Bay, Kodiak Island, and Lake & Peninsula, and the Census Areas of Aleutians West and Dillingham.

PNNL examined the economic viability of using food kelp waste as a feedstock for potential energy production in the form of biocrude, biodiesel, or biogas that could be used locally in the remote and isolated marine-dependent communities of Southwest Alaska. These communities are dependent on fuel shipped over great distances (e.g., ocean and air freight shipping). Most of these communities use diesel generators to generate the power used in local residences, businesses, and industrial plants. Fuel oil is used in some places to provide district heating of homes and businesses. At recent (pre-COVID) delivered fuel costs, kelp-based biofuel may be economically viable in these communities under conditions analyzed in this report.

Apart from Alaska's emerging kelp market, the state is well-known for its substantial ocean fisheries including many food species of finfish, shellfish, and mollusks. These marine fisheries are the economic life blood of the communities of Southwest Alaska. The seafood processing industry is the largest industry in each of the marine-dependent communities.

Early in the study it became apparent that if the seafood processing waste could be combined with the kelp food processing waste, the economic viability of these waste streams for use in fuel production would be improved. PNNL also analyzed the economic viability of this combining of feedstocks for fuel production.

Economic viability occurs when the life cycle benefits exceed life cycle costs. Life cycle benefits and costs reflect the time value of money using the net present value metric. Net present value is the summation of all benefits or costs over the lifetime of a particular project or venture, discounted to reflect a societal preference for early revenues over revenues later in the project lifetime. Economically viable ventures show a ratio of life cycle benefits to costs of 1 or greater, subject to alternative discount rates to indicate the influence of the time preference for money. Of course, projects that may not be strictly economically viable may still be pursued for other societal benefits or objectives that may not be reliably priced in dollar terms (e.g., job creation, climate adaptation, community resilience, etc.).

Simple payback period is another financial metric used in this report to provide additional perspective of the viability of kelp biofuel production for use in Southwest Alaska communities. The simple payback period is the time required to make back in project revenue the initial investment needed to generate the revenue stream. Criteria for financial viability using this metric vary by the entity of interest. Risk-averse private investment entities might require a short payback period (e.g., 1–2 years) to have reasonable assurance that their investment will be quickly recouped. Intuitively, the longer the payback period the less likely private investors would be to fund the investment.

Finally, this report does not provide investment-grade information. It represents an initial investigation of the potential economic viability of the ventures described. Only simple economic metrics are reported; more thorough study would be needed to provide additional metrics. The costs and benefits examined are based on publicly available data, informed judgment, reasonable assumptions, and performance estimates for systems that currently are design concepts, not existing manufactured systems available in the market. Literature values are adapted and used to enable the analysis where possible. The study assumes research success in the areas of modular fuel product manufacturing, waste product feedstock characterization, and other advances needed to bring products to market. The reader is cautioned to keep these concerns in mind while interpreting the economic findings in this report.

4.2 Marine-Dependent Fuel Market

To provide the market context for the study, PNNL reviewed data supplied by Alaska’s PCE program (AEA 2020). In fiscal year 2019, 193 remote communities representing about 82,000 people participated in this this program. The program aims to offset power costs in small remote villages, which often face power costs three to five times higher than those in more urban areas of the state. The PCE program publishes data about each participating community including their diesel use, electricity generation, fuel costs and power costs, population, number of electricity customers, etc. Figure 4.1 illustrates the distribution of diesel costs for power generation and the cost of producing electricity.

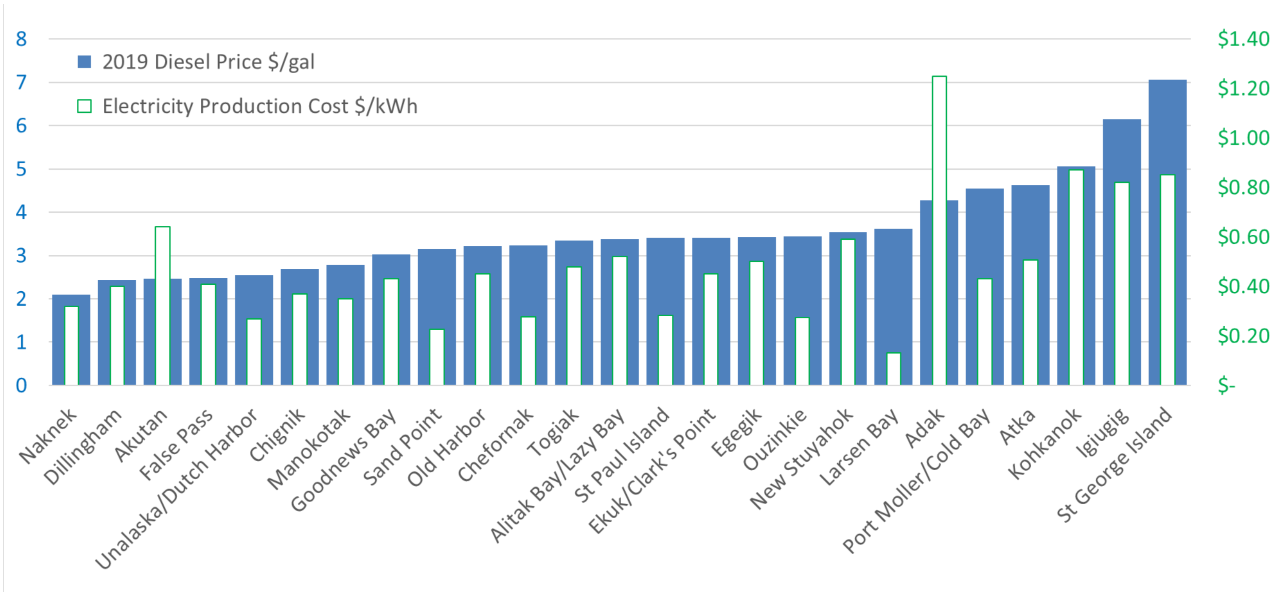

Figure 4.1. Distribution of diesel prices and electricity production costs for communities in Southwest Alaska.

In most of these communities, diesel generators are used to produce the community electricity. Fuel oil diesel is used to heat residences and businesses, either from a central steam heating plant serving all the buildings or via fuel oil furnaces at each customer home or business. Some areas in close proximity to Anchorage or Kodiak rely on hydroelectric power and are not included in the PCE program. Table 4.1 summarizes the annual diesel fuel use in selected southwestern Alaska communities. PNNL estimates that these communities represent annual diesel demand approaching 10 million gallons for electricity and heating energy production.

Table 4.1. Annual diesel fuel demand in selected Southwest Alaska and other communities for electricity and heat production.

Community	Air Miles from Anchorage	Population	2019 Diesel Gallons	2019 kWh Sold
Adak	1,192	308	178,117	1,259,811
Akutan	759	993	52,274	521,960
Akhiok (Alitak Bay/Lazy Bay)	332	88	25,808	218,065
Atka	1,097	54	10,279	93,484
Attu	1,488	17	Not in PCE Program	
Chefornak[(a)]	488	432	112,333	1,311,803
Chignik	455	110	52,850	687,727
Dillingham	329	2,572	1,280,522	17,675,418
Egegik	331	76	52,502	547,096
Ekuk/Clark's Point	336	55	34,636	260,308
False Pass	655	73	59,204	600,084
Goodnews Bay[(a)]	422	277	20,366	694,089
Homer[(a)]	117	5,810	Not in PCE Program	

Community	Air Miles from Anchorage	Population	2019 Diesel Gallons	2019 kWh Sold
Igiugig	239	57	24,279	253,894
Kenai[(a)]	59	7,778	Not in PCE Program	
King Cove	611	1,065	Not in PCE Program	
Kodiak	253	5,968	Not in PCE Program	
Kohkanok[(a)]	204	173	41,333	358,732
Larsen Bay	288	86	3,524	96,354
Manokotak	346	487	66,874	943,063
Naknek	296	887	1,758,588	24,231,563
New Stuyahok	279	504	140,546	1,330,535
Old Harbor	297	214	53,714	719,677
Ouzinkie	239	146	28,602	359,110
Port Moller/Cold Bay	521	72	181,281	1,932,669
Sand Point	556	915	193,018	2,675,393
St George Island	767	70	48,849	465,775
St Paul Island	764	389	235,383	2,848,518
Togiak	386	870	236,618	2,904,949
Unalaska/Dutch Harbor	792	4,341	3,439,665	50,930,888
Totals		34,887	8,331,165	113,920,965

(a) Communities not in the SWAMC region but are included for comparison to other recent TEA studies

These marine-dependent communities are quite remote from Alaska's principal urban center and shipping hub of Anchorage—generally several hundred miles by air. Ocean shipping distances can be substantially farther and require detailed planning and logistics to accomplish economically. Each port has varying levels of facilities for docking, on- and off-loading, fuel storage, and industrial infrastructure. Typical practice is to acquire the full winter's supply of fuel before winter weather conditions make transportation prohibitive, then ride out the winter months using the fuel storage. In some communities there are no port facilities and fuel must be flown in by cargo plane, adding substantially to the cost of electricity and heat production.

4.3 Methodology

This techno-economic analysis (TEA) assesses the economic feasibility of converting kelp and fish waste into biocrude and biodiesel using an HTL process. The HTL process is amenable to these types of feedstocks because the feedstock does not require a drying process before it can be used. The drying process requires high energy input that significantly reduces profitability. The HTL process uses a feedstock that is typically less than 20% solids and thus consumes approximately 12% of the energy required for dewatering alone (Barreiro et al. 2013).

Figure 4.2 shows a flow diagram of the HTL process that is modeled. The feedstock is milled and slurried to around 20% solids by weight. The feedstock is then pumped into an HTL reactor, where the feedstock is brought to 250–375°C at a high pressure of 1–20 MPa (Barreiro et al. 2013). At this temperature and pressure, the water in the feedstock is used as a reactor medium to convert the feedstock to biocrude and an aqueous phase. After extracting the biocrude, it may be possible to extract value-added compounds, such as nitrogen, phosphorous, and valuable metals, from the aqueous phase that is left over.

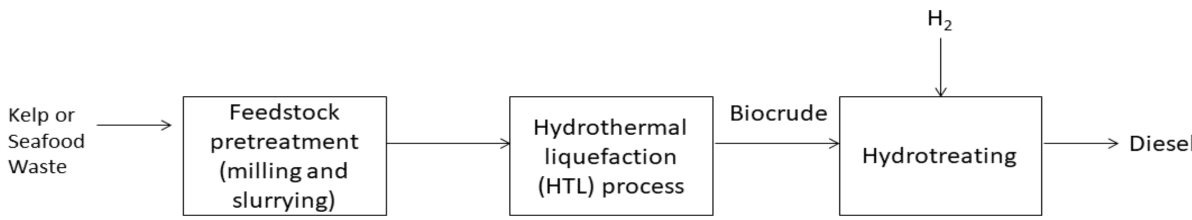

Figure 4.2. HTL process flow diagram modeled.

The biocrude is then subjected to a hydrotreating stages to upgrade the biocrude. Hydrotreating involves raising the biocrude to temperatures around 165°C, pressure around 13.5 MPa, and bringing the oil into contact with hydrogen gas.

For more detail about the HTL process, see Davis et al. (2014), Jones et al. (2018), or Bach et al. (2014). The costs of the HTL process modeled in this analysis are the costs of capital equipment, energy, chemicals, and feedstocks.

The conceptual model for the needed facilities includes the co-location of kelp processing facilities with existing seafood processing facilities such that shipping, and off-loading can be handled using the same port infrastructure used by the seafood processors. These additional facilities would include the waste kelp processing line and upgrading of the seafood waste processing line to route feedstock to the HTL process steps. The HTL processing equipment would route fuel product to the fuel packaging and storage area, most likely as barrels stored in some storage building or pad.

4.3.1 Cost Data Inputs

The cost inputs presented are inherently uncertain because these processes do not yet exist in a commercially viable operation. As part of the analysis, a number of these uncertain input values are varied to illustrate their effects on the resulting economic and financial metrics. Table 4.2 highlights key inputs used in this analysis.

Table 4.2. Inputs and assumptions for the TEA of an HTL process.

Assumption	Value	Source
Size of plant	100,000 lb. feedstock per day	Assumption
Annual days of operation	250	Assumption
Cost of HTL capital	$12M	Greene et al. (2020)
Labor cost	$175,000 per year	Davis et al. (2014)
Maintenance cost	$375,000 per year	Davis et al. (2014)
Discount rate	8% and 3%	Assumption: 8% represents typical internal rate of return for private capital, and 3% represents return for publicly funded projects
Federal tax rate	21%	
AK State tax rate	9.4%	

Assumption	Value	Source
Tax depreciation system	MACRS 7 years	Capital costs are depreciated to offset tax bill over time according to IRS allowance.[a]
Lifetime	30 years	Assumption
Kelp		
Energy cost per kWh	$0.4488/kWh	Average of energy rates in SW AK
Energy amount required per lb.	0.191 kWh	Greene et al. (2020), Jones et al. (2014), Frank et al. (2013)
Chemical cost for kelp	$0.00988 per lb.	Greene et al. (2020)
Kelp cost per unit	$10 per ton for waste inputs	Assumption: costs of transporting and aggregating into plant feedstock
Yield from kelp (% AFDW)	0.34	Greene et al. (2020), Cruce and Quinn (2019), Jones et al. (2014), Broch et al. (2019), Frank et al. (2013)
Seafood Waste		
Yield from seafood waste (% AFDW)	0.50	Conti et al. (2020)
Energy cost per kWh	$0.4488/ kWh	Average of energy rates in SW AK
Energy amount required per lb.	0.191 kWh	Greene et al. (2020), Jones et al. (2014), Frank et al. (2013)
Chemical cost for seafood waste	$0.00988 per lb.	Greene et al. (2020)
Seafood waste cost per unit	$0	Assumption: Waste available onsite
Upgrading		
Cost of upgrading capital	$2M	Brigljević et al. (2019), Zhu et al. (2014)
Cost of hydrogen gas	$2.05 /lb.	Brigljević et al. (2019)

AFDW = ash-free dry weight; AK = Alaska; HTL = hydrothermal liquefaction; IRS = Internal Revenue Service; SW = Southwest.

(a) Modified Accelerated Cost Recovery System (MACRS) 7-year schedule is Year 1: 14.29%, Year 2: 24.49%, Year 3: 17.49%, Year 4: 12.49%, Year 5: 8.93%, Year 6: 8.92, Year 7: 8.93%, Year 8: 4.46%. Accessed Nov 3, 2020 at https://www.irs.gov/pub/irs-pdf/p946.pdf.

4.3.1.1 Kelp (Food Kelp Waste) Feedstock Acquisition

A variety of feedstocks can be used as input to an HTL process. Macroalgae has been shown to produce biocrude with yields around 35% in a variety of studies, making it a promising feedstock candidate. This report examines using kelp waste that can be obtained at low cost. We assume a cost of $10 per ton would cover transportation and handling, but zero procurement costs. Kelp processing for food is a nascent-to-emerging industry in Southwest Alaska, and the waste from this industry could potentially be converted to biofuel that would improve the viability of such a production plant.

4.3.1.2 Seafood Processing Waste Feedstock Acquisition

Fish and other seafood waste can be used as a feedstock for an HTL process. Currently Southwest Alaska does a large amount of fish processing and has a high amount of fish waste that requires costly disposal. This waste is typically converted to fish meal that provides little added value. Converting the fish waste to biodiesel could yield higher returns than fertilizer and reduce disposal costs. It is assumed for this analysis that fish waste is available onsite at zero cost.

4.3.1.3 Feedstock Processing

One of the advantages of processing kelp and fish waste is that the feedstock does not require pre-drying (Bach et al. 2014), so the energy costs are significantly lower. The whole biomass can be processed including fronds, stems, and blades. Some studies recommend milling prior to processing (Raikova et al. 2017). The feedstock needs to be dewatered or slurried to approximately 20% weight of solid material and 80% water weight and is then ready for introduction to the HTL process.

4.3.1.4 Fuel Processing

The output from the HTL processing is a biocrude oil that is high in water, oxygen, sulfur, and nitrogen. Zhu et al. (2014), Conti et al. (2020), and Choi et al. (2014) recommend upgrading the oil by hydrotreating. It is assumed that the fuel does not go through the complete hydrocracking process done at full-scale refineries. The costs associated with this process are capital costs and operations costs, including the purchase of hydrogen gas. Labor costs for this step are included.

4.3.1.5 Fuel Packaging and Delivery

The costs analyzed in this report do not include costs to package and store the fuel or transportation costs to deliver the fuel to any locations. Delivery costs may be significant, especially to locations that require air transportation of the fuel. Szymoniak et al. (2010) estimate that remoteness factors add $1.00/gal to the prevailing diesel prices in these remote locations.

4.3.1.6 Residual Products Cost of Recovery

There are two types of other products that could potentially be recovered from the aqueous phase of the HTL output. Phosphorous and nitrogen that can be used for agricultural fertilizer can be recovered after an HTL process. This sub-process is not modeled in this report, but it may be possible to market these products as high-end organically produced fertilizer inputs. Valuable rare-earth minerals that are present in the kelp or the fish waste could also be extracted using solvents. This is also not modeled in this report because lab tests are required to determine the mineral concentrations in the kelp.

4.3.2 Benefit Data Inputs

4.3.2.1 Fuel Revenues

The main source of revenue for this type of facility would be the sale of biocrude fuel that would be obtained from the HTL process. This TEA uses $4/gal of diesel as the base output price. Prices are somewhat lower currently (COVID-induced) because of world market conditions that have lowered the price of oil, so while $4 is higher than current prices, it is more representative of average fuel prices expected over the lifetime of this type of project in Alaska. The price of the biocrude can then be calculated using the higher heating value (HHV) of the biocrude fuel and the HHV of diesel using the following formula:

$$P_{Diesel} = \frac{P_{biocrude} \times HHV_{diesel}}{HHV_{biocrude}}$$

The HHV of diesel is 45.6 and the HHV of biocrude from kelp and fish waste are both 36.5 (Anastasakis and Ross 2011; Conti et al. 2020; Michalak 2018).

4.3.2.2 Subsidies and Incentives

There may be some opportunity for an HTL processing plant to receive grants or government-subsidized loans to lower the costs of procuring capital or lowering the tax bill associated with plant operation. The following is a short list of potential options:

- U.S. Department of Agriculture (USDA) – Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program (DSIRE 2020a). This program offers subsidized loans for projects that develop and construct commercial scale biorefineries. The maximum loan amount is for 80% of the project or $250 million, and the remaining 20% must use a different funding source.
- USDA – Rural Energy for America Program (REAP) & Energy Audit and Renewable Energy Development Assistance (EA/REDA) Grants (DSIRE 2020c). The EA/REDA grant provides funding for grantees to provide subsidized energy audits and/or renewable energy technical assistance, including renewable energy site assessments, to rural small businesses. The EA/REDA grant can be used for salaries, travel expenses, office supplies, and administrative expenses, but not for construction-related activities. The REAP grant can be used by rural small businesses to help offset their costs (up to 25%) up implementing energy efficiency upgrades or renewable energy installations.
- Renewable Energy Grant Program (DSIRE 2020b). This grant fund is administered by the Alaska Energy Authority and approved by the state legislature. Projects must be constructed and operated for the public benefit to qualify. Grant amounts are up to $4 million in High Energy Cost Areas.

It is noted that SWAMC is currently operating their third USDA EA/REDA grant, providing reduced-cost energy audits to rural small businesses, and helping them access USDA REAP grants to implement the energy efficiency measures identified in their audit.

4.3.2.3 Revenues from Residual Products

In addition to revenue from fuel products, it may be possible to produce and sell additional byproducts. These revenues are not included in the current TEA because of uncertainty in the cost of extraction. However, they could provide additional sources of revenue that would increase the profitability of the processing facility. The first byproduct is nitrogen and phosphorous that can be used in fertilizer. It would also be possible to extract high-value minerals after the HTL process. Lab tests are currently being conducted to determine the mass fractions of these minerals to determine the potential revenues associated with their extraction. It is also possible to extract high-value carbohydrates and proteins such as alginate. These carbohydrate products would be unlikely to be found in waste kelp, but a processing facility considering using non-waste kelp could consider extracting these compounds before subjecting the material to HTL processing.

4.3.3 Metric Calculations

Several metrics are calculated to assess the potential of HTL processing of kelp and fish waste. The first of these metrics is the discounted net present value (NPV). For this calculation, revenues and costs are calculated for each year of the project and are then appropriately discounted. The discounted NPV is then determined by adding up the revenues and costs for all years during the lifetime of the project. The capital costs are depreciated to offset tax payments using the 7-year MACRS schedule, and federal and Alaska State taxes are applied to the annual profits before discounting. A discounted NPV larger than zero indicates that the project will be profitable over the course of its lifetime. The formula for computing NPV is as follows:

$$NPV = \sum_{n=0}^{T} \frac{B_n - C_n}{(1+r)^n}$$

For this analysis, the capital costs are assumed to be incurred at n = 0. For all subsequent years, the benefits B_n are the revenues from sale of the fuel and the costs C_n are the operating costs that include labor, maintenance, energy, chemical, and feedstock costs as well as taxes paid. Discount rates (r) of 8% and 3% are used.

We also compute the discounted benefit-to-cost ratio (BCR). The BCR is sometimes preferred to the discounted NPV because the discounted NPV often has a large numeric scale that is difficult to interpret, and the BCR tends to be close to one. If the BCR ratio is one, this is equivalent to the discounted NPV being equal to zero. A ratio larger than one indicates a project that will be profitable over its lifetime, and larger values indicated higher profitability. The formula for calculating BCR is

$$BCR = \frac{\sum_{n=0}^{T} \frac{B_n}{(1+r)^n}}{\sum_{n=0}^{T} \frac{C_n}{(1+r)^n}}$$

The simple payback period is also calculated. This value represents the time that the project will require to recoup the initial investment costs. This measure informs an investor of the time scale required for the investment to become profitable. The measure does not use discounting, and is calculated by finding the value of n such that

$$PV = \sum_{n=0}^{T} B_n - C_n = 0$$

The final value computed is the minimum fuel selling price (MFSP) that is required to make the project profitable. This value is determined by varying the price of the diesel output until the discounted NPV is zero over the entire time horizon.

$$NPV = \sum_{n=0}^{T} \frac{B_n - C_n}{(1+r)^n} = 0$$

This value is useful for gauging the potential market for this type of project. Fuel prices tend to vary over time and by location, so this value allows for quick analysis of the market conditions that will tend to favor profitability.

4.4 Results

The results of the TEA analysis are presented in Table 4.3. The basic assumptions included in this analysis are that there are minimal costs for the feedstock (using a waste stream), and that the fuel output can be sold for $4/gal of diesel equivalent. Discount rates of 8% and 3% are used. The assumptions used as model inputs are given above in Table 4.1. The plant is assumed to operate for 250 days a year and Table 4.3 shows results for a kelp-only facility as well as one that splits time between kelp processing (40%) and seafood waste processing (60%).

Table 4.3. Results of the techno-economic analysis.

	Kelp Only		**Seafood Waste (60%) and Kelp (40%)**	
Discount rate	8%	3%	8%	3%
Annual gallons of diesel equivalent produced	1.21M	1.21M	1.55M	1.55M
Discounted net present value	-$6,807,772	-$2,321,781	$3,986,593	$15,694,821
Benefit-cost ratio	0.865	0.97	1.08	1.19
Simple payback period	20+ years	20+ years	8 years	8 years
Diesel price at break-even (kelp price = $10/T)	$4.75/gal	$4.16/gal	$3.64/gal	$3.18/gal
Kelp price at break-even (diesel price = $4)	$0	$0	$99/T	$215/T

These results show that at a price of $4/gal of diesel equivalent, a first-of-a-kind plant that uses an HTL process to convert kelp to biodiesel is not likely to be profitable, but that including fish waste as an additional feedstock could have potential viability. If seafood waste is available seasonally, kelp could be used as a feedstock during alternate times to sustain operation. The profitability would be greater in more remote communities where the price of diesel is highest. These results also indicate that if kelp procurement requires costs, profitability would be lower.

4.4.1 Use Case Options

Figure 4.3 shows how the minimum output price required to ensure profitability changes as some of the input parameters are changed. These parameters are increased and decreased by 20% and the required output price is recalculated. It is important to note that the parameters are being changed one at a time, with the other parameters held fixed. The differences could be larger if multiple parameters are simultaneously different from the assumed values.

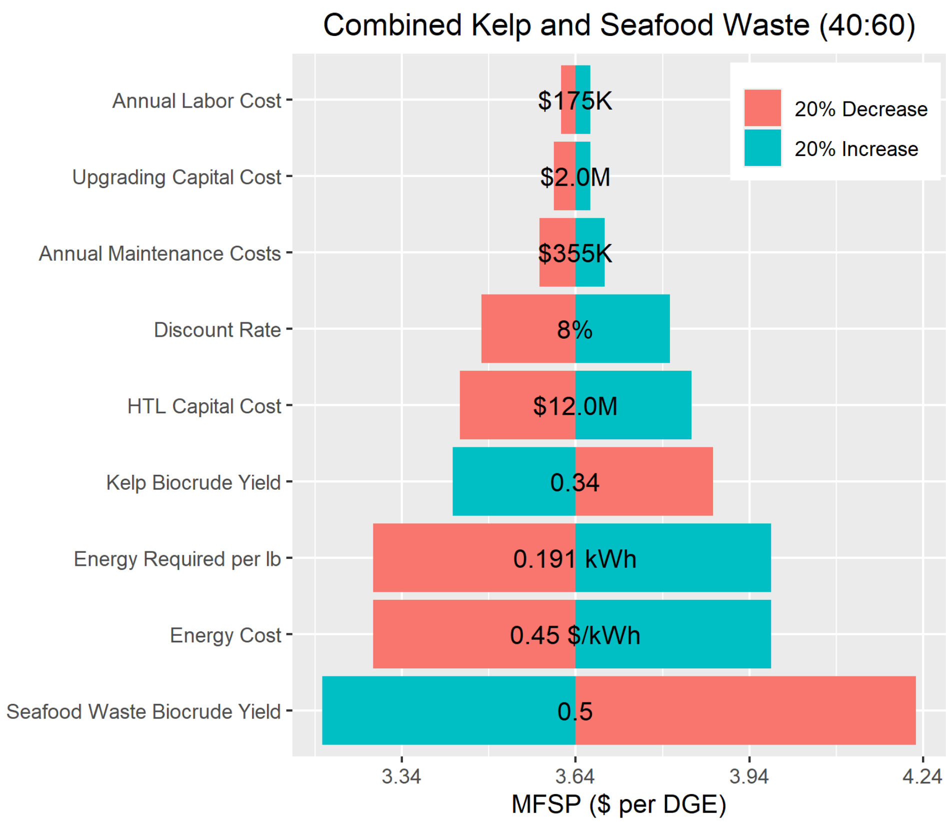

Figure 4.3. Sensitivity analysis of minimum fuel selling price (MFSP) per gallon of diesel equivalent (DGE) for varying economic parameters. Sensitivity variables increased and decreased by 20%.

This analysis indicates that the MFSP required is likely to be between $3.25 and $4.25/gal for a processing plant that includes both kelp and seafood waste. The parameters that have the largest sensitivity are the biocrude yields and the energy costs.

The values for biocrude yield were imputed from literature, and most of the values are determined from small-scale experiments. This would be the first large-scale kelp HTL processing plant, and so this variable should be regarded with more uncertainty than some other variables.

The variable not shown in the sensitivity analysis that is also important to profitability is the cost of the feedstock. These results use feedstock procured for little or no cost, so varying this cost by 20% would not show the full possible range of procurement costs. Figure 4.4 shows results when the feedstock costs are varied up to $1,000/T ($0.5/lb.). These results are significantly less optimistic for non-waste costs and would require market conditions that are less likely.

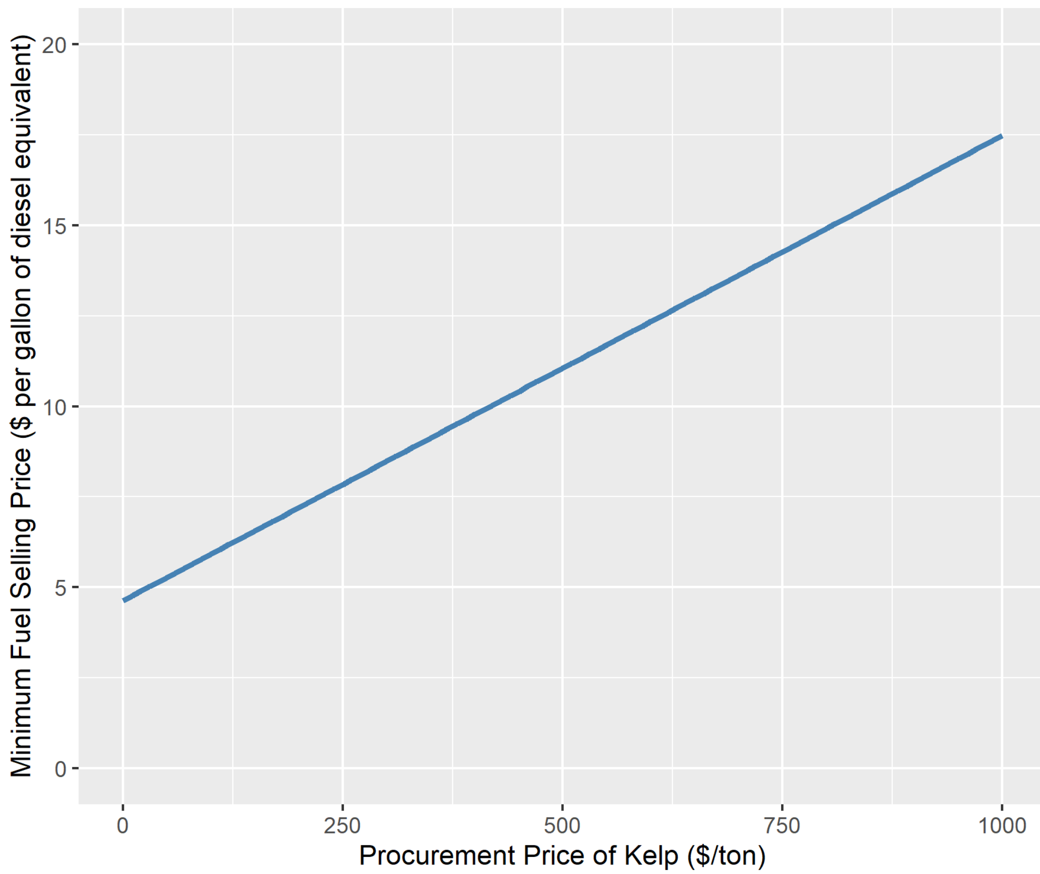

Figure 4.4. Effect of procurement price of kelp on the minimum fuel selling price. (Kelp-only feedstock)

4.5 Discussion

This TEA models a processing plant that converts kelp and fish waste into biocrude and biodiesel. The plant modeled has a capacity of 100,000 lb./d of feedstock running 250 d/yr. This would yield an annual production of around 1.5 million gallons of fuel per year. This would supply around 18% of the total annual consumption in Southwest Alaska. This facility could be scaled up if market conditions are favorable and sufficient feedstock is available.

The largest factor in determining the economic feasibility an HTL plant is the feedstock cost. Using waste kelp and fish waste as the feedstock, the MFSP of the diesel is similar to current market prices and may be feasible. However, if procurement costs of kelp are significant, the MFSP required rises to prices that are above prevailing market prices.

The yield of biocrude from the HTL process is an influential parameter that has some uncertainty. A conservative estimate of 34% biocrude recovery for kelp (Greene et al. 2020) is used in this report. Bach et al. (2014) report yields of up to 79% from Norwegian sugar kelp, but this required a small-scale laboratory reactor rather than the industrial-size reactor examined in this report. It is possible that yields could be higher than the 34% assumed in this report leading to increased profitability. The biocrude yield from fish waste is assumed to be 50%, but there is only one study documenting this assumption (Conti et al. 2020), so it should be viewed with some uncertainty.

A final potential uncertainty is the added costs of the remote location. The electricity costs used in the model were obtained from prevailing Southwest Alaska rates, and reflect the higher energy costs present in the area. However, the labor cost and capital costs are not location specific. If the costs to install and transport the capital are higher because of the remote location, this report does not incorporate those increases and would underestimate the MFSP required and overestimate the discounted NPV and BCR.

4.6 Conclusion

This study provides an initial analysis of the financial metrics associated with using two food waste streams that exist in southwestern Alaska and converting them to feedstocks for biodiesel fuel production. The emerging kelp food products industry is poised to grow substantially as new food products using the kelp are identified and developed. As the volume of kelp harvested grows, the related waste stream from processing the kelp for food will grow in tandem. This growing volume of waste kelp can be economically viable in the production of biodiesel for use by the marine-dependent communities of southwestern Alaska. These communities face extreme prices for diesel fuel used for electricity generation and local steam heating of residences, businesses, and community facilities.

The financial metrics of Alaska biodiesel production via a modular HTL process improve with the addition of seafood processing waste from well-established seafood processors in Alaska. Configuring existing or new processing plants to capture and use the seafood waste along with processing the kelp waste stream appears to have economic potential. Depending on the opportunity cost of capital used, the break-even price of biodiesel using a modular Alaska HTL process would range from $3.18–$3.64/gal.

These initial estimates are highly uncertain and rely on important assumptions. The costs of the HTL process are adapted from literature values and may not adequately represent what would be the Alaska experience. Also, some important costs, including fuel transportation to remote locations, may not have been fully addressed at this stage. Similarly, there are likely to be federal and state economic incentives or subsidies that could be used to defray costs to initial investors in these ventures, which also have not been fully addressed. To the degree that the available incentives and the estimated costs would offset each other, the economic metrics in this report would be valid, subject to further analysis and confirmation.

These findings suggest that there is an economically viable role for a local biodiesel production industry in southwestern Alaska. Such an industry can create an environmental win-win by converting two Alaska food processing waste streams into a fuel resource needed by Alaska's marine-dependent communities. The biodiesel would offset a portion of the fossil-based diesel now being used to meet these demands.

4.7 References

AEA (Alaska Energy Authority). 2020. Power Cost Equalization Program Statistical Report: FY 2019, February 2020. Accessed online from: http://www.akenergyauthority.org/LinkClick.aspx?fileticket=qgKDRJywe2M%3d&portalid=0

Al-Degs YS, M Al-Ghouti, and G Walker. 2012. "Determination of higher heating value of petro-diesels using mid-infrared spectroscopy and chemometry." *Journal of Thermal Analysis Calorimetry* 107, 853–862. https://doi.org/10.1007/s10973-011-1574-x

Anastasakis K and AB Ross. 2011. “Hydrothermal liquefaction of the brown macro-alga Laminaria Saccharina: effect of reaction conditions on product distribution and composition.” *Bioresources Technol*. 102 (7) (Apr. 2011) 4876–4883. https://doi.org/10.1016/j.biortech.2011.01.031

Bach QV, MV Sillero, KQ Tran, J Skjermo. 2014. “Fast hydrothermal liquefaction of a Norwegian macro-alga: Screening tests.” *Algal Research* Volume 6, Part B, pp 271-276. https://doi.org/10.1016/j.algal.2014.05.009.

Barreiro DL, W Prins, F Ronsse, and W Brilman. 2013. “Hydrothermal liquefaction (HTL) of microalgae for biofuel production: State of the art review and future prospects.” *Biomass and Bioenergy* Volume 53, p. 113-127. https://doi.org/10.1016/j.biombioe.2012.12.029.

Brigljević B, JJ Liu, and H Lim. 2019. “Comprehensive feasibility assessment of a poly-generation process integrating fast pyrolysis of S. japonica and the Rankine cycle.” *Applied Energy* 254. 113704, https://doi.org/10.1016/j.apenergy.2019.113704.

Broch OJ, MO Alver, T Bekkby, H Gundersen, S Forbord, A Handa, J Skjermo, and K Hanke. 2019. “The kelp cultivation potential in coastal and offshore regions of Norway.” *Front. Mar. Sci.* 5, https://doi.org/10.3389/fmars.2018.00529.

Choi JH, HC Woo, and DJ Suh. 2014. “Pyrolysis of seaweeds for bio-oil and bio-char production.” *Chemical Engineering Transactions* 37, p. 121–126.

Conti F, SS Toor, TH Pedersen, TH Seehar, AH Nielsen, and LA Rosendahl. 2020. “Valorization of animal and human wastes through hydrothermal liquefaction for biocrude production and simultaneous recovery of nutrients.” *Energy Conversion and Management 216*, [112925]. https://doi.org/10.1016/j.enconman.2020.112925.

Cruce JR and JC Quinn. 2019. “Economic viability of multiple algal biorefining pathways and the impact of public policies.” *Applied Energy* Volumes 233–234, pp. 735-746. https://doi.org/10.1016/j.apenergy.2018.10.046.

Davis R, C Kinchin, J Markham, E Tan, L Laurens, D Sexton, D Knorr, P Schoen, and J Lukas, 2014. *Process Design and Economics for the Conversion of Algal Biomass to Biofuels: Algal Biomass Fractionation to Lipid- and Carbohydrate-Derived Fuel Products*. NREL/TP-5100-62368, National Renewable Energy Laboratory, Golden, Colorado. https://doi.org/10.2172/1159351.

DSIRE. 2020a. "USDA – Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program.” Accessed November 3, 2020 at https://programs.dsireusa.org/system/program/detail/5313.

DSIRE. 2020b. “Renewable Energy Grant Program.” Accessed November 3, 2020 at https://programs.dsireusa.org/system/program/detail/3080.

DSIRE. 2020c. “USDA – Rural Energy for America Program (REAP) Energy Audit and Renewable Energy Development Assistance (EA/REDA) Program.” Accessed November 3, 2020 at https://programs.dsireusa.org/system/program/detail/5681.

Frank ED, A Elgowainy J Han, and Z Wang. 2013. "Life cycle comparison of hydrothermal liquefaction and lipid extraction pathways to renewable diesel from algae." *Mitigation and Adaptation Strategies for Global Change* 18(1): 137–158. https://doi.org/10.1007/s11027-012-9395-1.

Greene JM, J Gulden, G Wood, M Huesemann, and JC. Quinn. 2020. "Techno-economic analysis and global warming potential of a novel offshore macroalgae biorefinery." *Algal Research* 51. https://doi.org/10.1016/j.algal.2020.102032.

Jones SB, T Zhu, DB Anderson, RT Hallen, DC Elliott, AJ Schmidt, KO Albrecht, TR Hart, MG Butcher, C Drennan, LJ Snowden-Swan, R Davis, and C Kinchin. 2014. *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*. PNNL–23227, Pacific Northwest National Laboratory, Richland, Washington. https://doi.org/10.2172/1126336.

Michalak I. 2018. Experimental processing of seaweeds for biofuels. *WIREs Energy Environ*. Volume 7, Issue 3. https://doi.org/10.1002/wene.288.

Raikova S, CD Le, TA Beacham, RW Jenkins, MJ Allen, and CJ Chuck. 2017. "Toward a Marine Biorefinery through the Hydrothermal Liquefaction of Macroalgae Native to the United Kingdom." *Biomass and Bioenergy* 107, pp. 244-253). https://doi.org/10.1016/j.biombioe.2017.10.010.

Szymoniak N, G Fay, A Villalobos-Melendez, J Charon, M Smith, Mark. 2010. *Components of Alaska Fuel Costs: An Analysis of the Market Factors and Characteristics that Influence Rural Fuel Prices*. University of Alaska Anchorage, Institute of Social and Economic Research. Prepared for the Alaska State Legislature, Senate Finance Committee, 77 pages. Accessed online from: https://iseralaska.org/static/legacy_publication_links/componentsoffuel3.pdf.

Zhu Y, MJ Biddy, SB Jones, DC Elliott, AJ Schmidt. 2014. "Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading." *Applied Energy* Volume 129, 2014, pp. 384-394. https://doi.org/10.1016/j.apenergy.2014.03.053

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5.0 Greenhouse Gas Life Cycle Assessment of Kelp-to-Bioenergy Pathways in Alaska

Kelp is a macroalgal seaweed found across the globe and cultivated primarily for food and nutritional products. Aside from food, feed, and nutritional supplements, kelp coproducts can include biofuel and bioenergy, pharmaceuticals and cosmetics, and fertilizer and biochemicals. Kelp generally contains significant levels of essential nutrients such as carbohydrates, proteins, minerals, vitamins, thickening agents, and trace elements like iodine (van Oirschot et al. 2017), as well as rare-earth elements that are commercially valuable in many industries (Seghetta et al. 2017). Kelp cultivation also provides environmental benefits through capture of carbon and removal of runoff agricultural nutrients such as nitrogen and phosphorus, which can help mitigate greenhouse gas (GHG) emissions, reduce ocean acidification, and improve local ecosystem health (van Oirschot et al. 2017). Although most attention worldwide has focused on kelp uses for food and pharmaceuticals (Alvarado-Morales et al. 2013), there is renewed interest globally in kelp as a feedstock for fuel to increase energy independence and meet renewable energy targets (Roesijadi et al. 2010). However, more research is needed to determine the environmental tradeoffs of kelp-based biofuels compared with conventional fossil fuel use (Langlois et al. 2012).

Despite substantial kelp production in Asia, and to a lesser extent in South America and Africa, development of this trade has been slower in North America. Alaska, with its thriving seafood industry is poised to increase its maricultural production (i.e., agriculture at sea) to include kelp. However, unique challenges arise from Alaska's remote Arctic landscape and existing policy, socioeconomic, and cultural norms. Alaskans in support of this effort are particularly interested in developing feasible kelp product pathways that are economically beneficial to local communities but that minimize environmental and social tradeoffs and unintended consequences. Kelp mariculture in Alaska shows promise but needs additional innovation, research, and development to create feasible best use cases for kelp feedstocks and products.

To aid the Alaska kelp production industry beyond its nascent state, PNNL researchers teamed up with the SC of Alaska stakeholders and subject matter experts (SMEs) to begin navigating these uncharted waters. The DOE AMO Alaska Manufacturers Business Pilot Project (AMPP) funded PNNL, along with the SWAMC, Blue Evolution (a commercial company growing and harvesting kelp in Alaska), and other key stakeholders and SMEs within the SC to complete a Seafood Processing Pilot Project: Kelp Processes and Product Forms study. The goal of the study was to determine the feasibility of kelp production in Alaska, not solely from an economic perspective, but from a more comprehensive suite of perspectives, including environmental, ecosystem, systems engineering, and sociocultural considerations.

A large portion of Alaska's economy is based on seafood production activities. However, these activities have largely been seasonally based on fish life cycles and populations. Although there is variation between communities, the fishing season tends to be focused between April and September (ADFG 2016). Conversely, the kelp cultivation season takes place between September and May, although the season can be extended to include multiple harvesting cycles. Therefore, assuming a single kelp harvest, there is huge potential in off-season utilization of the massive seafood industry capacity in Alaska to support the processing of kelp for potential value-added products. Such dual-use activities have the potential to decrease downtime, increase productivity, create year-round jobs for Alaskans, improve environmental performance, and develop new products for the Alaska ecosystem and economy.

Life cycle assessment (LCA) is a sustainability engineering tool that quantifies, tallies, and compares environmental impacts of a product or system over its entire or specified portion of its cradle-to-grave life cycle. Carbon foot-printing is a form of LCA that focuses on GHG emissions, known as GHG-LCA, and presents results in the form of global warming potential in units of mass of carbon dioxide equivalents (CO2eq). This chapter presents the details and results of a GHG-LCA examining the environmental feasibility of kelp-to-bioenergy production in terms of life cycle GHG emissions. However, because global warming potential (GWP) is only one of many environmental impact categories of importance and because avoiding tradeoffs and unintended consequences are vital components of sustainability and environmental feasibility evaluations, we have included evaluations of additional environmental impact and indicator categories when possible.

5.1 SWAMC Seafood and Kelp Production

The SWAMC region in Alaska includes some of the most isolated and seafood industry-dependent Alaska communities. SWAMC serves six subregions: the Aleutians East Borough, the Aleutians West Census Area, the Bristol Bay Borough, the Dillingham Census Area, the Kodiak Island Borough, and the Lake & Peninsula Borough (Vaught 2020). Seven diverse communities were selected for closer analysis, one community from each sub-region (with the exception of Aleutians West where two communities were chosen because of the extended distances within the census area) to determine community feasibility and impact. Communities within each area were selected based primarily on two criteria categories: energy factors and seafood processing activities. Energy costs and per capita energy use were evaluated because higher costs and higher energy use increase the potential for biofuel applications. The number of registered fish processing facilities were evaluated to ensure proposing dual-use activities is feasible using the existing mariculture infrastructure. The final communities selected are False Pass, Unalaska, Adak, Naknek, Dillingham, Kodiak, and Egegik. See Figure 5.1 for a map of these communities in the SWAMC region.

Figure 5.1. Map of SWAMC communities selected for closer analysis.

A fundamental assumption for this research is that any potential product pathway under consideration must be feasible for the rural communities of Alaska. Therefore, two unique Alaska conditions are integral to understanding the main drivers of the project: the remoteness of communities and the cost of and demand for energy products. Many communities in Alaska are characterized by their remote locations, which create immense transportation challenges when acquiring or developing profitable products because communities may only be accessible via boat or airplane, making transportation extremely costly. The cost of fuel for heating and electricity, both for individual homes and industry, is particularly burdensome on local economies and families (Feidt 2018). Transportation costs may also incentivize use of a product produced and used locally, because it reduces the need for additional transportation, which can be cost prohibitive.

5.1.1 LCA Goal and Scope

The goal of the LCA study reported here was to determine the environmental feasibility of producing energy from kelp feedstock cultivated and processed in Alaska. More specifically, to determine whether nearshore, long-line cultivated brown kelp is a more environmentally friendly feedstock for bioenergy production in terms of global warming potential (GWP) than traditional mostly fossil fuel counterparts. The project team focused on nearshore cultivation methods of brown kelp species due to developing kelp farming practices in Alaska and primarily focused on biofuel and bioenergy production to meet the requirements of the funding agency. However, previous studies of the energy content of kelp showed the high-water content of kelp feedstocks made it a less than ideal bioenergy feedstock when cultivated exclusively for energy production. Therefore, in addition to comparing raw kelp-to-energy processing, we developed scenarios to compare kelp waste-to-energy feedstock processing to verify previous study results and determine if kelp coproduct-to-energy processing showed more promising results in terms of environmental feasibility. Additionally, we modeled scenarios that included co-processing of both fish and kelp waste because of the high energy content of fish waste and current challenges with fish waste management for small coastal communities.

The life cycle scope of the study includes all upstream processes (meaning all stages in product production), but the use of the final energy product was excluded, i.e., a cradle-to-gate scope (see Chapter 3 for more system boundary information). The functional unit for the study is million British thermal units (MBTU), however, for the bioenergy production models a sub-functional unit of 10,000 pounds of biomass is used.

We used an economic input-output–based LCA (EIO-LCA) for this pilot feasibility study, which relates economic transactions to environmental emissions using industry-level models developed with publicly available data (Gan and Matthews 2018). The EIO-LCA produces results based on industry average EIO tables collected from bi-decadal national surveys (CMU 2002). These data tables describe the complex interdependencies of industries in the U.S. economy and were extended to include environmental characterization factors that then estimate the sector-level environmental impacts based on economic activity in that sector. Because EIO-LCA provides results based on general industry averages, it is generally preferred to use a process-LCA methodology that uses detailed energy and material flow data. However, because this was a pilot feasibility study with limited resources, we determined EIO-LCA results would be appropriate as a cursory effort to be expanded in future research. Although EIO-LCAs have a high amount of data uncertainty and are based on linear economic models that may not reflect actual environmental impacts, they provide guidance on relative environmental impacts and serve as a baseline for decision-making and future work.

Section 5.2 discusses factors that heavily influence the feasibility of kelp production systems. These factors include the selection of appropriate feedstocks based on their availability and characterization (brown kelp and fish waste), cultivation practices, and energy processing pathways (anaerobic digestion, hydrothermal liquefaction, and fermentation). Section 5.3 s the methodological approach, comparison scenarios, and provides an inventory of data that were gathered. Section 5.4 presents the results of three different kelp-to-energy process scenarios. Section 5.5 discusses the limitations of this assessment and considerations for future kelp product pathway development, including comparison of impacts from biofuel produced with kelp versus terrestrial biomass (corn) and the potential scale of energy production given current mariculture practices.

5.2 Kelp Feedstock, Cultivation, and Processing Pathways

The feasibility of potential kelp production systems in Alaska depends heavily on three major factors: (1) feedstock characterization and availability; (2) cultivation methods, and (3) processing pathways. The following sections discuss the nuances of these options and the logic behind the those modeled for the study.

5.2.1 Kelp Feedstocks

There are three different groups of seaweeds: brown (*Phaeophyta*), red (*Rhodophyta*), and green (*Chlorophyta*) (Øverland. 2019). The project team determined four species of kelp to be most viable for production in Alaska: sugar kelp (*Saccharina latissima*), ribbon kelp (*Alaria marginata*), bull kelp (*Nereocystis luetkeana*), and dragon kelp (*Eualaria fistulosa*), all of which are brown species. Brown kelp are characterized by their large size and high productivity and have been widely studied for their feasibility of use in a number of different products (Øverland et al. 2019). These species were also chosen based on current species approved for cultivation in Alaska (Group 2017a)

Brown kelp has a general characterization that is similar to green and red kelp. It is mostly composed of polysaccharides (carbohydrates), has a low protein and lipid content, but a relatively high proportion of fatty acids (Øverland et al. 2019), and a high ash content (Olsson et al. 2020). Lipids and proteins are generally a small fraction of kelp biomass and unlikely to be the main product. However, isolation, extraction, and concentration of these nutritious components could provide an economically valuable coproduct (Olsson, et al. 2020). Additionally, the high ash content in brown kelp indicates the potential availability of heavy metals. Although the latter can pose challenges in processing, rare-earth metals may be an additional economically valuable coproduct, but limited literature address this topic (Olsson, et al. 2020). It is important to note that "even within a small geographic area, growth rate and chemical composition may vary depending on, e.g., harvest season, sunlight, salinity, depth in the sea, local water currents, or closeness to aquacultural plants" (Øverland et al. 2019).

Kelp is often compared to traditional terrestrial biomass to determine tradeoffs in biofuel feedstocks. Kelp have been shown to have higher growth capacities, and can have longer seasons than terrestrial biomass, resulting in higher yields (van Oirschot, et al. 2017). Kelp also contains complex polysaccharides (algin, laminarian, mannitol, and fucoidan) which may have alternative commercial values, something not found in terrestrial biomass (Roesijadi et al. 2008). Kelp is of interest to the biofuel community because it does not require agriculture land (as other terrestrial biomass does). While kelp cultivation and processing require some land space in the nursery and post-processing stages, the current small scale of kelp development avoids the traditional debate in the U.S. about food versus fuel. Additionally, because kelp production is underdeveloped in North America, there is excitement about potential yields from a large amount of otherwise unoccupied ocean space. Additionally, terrestrial biomass can generate problems in terms of land use change and deforestation (Seghetta, et al. 2017). While kelp cultivation may also have negative consequences for the environment, particularly at large scales, direct and indirect consequences have not been studied extensively (van Oirschot, et al.

2017). LCA allows us to model the potential environmental consequences of bioenergy production using kelp as a feedstock. Additionally, some have suggested that kelp is more preferable for certain energy processing than terrestrial biomass because of the lack of lignin in marine biomass, which can act as an inhibitor of anaerobic digestion (Roesijadi, et al. 2008).

5.2.2 Kelp Cultivation in Alaska

Kelp can be harvested from wild kelp forests or cultivated in engineered systems. Interest in harvesting wild kelp for processing has mainly been explored in Europe (Risén, et al. 2014, Seghetta,et al. 2014). However, wild harvesting limits potential yields, increasing challenges in any post collection product processing, and there is increasing concern about its negative environmental impacts. Therefore, attention has focused on kelp cultivation (van Oirschot, et al. 2017). In addition, wild harvesting is currently not a major driver in the growing Alaska kelp industry and therefore was not considered for this report. Three main types of kelp cultivation exist: nearshore, deep seafloor, and floating systems. Nearshore mariculture includes producing kelp spores in a nursery onshore that are then attached to a buoy and netting system deployed about a quarter mile offshore. Deep sea mariculture is located farther from shore, and thus is also located in deeper waters. Deep sea sites can be located where there are existing kelp forests, in man-made seafloor kelp forests, or in infrastructure mounted suspended systems. Deep sea kelp cultivation is increasingly only considered in tandem with offshore wind farms because the synergies between the two increase their feasibility. Open-ocean floating kelp cultivation systems are more novel, and the technology was determined not to be at a mature enough level of readiness for inclusion in this study. Nearshore mariculture practices are most often used by Alaska kelp startups and were thus selected to use in this pilot study; deep seafloor and floating kelp cultivation methods were not explored for this project.

5.2.3 Kelp-to-Energy Processing Pathways and Products

New products and pathways originally under consideration for these Alaska kelp feedstocks included food and feed, nutrients and supplements, pharmaceuticals and cosmetics, fertilizer and biochemicals, and biofuel and bioenergy. Evaluating considerations and tradeoffs between products can be complex because there are often multiple ways to make each product, each having a different combination of coproducts. Significant local work is already being done to develop an Alaska kelp food industry, and in the spirit of developing additional product pathways and given the scope of this project, food and nutritional kelp products were not modeled in this study. The use of kelp biomass to produce renewable energy products, namely renewable diesel biofuel and renewable combined heat and power (CHP) bioenergy, were determined to be the most viable options for securing local community energy supplies and reducing the dependence on fossil fuels (Alvarado-Morales, et al. 2013). Coproducts resulting from the various kelp bioenergy product pathways include high-yield fertilizer and animal feed nutrient additives, while a co-benefit could be disposal and processing of fish processing and municipal food waste. Extraction of valuable materials such as trace rare metals and chemicals from the bioenergy waste streams is possible, but not modeled in this study.

Processes for extracting energy from kelp can be broken into two distinct groups: (1) processes that require dry feedstock, and (2) processes that are feasible for wet feedstocks. For the first scenario, the feedstock requires drying prior to energy extraction. Kelp has a high-water content (between 80% and 90%), and removal of this water is extremely energy intensive. One study estimated that 87% of the total calorific value of the raw biomass was required for drying. As a result, previous research has concluded that in order for kelp to be a feasible feedstock for producing biofuels, conversion technology that can tolerate a wet feedstock is vital (Milledge, et al. 2014). Therefore, energy processing methods that require a dry feedstock, such as direct combustion, pyrolysis, gasification, and transesterification, were not considered feasible. Three energy production scenarios were explored because they can tolerate wet feedstocks: (1) AD, (2) HTL, and (3) fermentation. In addition to being suitable for wet feedstocks, kelp-based biofuel and bioenergy production from these processes has been previously researched.

The three energy production scenarios produce different biofuel products and coproducts of interest. In terms of biofuel products, AD produces biogas, HTL produces bio-oil, and fermentation produces ethanol. Yields are highly dependent on the characterization of the feedstocks: AD yield depends heavily on carbohydrate and lipid content, HTL yield depends heavily on lipid and protein content (Arvanitoyannis and Kassaveti 2008), and ethanol yield depends heavily on glucose-based polysaccharides (Milledge, et al. 2014).

Brown kelp has a high carbohydrate content, 51–55% of dry weight (Seghetta, et al. 2017), making it a suitable feedstock for AD (biogas production) (Alvarado-Morales, et al. 2013) and fermentation (bioethanol production). However, one of the main carbohydrates in brown kelp, alginate, cannot currently be directly used for fermentation, thereby severely limiting the potential of ethanol production from macroalgae (Milledge, et al. 2014). Because alginate is a valuable coproduct for use in a range of sectors, it would be most beneficial to extract it prior to fermentation. However, because the characterization of Alaska kelp samples was ongoing, the environmental impacts of alginate extraction and processing were excluded from the scope of this study. Microalgae has a much higher lipid and protein content than macroalgae and is thus regularly explored in HTL literature. However, because of its wider cultivation, macroalgae for HTL has also gained traction (Milledge, et al. 2014). The criticism of HTL in comparison to AD is that it uses a relatively small amount of the feedstock. While HTL mainly uses lipids and proteins, AD has the capacity to use all the organic carbon material of algae, and biogas systems tend to yield more energy from crops per hectare than liquid biofuel systems (Milledge, et al. 2019). Although respective yields are different, the energy content of the resulting products is also different (Nges, et al. 2012).

AD converts biomass into biogas, digestate, and water (Milledge, et al. 2014). The biogas is mostly methane (about 60%), carbon, and other trace gases. This biogas is a low-grade fuel that can be used either for thermal applications or upgraded to a drop-in replacement for natural gas. Upgrading biogas involves refining the methane content, from about 60% to 97% methane for biomethane or renewable natural gas. Once upgraded, this biogas is comparable to conventional natural gas and can be used as a "drop-in" replacement for natural gas. The digestate is the remnants of the original feedstock input that cannot be digested and contains most of the nutrients from the feedstock and therefore can be used as a nutrient-rich fertilizer (Center 2012). Digestate yield from the AD process is about 80% of the volume of the feedstock material (Pechsiri, et al. 2016). Developing uses for both the biogas and digestate achieves maximum recovery while creating an additional value add product (Angelidaki, et al. 2017). AD has also received a lot of attention because it is a relatively simple process that requires minimal infrastructure and process management and can co-digest a wide variety of other organic waste streams such as fish processing and municipal solid waste (Cappelli, et al. 2015). Kelp has been shown to be a feedstock that is in energy, highly digestible, and has high specific methane yields.

HTL converts biomass into liquid fuels in the presence of water or a water solvent and a catalyst. The process essentially "mimics the natural geological processes believed to be responsible for the formation of fossil fuels in a time frame measured in minutes rather than over a geological time span" (Gollakota, et al. 2018). HTL produces bio-oil, gas, bio-char, and water

(Anastasakis and Ross 2011). Bio-oil has an energy value of 70–95% of petroleum fuel oil, so it can be considered similar to conventional crude oil. However, biocrude has significantly higher oxygen and nitrogen contents. HTL is considered energy efficient: 10%–15% of the energy content of the feedstock s an energy efficiency of 85%–90% (Gollakota, et al. 2018). Despite this energy efficiency, HTL is still a relatively costly operation. Additionally, while yields are promising, this is the result of lab pilots, and no commercial-scale facility has been reported to be in operation (Gollakota, et al. 2018). Bio-char can also be used a fertilizer, and 20–30% of the original feedstock mass will end up as bio-char (Anastasakis and Ross 2011).

Compared to AD, HTL is a much faster process that results in a more complete conversion. AD requires 20 days and converts about 50% of the biomass, whereas HTL can be completed as quickly as 30 minutes and can convert about 99% of the biomass. Producing ethanol via fermentation (discussed below) converts only 35% of carbon in the feedstock to ethanol, whereas 70–85% of the carbon in the feedstock can be converted via HTL. The yield difference is exacerbated in fermentation because ethanol (alcohol fuel) has lower energy content than diesel (hydrocarbon based) fuel (Oyler 2014).

Many types of macroalgae have been considered as potential sources for bioconversion to ethanol, however this production process faces significant technical and economic challenges. Yields are highly dependent on pretreatment and efficient microorganisms to convert fermentable sugars to ethanol, which severely inhibit the economic and environmental feasibility of the process (Offei, et al. 2018). The most abundant sugars in brown macroalgae are alginate, mannitol, and glucan. However, current industrial microbes are unable to metabolize the alginate component, which severely limits the full potential of ethanol production from macroalgae (Kim, et al. 2011).

All three energy production pathways have been explored previously in the context of brown kelp, and they differ in technological readiness, infrastructure complexity, potential yields, energy content, and coproducts. AD has been shown to be economically feasible and has been operated at production scale; others need considerably more research (Milledge, et al. 2019). AD and HTL can be upgraded to a drop-in fuel or replacement and were thus continued through to the LCA portion of this assessment. Ethanol from fermentation, however, cannot be upgraded in this way and is instead blended with traditional fossil fuels producing a hybrid fuel. Additionally, to maximize the benefits of fermentation, it is often recommended that the byproducts be captured and used for AD to produce biogas, which would increase the complexity of the system and infrastructure required. While use of blended ethanol fuels decreases the amount of fossil fuels required, because small coastal communities would not benefit from a pure ethanol product, it was excluded from further consideration in this study.

5.2.4 Seafood Waste Co-Feedstock

In developing kelp-to-energy pathways, additional synergies were found between the mariculture and kelp industry by considering fish waste as a potentially valuable co-feedstock. Fishing is an integral component of Alaska's economy, contributing $5.6 billion a year (Group 2017b). All fish processing operations, large and small, have some form of byproduct (waste) that can pose economic and environmental problems. Some processors limit this waste while creating additional economic generating activities by producing additional products such as fishmeal, fish oil, bone meal, and/or bait from the waste. However, post-processing is limited because of the low nutritional value (the most nutritious sections being used for human consumption products) and economic feasibility of post-processing in smaller-scale operations located in remote areas. Therefore, a significant portion of fish processing waste continues to be discharged back into the ocean, legally and illegally, which can have severe environmental implications such as the creation of eutrophic “dead zones” that threaten ecosystem health (Solow 2005). Using fish waste can reduce the economic burden of proper waste disposal, decrease environmental impacts of discharging large quantities of waste back into the ocean, legally or illegally, and provide a supplemental fuel source, thereby improving the economic and environmental performance of fishing operations. However, the performance will be dependent on further studies that include the characterization of Alaska fish waste, which depends on the type of fish and any post-processing that occurs because this alters chemical and biophysical properties. Municipal solid waste (i.e., household waste) can also be a burden to rural communities (Mutter 2014). However, due to the project focus on mariculture as well as data limitations, municipal solid waste as a potential feedstock with co-benefits was not examined, but it could be a consideration for future work.

Fish waste has received less attention than macroalgae for biofuel production but nonetheless shows promise. Fish waste and fish sludge are rich in lipids and proteins (Nges, et al. 2012). AD of fish waste has been shown to have high theoretical methane yields (Nges, et al. 2012), but only 35.7–46.9% of the theoretical maximum yields may be achieved due to ammonium concentration that serves as an inhibiting factor (Gebauer and Eikebrokk 2006). The high content of protein in fish waste is thought to cause the high concentration of ammonium and subsequent inhibition. However, this may be mitigated by dilution with water (Gebauer 2006). Kelp, with a naturally high-water content, may decrease resources required to mitigate this effect. Additionally, even with the inhibition, AD of fish waste has the potential to generate feasible yields. The high lipid and protein content of fish waste is promising for HTL (Nges, et al. 2012). Fish waste is not an ideal co-feedstock for fermentation because of the limited carbohydrate content of fish waste, less than 10%.

5.3 Methods and Data Inventory

LCA is a well-established framework for analyzing the environmental performance of a product and/or service over the entire life cycle, from raw material extraction to use to final disposal. The four core phases of LCA are (1) goal and scope, (2) life cycle inventory (LCI) development, (3) life cycle impact assessment (LCIA), and (4) interpretation and analysis for evaluation and comparison of impacts, tradeoffs, and unintended consequences. The goal and scope definition specifies why and how a given LCA is performed. The LCI quantifies all inputs and outputs of the production system under consideration. The LCIA translates the data inventory into the selected environmental impacts. The fourth phase, interpretation, evaluates the results of LCI and impact assessment in relation to the defined goal and scope in order to draw conclusions. This section details phases one and two including the scenarios under consideration, system boundaries, and functional unit followed by an inventory of the data collected. Section 5.4 then presents the environmental impacts of each scenario (phases three and four of the LCA).

LCA can be used to study a range of impact categories from resource depletion to human health to ecosystem quality. For the purposes of this assessment, the main impact category considered was GHG emissions. Expressed in tons of CO2eq, this accounts for the GWP from total emissions of 14 different GHGs (e.g., carbon dioxide, methane, nitrous oxide) over 100 years (Gan and Matthews 2018). For further comparison and optimization of the bioenergy production scenarios, a more complete spectrum of environmental impacts was assessed including total energy, CO, NH_3, NOx, PM_{10}, $PM_{2.5}$, SO_2, and VOCs.

Feedstock, bioenergy processing, and business as usual scenarios are as follows:

- Bioenergy Feedstock Scenarios
  - A – Raw Kelp
  - B – Raw Kelp & Fish Waste
  - C – Kelp Waste & Fish Waste
- Bioenergy Processing Scenarios
  - 1 – HTL & Upgrade to Renewable Diesel
  - 2 – AD & Combustion to CHP
- Business as Usual Scenarios
  - I – Fossil Diesel
  - II – Grid Mix & Heating Oil

Three feedstock scenarios were considered to evaluate optimal environmental performance: raw kelp (A), raw kelp & fish waste (B), and kelp waste & fish waste (C).

- Feedstock scenario A included raw kelp only. This assumed kelp cultivation is undertaken solely for the purpose of energy production and thus must account for all associated environmental impacts.
- Feedstock scenario B included raw kelp and fish waste. This assumed the same about kelp cultivation: kelp cultivation is undertaken solely for the purpose of energy production and thus must account for all associated environmental impacts.

  However, fish waste, as the name suggests, is a waste product from fish processors in Alaska. Therefore, environmental impacts are assigned based on the quantity used by each process. Fish processing generates a significant amount of waste ranging from 40–75% of the initial harvest mass (Committee 2020). However, it was assumed that most of this waste would be sent for post-processing to produce additional products such as fishmeal, fish oil, bone meal, and/or bait. A more realistic final net fish waste estimate was determined to be 10% of fish harvests are waste materials that would otherwise be disposed of and are therefore available for use by the modeled energy systems. Therefore, fish waste was allocated 10% of environmental impacts associated with fish harvesting because that reflects only the portion used in this system.
- Feedstock scenario C included kelp waste and fish waste. This assumes the same amount of fish waste—10% of environmental impacts from the fishing industry were assigned to this process because this study only accounts for the waste product.

  A similar assumption is made in this scenario for kelp waste. Current kelp processing in Alaska generates significantly less waste than fish processing at about 4% of the initial harvest (Committee 2020) . Therefore, kelp waste was allocated 4% of environmental impacts associated with kelp cultivation because that reflects only the portion used in this system.

System boundaries for each of these three feedstock scenarios are shown in Figure 5.2. Dotted lines in the figure represent excluded components. The entire cultivation system boundary is shown in grey because it represents a decision point for the bioenergy system.

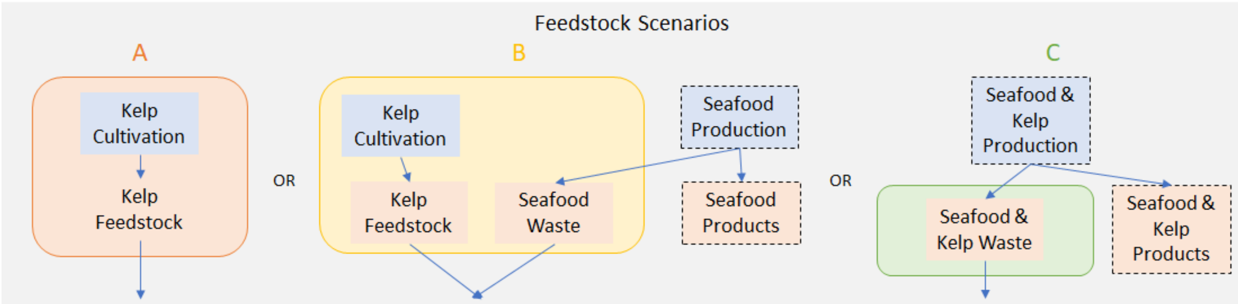

Figure 5.2. Feedstock scenarios system boundary.

As discussed above, two energy production pathways were modeled: AD, which produces biogas, and HTL, which produces bio-oil. The two energy production pathways were chosen because of their compatibility with an extremely watery feedstock (i.e., kelp) and were examined for feasibility using brown kelp to ensure similar characterization with the four species of kelp under consideration in Alaska. However, only AD and HTL were considered for final comparison because of the significant technical and economic challenges associated with fermentation. Different fuel types have different optimal uses. HTL produces a bio-oil that can be upgraded to a drop-in renewable diesel fuel. AD produces a biogas that can be upgraded to a drop-in fuel replacement for natural gas. However, more commonly, AD is used in CHP systems. Additionally, CHP was considered more feasible based on current use practices in Alaska; currently, no SWAMC community has natural gas infrastructure (Committee). Both AD and HTL produce a fertilizer product, digestate and biochar, respectively. However, the environmental offsets from fertilizer coproducts were only included at a community scale rather than system-level scale (see Section 5.5). The system boundary for both fossil energy scenarios is shown in Figure 5.3. The entire system boundary is shown in grey in the figure because it represents a decision point.

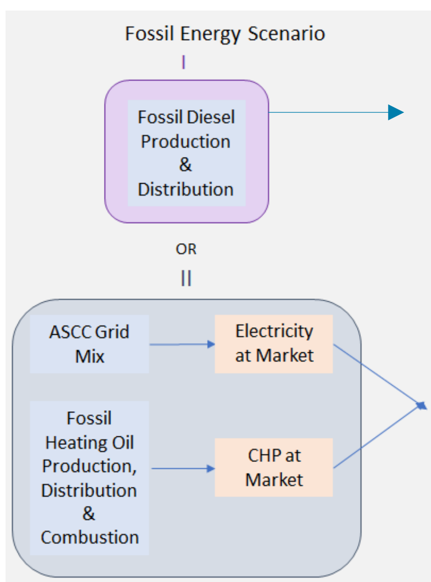

Figure 5.3. Fossil energy scenario system boundary.

Figure 5.4 shows the system boundary for the entire process, including where the appropriate feedstock and fossil energy scenario should be considered. For the purpose of this high-level assessment, the system boundary is the same for AD and HTL, although respective data are unique. Dotted lines in the figure represent excluded components. Grey boxes represent a decision point.

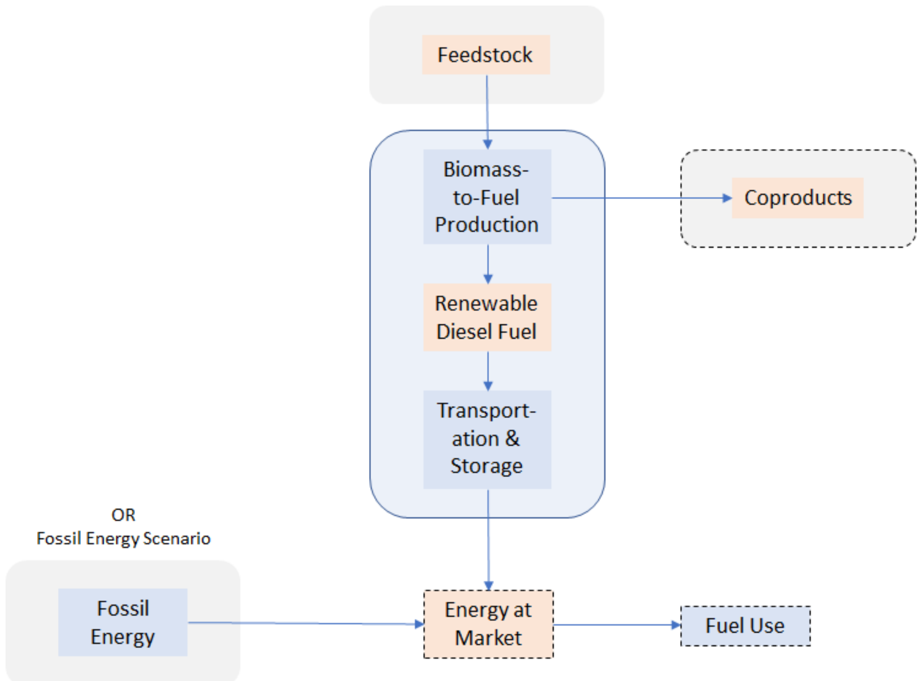

Figure 5.4. Feedstock to fuel vs. fossil energy system boundary.

Based on the bioenergy processing scenarios, appropriate fossil fuel comparisons had to be selected. It is most appropriate to compare biodiesel with traditional fossil fuel diesel and AD CHP with fuel oil and the Alaska electricity grid mix. Model Scenario 1 compared HTL Bio-oil Upgrade to Renewable Diesel (1) to traditional fossil diesel (I) across the three bioenergy feedstock scenarios (A, B, and C). Similarly, Model scenario 2 compared AD & Biogas Combustion to CHP (2) to Alaska Grid Mix & Heating Oil (II) across the three bioenergy feedstock scenarios: A, B, and C. This is summarized as follows:

- Model scenario 1:
  - A1 vs. I: Raw Kelp for HTL & Upgrade to Renewable Diesel vs. Fossil Diesel
  - B1 vs. I: Raw Kelp & Fish Waste for HTL & Upgrade to Renewable Diesel vs. Fossil Diesel
  - C1 vs. I: Kelp Waste & Fish Waste for HTL & Upgrade to Renewable Diesel vs. Fossil Diesel
- Model scenario 2:
  - A2 vs. II: Raw Kelp for AD & Combustion to CHP vs. Grid Mix & Heating Oil
  - B2 vs. II: Raw Kelp & Fish Waste for AD & Combustion to CHP vs. Grid Mix & Heating Oil
  - C2 vs. II: Kelp Waste & Fish Waste for AD & Combustion to CHP vs. Grid Mix & Heating Oil

Yield data for AD and HTL were collected from existing literature and are shown in Table 5.1 and Table 5.2. Only yields from brown kelp species were considered. Yields are heavily influenced by the characterization of the feedstock, which can further change based on "harvest season, sunlight, salinity, depth in the sea, local water currents, or closeness to aquacultural plants" (Øverland, et al. 2019). Therefore, the data collected from a variety of species grown in diverse conditions already account for the expected variations between kelp feedstocks and wastes available for bioenergy production. All kelp data collected were normalized to a sub-functional unit of 10,000 lb. of wet feedstock. This functional unit was chosen based upon previous daily kelp harvest information. Any kelp cultivation system can be compared to this by scaling the data to the appropriate size. For final comparison compatibility, a functional unit of a million British thermal units was used.

Table 5.1. Anaerobic digestion yields.

Feedstock	Yield CH_4 m^3/10,000 lb. Wet Feedstock	Source
A. nodosum	146.6	Allen et al. 2015
A. nodosum	67.8	Milledge et al. 2019
A. esculenta	122.1	Allen et al. 2015
F. vesiculosus	88.1	Allen et al. 2015
F. spiralis	148.5	Allen et al. 2015
F. serratus	61.3	Allen et al. 2015
H. elongate	95.8	Allen et al. 2015
L. digitata	102.2	Allen et al. 2015
Laminaria saccharina	134.3	Gunaseelan 1997
Macrocystis pyrifera	181.0	Gunaseelan 1997
S. latissima	156.6	Allen et al. 2015
Saccharina latissimi	232.9	Milledge et al. 2019
S. polyschides	156.6	Allen et al. 2015
Sargassum fluitans	96.3	Gunaseelan 1997
Sargassum pteropleuron	84.7	Gunaseelan 1997
Average yield kelp:	***125.0***	
Cuttle fish waste	885.6	Kafle et al. 2005
Fish waste collected off beach in Tanzania; species not identified	439.7	Mshandete et al. 2004
Mackerel fish waste	708.9	Kafle et al. 2005
Mackerel fish waste	729.4	Eiora et al. 2012
Needle fish waste	686.0	Eiora et al. 2012
Pacific saury fish waste	544.4	Kafle et al. 2005
Tuna fish waste	374.4	Eiora et al. 2012
Sardine fish waste	393.2	Eiora et al. 2012
Average yield fish waste:	***595.2***	

Table 5.2. Hydrothermal liquefaction yields.

Feedstock	Yield (%, dry weight)	Source
Alaria esculenta	29.4%	Raikova et al. 2019
Enteromorpha prolifera (without catalyst)	20.4%	Zhou et al. 2010
Enteromorpha prolifera (with catalyst)	23.4%	Zhou et al. 2010
Fucus vesiculosus	22.0%	Raikova et al. 2019
Laminaria saccharina	19.3%	Anastasakis and Ross 2011
Laminaria saccharina	16.0%	Raikova et al. 2019
Laminaria digitata	20.9%	Raikova et al. 2019
Macrocystis sp.	19.2%	Raikova et al. 2019
Sargassum patens	32.0%	Li et al. 2012
Saccharina sp.	27.0%	Raikova et al. 2019
Average bio-oil yield kelp:	***22.4%***	
Fish sludge	50.0%	Conti et al. 2020
Average bio-oil yield fish waste:	***50.0%***	

The 2007 model of the free online EIO-LCA tool developed by Carnegie Mellon was used (see Appendix A, Section A.1, for the full inventory and environmental impacts). The model aggregated all economic activity into 388 sectors. For each sector, impacts are estimated per economic activity, with data normalized to $2013 dollars. Because of the level of aggregation, where the exact industry was not available, the most appropriate industry was selected. For example, kelp cultivation is not an individual industry. The most appropriate industry was determined to be wild-caught fish and game. Industries were selected for all included components in the system boundary. Excluded components are not included in the assessment. Independently collected cost data of kelp cultivation, biofuel processing and transport, and traditional fossil fuels in Alaska, were normalized to $2013 dollars, and these costs were translated into environmental burdens per 10,000 lb. of wet feedstock. When available, high and low ranges were also used to indicate the variability of the data.

Biogenic carbon credits were also included. Algal biomass uptakes CO_2 from the atmosphere during the photosynthesis process. In accounting for GHGs, carbon embodied in the biomass that is released during processing is considered a CO_2 reduction, or “negative emission” because it is CO_2 that was removed from the atmosphere and stored in the biomass until combustion (Biobased Products Working Group 2010). Additional credits were included for waste disposal when kelp and/or fish waste was included in the system boundary (1B, 1C, 2B, and 2C). Using this waste avoids the environmental effects of waste management. The complete data inventory is found in Appendix A, Section A.2.

5.4 Results

This GHG-LCA evaluated the feasibility of producing bioenergy products from kelp and fish waste feedstocks in Alaska coastal communities. Model scenario 1 compared the renewable diesel bioenergy product produced via HTL with that of traditional fossil diesel. Figure 5.5 shows GWP results from Model scenario 1. The GWP for each scenario is shown broken down into each system process, illustrating the different impacts at different life cycle stages. For example, in scenario 1A the HTL and upgrade process, represented by the yellow, accounts for the smallest amount of GWP in comparison to kelp cultivation, represented by the light blue, or waste disposal, represented by the darker blue. The biogenic carbon credit is shown in green, and the black bar represents the net impact, i.e., the impact accounting for the biogenic carbon credit. The black lines are uncertainty bars. As expected from results found in the existing literature, scenario 1A, only raw kelp cultivated exclusively for bioenergy production, showed a significantly greater GWP than fossil diesel represented by scenario 1, and thus is not environmentally feasible. Scenario 1B, raw kelp combined with fish waste at a ratio of 2:1 by mass, showed a significant improvement over scenario 1A, and showed a net impact comparable to scenario I. However, the range of uncertainty of scenario 1B shows potential GHG emissions greater than the fossil fuel counterpart. Scenario 1C, kelp waste and fish waste, showed a net reduction in GWP and was thus considered the preferred scenario in terms of carbon footprint in Model scenario I.

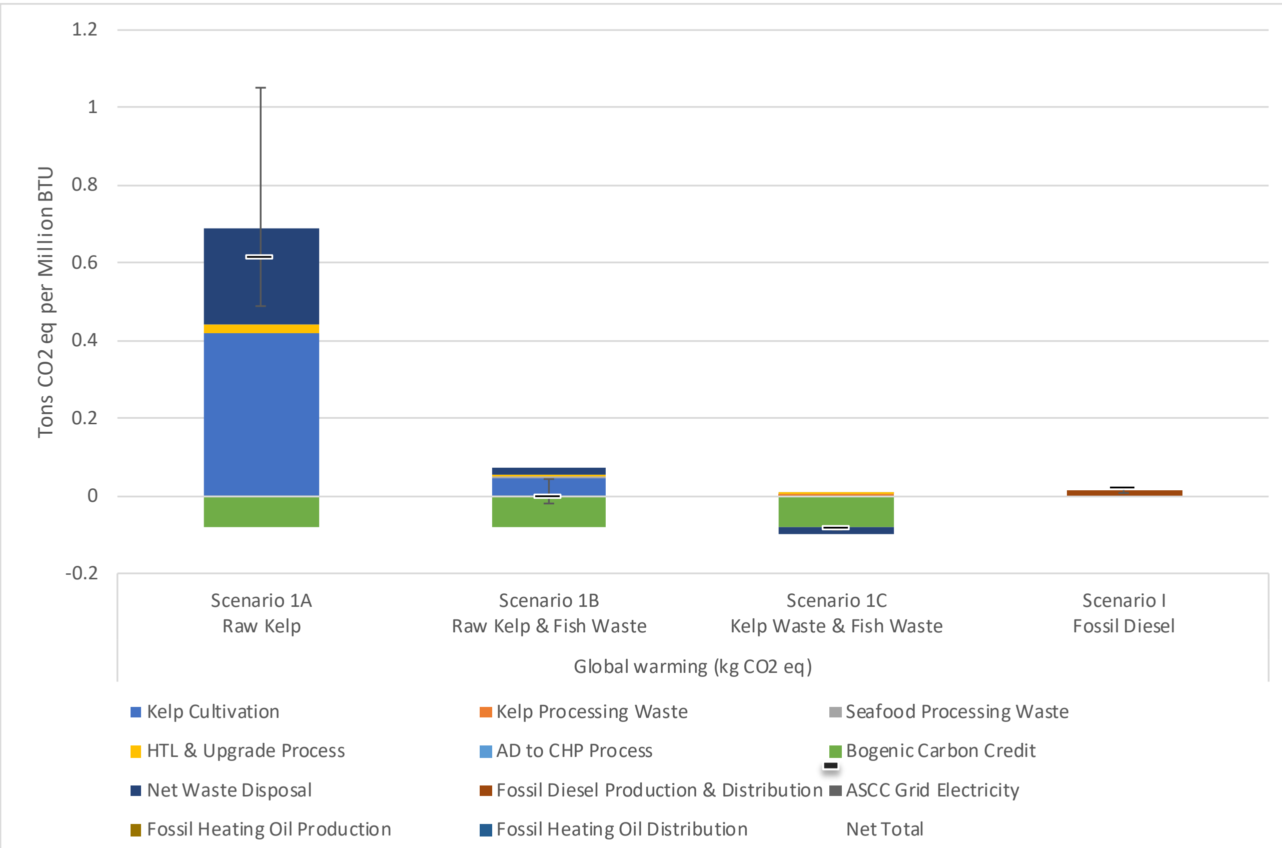

Figure 5.5. Global warming potential of Model scenario 1.

Scenario 2 compared the renewable CHP bioenergy product via AD with that of traditional electricity and process heat production. Figure 5.6 shows GWP results from scenario 2. The GWP for each scenario is shown broken down into each system process, illustrating the different impacts at different life cycle stages. For example, in scenario 2A, the AD to CHP process, represented by the lightest blue, accounts for the smallest amount of GWP in comparison to kelp cultivation, represented by the middle blue, or waste disposal, represented by the darker blue. The biogenic carbon credit is shown in green, and the black bar represents the net impact, i.e., the impact accounting for the biogenic carbon credit. The black lines are uncertainty bars.

As with scenario 1, the system processes for each scenario are represented along with the net result, including uncertainty bars illustrated by black lines. Model Scenario 2 showed the same general trends as those of scenario 1. Scenario 2A, only raw kelp cultivated exclusively for bioenergy production, showed a significantly greater GWP than traditional electricity and heat production represented by scenario II, and thus is not environmentally feasible. Scenario 2B, raw kelp combined with fish waste combined at a ratio of 2:1 by mass, showed a significant improvement over scenario 2A and showed a net impact comparable to scenario II. The range of uncertainties associated with scenarios 2B and II indicates that only under specific conditions would GWP be reduced by the bioenergy production. scenario 2C, kelp waste and fish waste, showed a net reduction in GWP and was the preferred scenario in terms of the carbon footprint in scenario II.

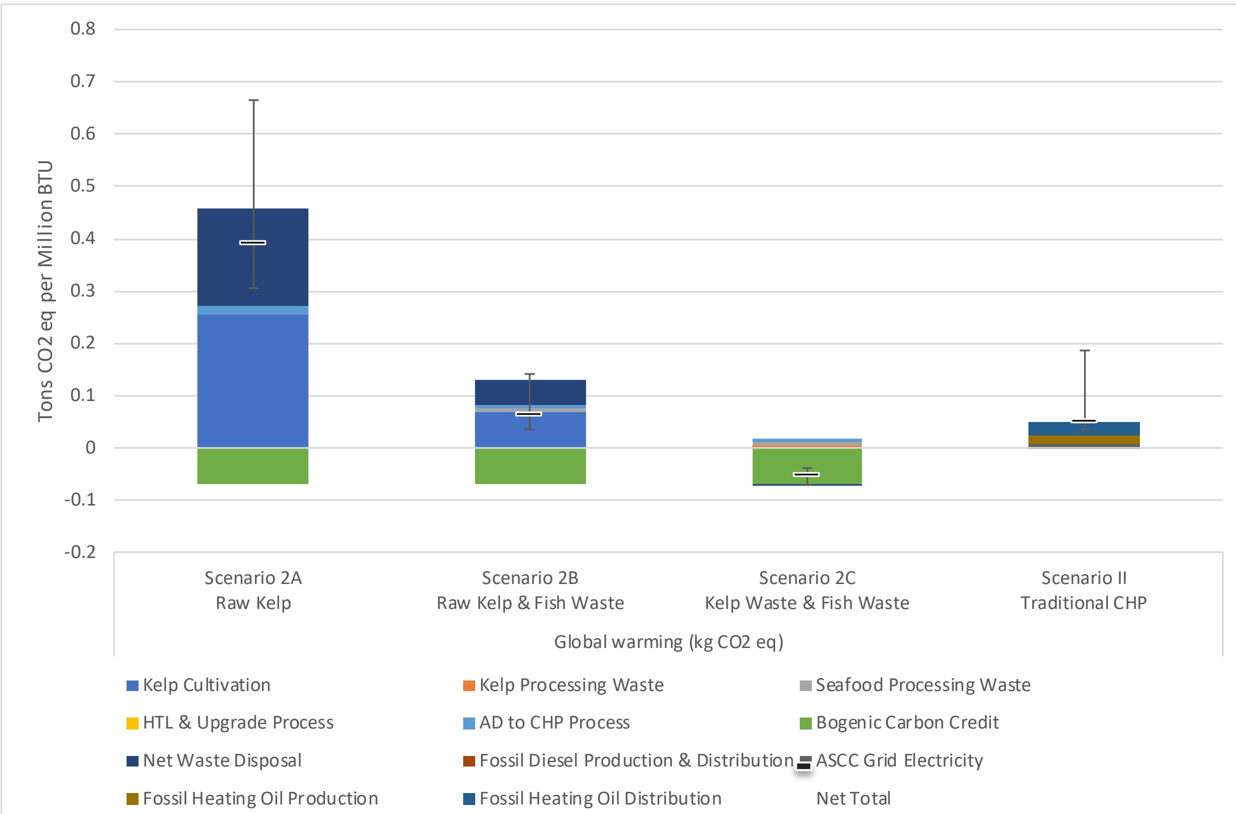

Figure 5.6. Global warming potential of Model scenario 2.

Based on the initial results, the optimal scenario is bioenergy produced from the combined kelp waste and fish waste, with either HTL or AD. Though the results from scenario 1C indicated a greater net reduction in GWP compared to scenario 2C, community demand for the two bioenergy products would dictate which process is most preferred. However, because GHGs are not the only environmental impact, GWP, total embodied energy, CO, NH_3, NOx, PM_{10}, $PM_{2.5}$, SO_2, and VOC results for Scenarios 1C, I, 2C, and II are presented in Appendix A, Section A.5.

5.5 Discussion

An explorative environmental LCA was performed for two energy production systems. Three feedstock scenarios were considered to highlight the potential viability of kelp-based energy as the primary product (scenarios 1A, 1B, 2A, and 2B) and energy as a coproduct of another kelp-based product system (scenarios 1C and 2C). An analysis of the life cycle environmental impacts of the systems showed that, from a GHG perspective, kelp-to-bioenergy production is not currently environmentally preferable to traditional fossil fuels when energy is considered the primary product.

The authors attempted to ensure the practicality of these results for rural Alaska communities in the selection of feedstocks and traditional fuel use comparisons. Biogas produced from AD, although it can be upgraded to a renewable natural gas, was instead compared to fuel oil and the electricity grid mix of Alaska based on current use practices. Internal communication with stakeholders revealed that no SWAMC community has natural gas hookups (Committee). In order for renewable natural gas to be useful, additional infrastructure would be required, introducing potential additional negative economic and environmental consequences. Therefore, it was determined that biogas for community heat and power would be the most useful product. Additionally, while the bio-oil produced by HTL can be used without upgrading it to a biodiesel, it cannot be used directly by the existing infrastructure (mainly generators) and poses challenges related to storage, transportation, and heating value. Therefore, it was determined that upgraded biodiesel would be the most useful product. If upgrading was not considered, HTL yield would have been significantly improved and the cost reduced, likely resulting in lower environmental impacts. However, this reduction would not have been great enough to change the overall impact ratio between the biodiesel and traditional diesel.

Furthermore, the study included CO_2 and environmental impact offsets from the production of fertilizer as a coproduct of producing energy from kelp. In 2011 Alaska purchased almost 3,000 T of fertilizer (Baum 2010). This amount could easily be generated by either energy production pathway. Therefore, the system should be credited for offsetting this fertilizer purchase because by using the waste product from the energy production, that amount of fertilizer would not have to be produced via conventional methods. The environmental impact of the fertilizer is already accounted for because it is a byproduct of the energy production systems. Therefore, the environmental impact of the avoided traditional fertilizer production and avoided waste disposal from the energy systems should be discounted. However, it cannot be appropriately included in the inventory because of the cap at 3,000 T/yr. The assessment found that, if included, the kelp to biofuel would generate a credit of more than 3,500 T of CO2eq. See Appendix A, Section 0, Data for Fertilizer and Diesel Offset Discussion, for a more detailed breakdown of environmental credits generated by this fertilizer offset that is otherwise unrepresented in the conclusions.

As mentioned in the chapter introduction, SWAMC serves six areas: the Aleutians East Borough, the Aleutians West Census Area, the Bristol Bay Borough, the Dillingham Census Area, the Kodiak Island Borough, and the Lake & Peninsula Borough. From each of these, one or two communities were chosen to evaluate current mariculture practices to determine the feasibility of kelp product production (fuel and fertilizer): False Pass, Unalaska, Adak, Naknek, Dillingham, Kodiak, and Egegik. Data gathered from the ADFG provided the net weight of harvests for specific species per year. Where information was not available for the specific communities of interest, a reasonable alternative was selected to serve as a proxy for the community. Based on this information, fish waste per day of a harvest period was calculated. Then, using fish waste yields as a proxy for kelp waste, if a kelp industry was to emerge in these Alaska communities, the total biodiesel produced in all SWAMC areas was calculated. Assuming one bioenergy plant was created in each of the seven communities, the SWAMC region would be able to generate 6% of their current diesel use. Although the environmental offset is not as large as in the case of fertilizer, at only -190 T CO2eq, it is nonetheless a credit that is otherwise unrepresented in the conclusions. Additionally, it should be noted that a significant portion of these data were confidential and therefore in actuality fish harvests are much higher. Therefore, these numbers represent an extremely conservative estimate.

This analysis included the biogenic carbon credit to account for kelp's sequestration and storage of carbon. The authors also provided the avoided environmental impacts from fertilizer production for the state of Alaska and for the avoided environmental impacts of using biofuel rather than diesel for the SWAMC region. However, some considerations that may improve environmental performance of the system were not included in this analysis. There is potential for energy systems to capitalize on additional feedstocks, such as municipal solid waste, that currently pose challenges to rural Alaska communities. This would increase the total available feedstock mass and, if optimal operating conditions can be met with the other feedstocks (kelp and fish waste), it may increase yield as well. However, this is highly dependent on the characterization of the waste. Additionally, once characterization of the Alaska kelp species has concluded, a more detailed assessment of coproducts could be conducted. Brown kelp has been shown to have high amounts of alginate and fucoidan, two high-value polysaccharides that are used in a variety of biomedical applications. Any coproduct processing will affect energy yields (for example, extracting most sugars before fermentation would severely limit yields), but optimization may allow for economic and environmental benefits. Kelp has also been shown to provide additional ecosystem management services that were not represented in this analysis, such as nutrient management (nitrogen and phosphorus) and reduction of ocean acidification. A process based LCA could be used to build in these additional ecosystem services.

As alternatives to fossil fuels are explored globally, interest in biomass, marine and terrestrial, are being widely explored. However, literature comparing the two has been extremely sparse, despite proclamations about the benefits of kelp in comparison to terrestrial biomass (reduced landmass, avoidance of the food vs. fuel debate, high growth rates, and additional high-value coproducts). Therefore, to contextualize the environmental impacts of the kelp-based bioenergy results discussed above, kelp cultivation results were compared with corn cultivation (Figure 5.7). Because the results are normalized to 10,000 lb. of feedstock, kelp data were adjusted to the same moisture content as corn to ensure appropriate comparison.

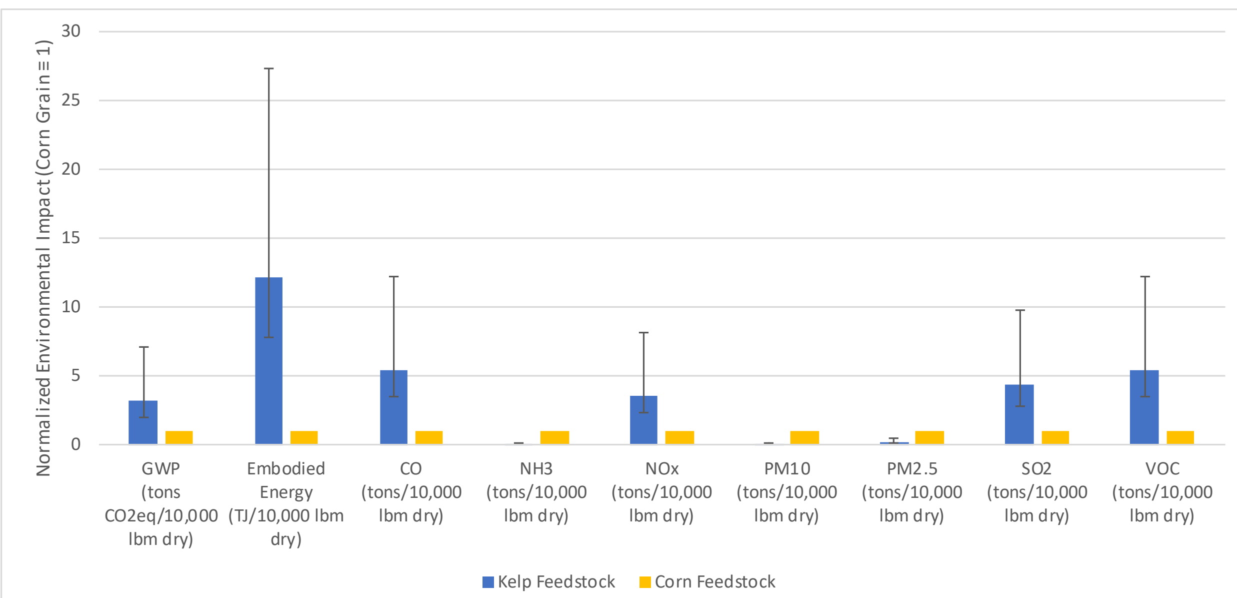

Figure 5.7. Environmental impacts of kelp cultivation vs. corn cultivation.

Previous life cycle research (Clarens et al. 2010) comparing the environmental effects of the cultivation of various feedstocks found that, compared to switchgrass, canola, and corn farming, kelp cultivation results in higher energy use and GHG emissions. However, kelp is favorable from a total land use and eutrophication potential view. Clarens et al. (2010) also demonstrated that most environmental impacts from kelp cultivation could be offset by coupling kelp production with wastewater treatment). Although the study by Clarens et al. (2010) only accounted for cultivation impacts and did not include processing into energy products similar to our results it finds that kelp may not be environmentally preferable to other terrestrial biomass unless combined with additional processes.

The results of this assessment are largely shaped by the methodology chosen, which is characterized by a linear financial model and industry-level aggregate data (and thus high uncertainty). Using a linear financial model to estimate the environmental impacts means that the results are affected by economic feasibility. Currently, kelp cultivation for bioenergy processing is not considered economically feasible and fossil fuels are currently much more cost-effective. For example, per MBTU produced, biodiesel was estimated to cost $90.62 compared to traditional fossil fuel diesel, which costs between $15.44 and $32.97/MBTU. However, as the costs of traditional fossil fuels rise, the difference between the environmental impacts of the systems shrink. Because the costs of fossil fuels are likely to rise in coming years because of resource availability and climate change, this is an important limitation to note. Additionally, in rural, isolated Alaska communities these cost increases are already evident. The state average for heating fuel is $4.50/gal, but the highest was $15/gal in Shishmaref (Feidt 2018). For comparison, at $15/gal, this would be $116/ MBTU and significantly affect the results of any environmental impact assessment conducted with this methodology.

There is a high amount of uncertainty in using EIO-LCA based approaches. Sectors are highly aggregated, and each industry sector can represent several industry types. Additionally, there is inherent uncertainty in the original EIO-LCA data (Chow 2012) and some sectors can be extremely broad and can undercount GHG emissions (Gan and Matthews 2018). EIO-LCAs are considered top-down approaches that model high-level proxy processes; they do not provide high-resolution results. Therefore, the results presented in this assessment are highly influenced by the representativeness of this model and the proxy processes used. For example, the EIO tables do not include a sector for kelp, and instead the impacts for kelp cultivation were based upon the “Wild-Caught Fish and Game” sector. Without a more detailed assessment, it is difficult to assess the potential discrepancies, and thus the results should be interpreted understanding the high degree of uncertainty. Some of the disadvantages of an EIO-LCA can be mitigated by using a process-based LCA, a bottom-up approach that tracks all mass and energy flows and would require more specific modeling of each energy process, and would require a significant amount of resources to complete. While a process based LCA would not eliminate any uncertainty, it would provide higher resolution results, which also would result in greater transparency where data are representative and where they are limited.

Additional uncertainty exists in collecting data from a wide range of existing literature, that itself has different limitations. AD has been studied more extensively across a range of different methods and feedstocks. Substantial literature existed for the biogas yields of both kelp and fish waste, using theoretical calculations (biomethane potential), batch reactors, and full-scale operational digestors. For HTL, however, there are no bio-oil yields reported in the literature from fully operational systems because HTL is still a relative novel technology. This novelty is reflected in the very high cost of operating a HTL system, and as this technology is refined and improved, the associated cost will likely also decrease. However, this means that all yields reported for HTL are based on small-scale, laboratory, batch assessments. Additionally, the authors found only one reference to bio-oil yields from fish waste, indicating the potential for significant variation. However, the authors reviewed data on bio-oil yields from food waste, which indicated yields between 25% and 40% (Zastrow and Jennings 2013). Although this is slightly reduced from the estimated bio-oil yields from fish waste at 50%, the limited characterization data that exist for the two feedstocks indicate that fish waste has a higher protein and lipid content, thereby producing the potential for higher HTL yields from fish waste.

This GHG-LCA study set out to shed light on the life cycle environmental impacts of potential energy production pathways for rural Alaska communities. This initial cursory LCA indicated that bioenergy produced via AD and HTL using combined feedstocks from kelp waste and fish waste results in reduced GHG emissions compared to conventional fossil fuel use in Alaska. In bioenergy production using kelp cultivated specifically for energy and fish waste, environmental effects are approximately comparable to those of traditional fossil fuels, although uncertainty indicates that under suboptimal conditions GHG emissions from bioenergy would be higher. Bioenergy production using only kelp cultivated specifically for energy is not environmentally preferable. However, these results are intended to provide a general sense of the environmental impacts of kelp-to-energy production. As kelp product pathways emerge and develop, further research is recommended to explore a process based LCA. All systems provide an environmental impact and process based LCAs can better examine environmental hotspots in a chosen process to optimize the process in terms of environmental performance.

5.6 References

DOE-EERE-BETO (U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office). 2016. *National Algal Biofuels Technology Review*. Washington D.C.

Alaska Mariculture Initiative Economic Analysis to Inform a Comprehensive Plan: Phase II, McDowell Group. 2017.

ACEP Rural Alaska Waste to Energy. ACEP, Alaska Center for Energy and Power

University of Alaska Center for Economic Development.
ADFG (Alaska Department of Fish and Game). 2016. Commercial Fishing Season in Alaska. Juneau, Alaska.

Allen E, DM Wall, C Herrmann, A Xia, and JD Murphy. 2015. 'What is the gross energy yield of third generation gaseous biofuel sourced from seaweed?', *Energy*, 81: 352-60.

Alvarado-Morales M, A Boldrin, DB Karakashev, SL Holdt, I Angelidaki and T Astrup. 2013. "Life cycle assessment of biofuel production from brown seaweed in Nordic conditions." *Bioresource Technology* 129: 92-99.

Anastasakis K and A Ross. 2011. "Hydrothermal liquefaction of the brown macro-alga Laminaria saccharina: effect of reaction conditions on product distribution and composition." *Bioresource Technology* 102(7): 4876-4883.

Angelidaki I, D Karakashev, and M Alvarado-Morales. 2017. "Anaerobic Co-Digestion of Cast Seaweed and Organic Residues." *Life* 1: 6.

Arvanitoyannis IS and A Kassaveti. 2008. "Fish industry waste: treatments, environmental impacts, current and potential uses." *International Journal of Food Science & Technology* 43(4): 726-745.

Baum SD. 2010. "Is humanity doomed? Insights from astrobiology." *Sustainability* 2(2): 591-603.

Biobased Products Working Group, B. I. O. 2010. "POSITION PAPER: Principles for the accounting of biogenic carbon in product carbon footprint (PCF) standards." *Industrial Biotechnology* 6(6): 318-320.

Cappelli A, E Gigli, F Romagnoli, S Simoni, D Blumberga, M Palerno, and E Guerriero. 2015. "Co-digestion of macroalgae for biogas production: an LCA-based environmental evaluation." *Energy Procedia* 72: 3-10.

Center SG. 2012. "Basic data on biogas." Sweden.

Chen X, G Liu, and W Jin. 2020. "Natural Gas Purification by Asymmetric Membranes: An Overview." *Green Energy & Environment*

Chow T. 2012. "UNCOPUOS Long-Term Sustainability of Space Activities Working Group fact sheet." *Secure World Foundation* (June 21, 2012) http://swfound. org/media/84709/SWF.

Clarens AF, EP Resurreccion, MA White, and LM Colosi. 2010. "Environmental life cycle comparison of algae to other bioenergy feedstocks." *Environmental Science & Technology* 44(5): 1813-1819.

CMU (Carnegie Mellon University). 2002. *Economic Input-Output Life Cycle Assessment (EIO-LCA) Model*. Carnegie Mellon Green Design Initiative, Pittsburgh, Pennsylvania

Committee, S. (2020). Seafood Processing Pilot Project: Kelp Processes and Product Forms. PNNL.

Conti, F, SS Toor, TH Pedersen, TH Seehar, AH Nielsen, and LA Rosendahl. 2020. 'Valorization of animal and human wastes through hydrothermal liquefaction for biocrude production and simultaneous recovery of nutrients', *Energy Conversion and Management*, 216: 112925.

Elliott DC, TR Hart, GG Neuenschwander, LJ Rotness, G Roesijadi, AH Zacher, and JK Magnuson, 2014. "Hydrothermal Processing of Macroalgal Feedstocks in Continuous-Flow Reactors." *ACS Sustainable Chemistry & Engineering* 2(2): 207-215.

Elroa M, JC Costa, MM Alves, C Kennes, and MC Veiga. 2012. 'Evaluation of the biomethane potential of solid fish waste', *Waste management*, 32: 1347-52.

Feidt A. 2018. "The Cost of Cold: When the only option is diesel." from https://www.alaskapublic.org/2018/03/19/the-cost-of-cold-when-the-only-option-is-diesel/.

Gan Y and HS Matthews. 2018. A Comparison of Methods and Results from the 2007 Benchmark USEEIO Model and the 2002 EIO-LCA Model.

Gebauer R and B Eikebrokk. 2006. "Mesophilic anaerobic treatment of sludge from salmon smolt hatching." *Bioresource Technology* 97(18): 2389-2401.

Ghadiryanfar M, KA Rosentrater, A Keyhani, and M Omid. 2016. "A review of macroalgae production, with potential applications in biofuels and bioenergy." *Renewable and Sustainable Energy Reviews* 54: 473-481.

Gollakota A, N Kishore, and S Gu. 2018. "A review on hydrothermal liquefaction of biomass." *Renewable and Sustainable Energy Reviews* 81: 1378-1392.

Group M. (2017a). Alaska Mariculture Initiative Economic Analysis to Inform a Comprehensive Plan PHASE II. Alaska Mariculture Task Force. http://www.mcdowellgroup.net/wp-content/uploads/2017/10/mtf-phase-ii-full-report-draft-2017-08-14.pdf,

Group, M. (2017b). "The economic value of Alaska's seafood industry." Alaska Seafood Marketing Institute.

Gunaseelan VN. 1997. "Anaerobic Digestion of Biomass for Methane Production: A Review." *Biomass and Bioenergy* 13(1/2): 83-114.

Kafle, GK, S Kim, and K Sung III. 2013. 'Ensiling of fish industry waste for biogas production: a lab scale evaluation of biochemical methane potential (BMP) and kinetics', *Bioresource technology*, 127: 326-36.

Kim N-J, H Li, K Jung, HN Chang, and PC Lee. 2011. "Ethanol production from marine algal hydrolysates using Escherichia coli KO11." *Bioresource Technology* 102(16): 7466-7469.

Langlois J, JF Sassi, G Jard, JP Steyer, JP Delgenes, and A Hélias. 2012. "Life cycle assessment of biomethane from offshore-cultivated seaweed." *Biofuels, Bioproducts and Biorefining* 6(4): 387-404.

Li, D, L Chen, D Xu, X Zhang, N Ye, F Chen, and S Chen. 2012. 'Preparation and characteristics of bio-oil from the marine brown alga Sargassum patens C. Agardh', *Bioresource technology*, 104: 737-42.

Milledge JJ, BV Nielsen, S Maneein, and PJ Harvey. 2019. "A brief review of anaerobic digestion of algae for bioenergy." *Energies* 12(6): 1166.

Milledge JJ, B Smith, PW Dyer, and P Harvey. 2014. "Macroalgae-derived biofuel: a review of methods of energy extraction from seaweed biomass." *Energies* 7(11): 7194-7222.

Mshandete, A, A Kivalsi, M Rubindamayugi, and BO Mattiasson. 2004. 'Anaerobic batch co-digestion of sisal pulp and fish wastes', *Bioresource technology*, 95: 19-24.

Mutter EA. 2014. Assessment of contaminant concentrations and transport pathways in rural Alaska communities' solid waste and wastewater sites.

Nges IA, B Mbatia, and L Björnsson. 2012. "Improved utilization of fish waste by anaerobic digestion following omega-3 fatty acids extraction." *Journal of Environmental Management* 110: 159-165.

Offei F, M Mensah, A Thygesen, and F Kemausuor. 2018. "Seaweed bioethanol production: A process selection review on hydrolysis and fermentation." *Fermentation* 4(4): 99.

Olsson J, GB Toth, and E Albers. 2020. "Biochemical composition of red, green and brown seaweeds on the Swedish west coast." *Journal Oof Applied Phycology.*

Øverland M, LT Mydland, and A Skrede. 2019. "Marine macroalgae as sources of protein and bioactive compounds in feed for monogastric animals." *Journal of the Science of Food and Agriculture* 99(1): 13-24.

Oyler J. 2014. Hydrothermal Processing of Wet Wastes. Genifuel.

Pechsiri JS, J-BE Thomas, E Risén, MS Ribeiro, ME Malmström, GM Nylund, A Jansson, U Welander, H Pavia, and F Gröndahl. 2016. "Energy performance and greenhouse gas emissions of kelp cultivation for biogas and fertilizer recovery in Sweden." *Science of the Total Environment* 573: 347-355.

Quinn R. 2020, 01/08/2020. "DTN Retail Fertilizer Trends." Retrieved 10/30/2020, from https://www.dtnpf.com/agriculture/web/ag/crops/article/2020/01/08/fertilizer-prices-mostly-lower-start#:~:text=The%20starter%20fertilizer%20had%20an,N%2C%20UAN28%20%240.42%2Flb.

Raikova S, MJ Allen, CJ Chuck. 2019. 'Hydrothermal liquefaction of macroalgae for the production of renewable biofuels', *Biofuels, Bioproducts and Biorefining,* 13: 1483-504.

Risén E, O Tatarchenko, F Gröndahl, and ME Malmström. 2014. "Harvesting of drifting filamentous macroalgae in the Baltic Sea: an energy assessment." *Journal of Renewable and Sustainable Energy* 6(1): 013116.

Roesijadi G, A Copping, M Huesemann, J Forster, and J Benemann. 2008. "Techno-economic feasibility analysis of offshore seaweed farming for bioenergy and biobased products." Report Number PNWD-3931: 1e115, Battelle Pacific Northwest Division, Richland, Washington.

Roesijadi G, SB Jones, LJ Snowden-Swan, and Y Zhu. 2010. *Macroalgae as a Biomass Feedstock: A Preliminary Analysis*. PNNL-19944-2, Pacific Northwest National Laboratory, Richland, Washington.

Ross AM, DE Hastings, JM Warmkessel, and NP Diller. 2004. "Multi-attribute tradespace exploration as front end for effective space system design." *Journal of Spacecraft and Rockets* 41(1): 20-28.

Seghetta M, H Østergård, and S Bastianoni. 2014. "Energy analysis of using macroalgae from eutrophic waters as a bioethanol feedstock." *Ecological Modelling* 288: 25-37.

Seghetta M, D Romeo, M D'este, M Alvarado-Morales, I Angelidaki, S Bastianoni, and M. Thomsen. 2017. "Seaweed as innovative feedstock for energy and feed–Evaluating the impacts through a Life Cycle Assessment." *Journal of Cleaner Production* 150: 1-15.

Solow AR. 2005. "Red tides and dead zones: The coastal ocean is suffering from an overload of nutrients." *Oceanus* 43(1): 43-46.

van Oirschot R, J-BE Thomas, F Gröndahl, KP Fortuin, W Brandenburg, and J Potting. 2017. "Explorative environmental life cycle assessment for system design of seaweed cultivation and drying." *Algal Research* 27: 43-54.

Vaught L. 2020. *Southwest Alaska Energy Network-Final Report*. Southwest Alaska Municipal Conference.

Zastrow DJ and PA Jennings. 2013. *Hydrothermal Liquefaction of Food Waste and Model Food Waste Compounds.* Florida Institute of Technology Melbourne, Florida.

Zhou, D, L Zhang, S Zhang, H Fu, J Chen. 2010. 'Hydrothermal liquefaction of macroalgae Enteromorpha prolifera to bio-oil', *Energy & Fuels*, 24: 4054-61.

6.0 Aquatic Ecology Assessment in Southwest Alaska

In Alaska, fisheries and related activities such as seafood processing have a large impact on the economy. Seafood processing is the largest manufacturing sector, representing over 70% of the manufacturing employment.[1] Because Alaska fisheries are seasonal, the associated manufacturing jobs are mostly for nonresident workers, and the industry is only operational half of the year. The PNNL, SWAMC, and Blue Evolution partnered to assess the potential to develop a dual use of the seafood processing and manufacturing facilities in Southwest Alaska, by focusing on kelp harvesting and processing that can be executed when facilities are typically unused.

Kelp is a brown macroalgae seaweed inhabiting the cold water of coastal regions. Kelp farming, harvesting, and processing represent an important industry in Asia, such as in China and Japan, and are increasing in Europe (Sweden, Norway), North America (United States, Canada), and South America (Chile). In the United States, there is potential for kelp farming and processing in Southwest Alaska, however, some key environmental challenges need to be overcome. For example, harvesting kelp from their natural habitat may have an effect on the ecosystem, particularly on aquatic species that use kelp during critical life stages.

In this chapter, PNNL describes the aquatic ecologic assessment performed in Southwest Alaska to assess the potential influence of kelp farming on the marine ecosystem. Species that are federally listed, as well as critical and essential fish habitats in Southwest Alaska are described. The use of kelp habitat by aquatic species as well as the potential effects of kelp farming on these species are discussed. A conceptual framework is proposed to determine the aquatic species and habitat that may be affected by kelp harvesting.

6.1 Species and Critical Habitats in Southwest Alaska

The following aquatic species are federally listed and known to be present in southwestern Alaska (seasonally or annually).

- Endangered species:
  - beluga whale (*Delphinapterus leucas*); distinct population segment in Cook Inlet (73 FR 62919); designated critical habitat in Cook Inlet (76 FR 20179)
  - humpback whale (*Megaptera novaeangliae*) (81 FR 62259)
  - North Pacific right whale (*Eubalaena japonica*) (73 FR 12024); designated critical habitat in the Gulf of Alaska (73 FR 19000)
  - fin whale (*Balaenoptera physalus*) (83 FR 4032)
  - gray whale (*Eschrichtius robustus*); western North Pacific distinct population segment (83 FR 4032)
  - blue whale (*Balaenoptera musculus*) (35 FR 18319)
  - sei whale (*Balaenoptera borealis*) (35 FR 12222)
  - sperm whale (*Physeter macrocephalus*) (35 FR 18319)

[1] https://www.akrdc.org/fisheries

- – Steller sea lion (*Eumetopias jubatus*); western distinct population segment (64 FR 14052); designated critical habitat (79 FR 46392)

- Threatened species:
  - – Northern sea otter (*Enhydra lutris kenyoni*); Southwest Alaska distinct population segment (74 FR 51988)

6.1.1 Endangered Species

All the species described in the following sections are listed as endangered under the Endangered Species Act (ESA). **Error! Reference source not found.** shows the habitat of ESA-listed marine mammals in Southwest Alaska.

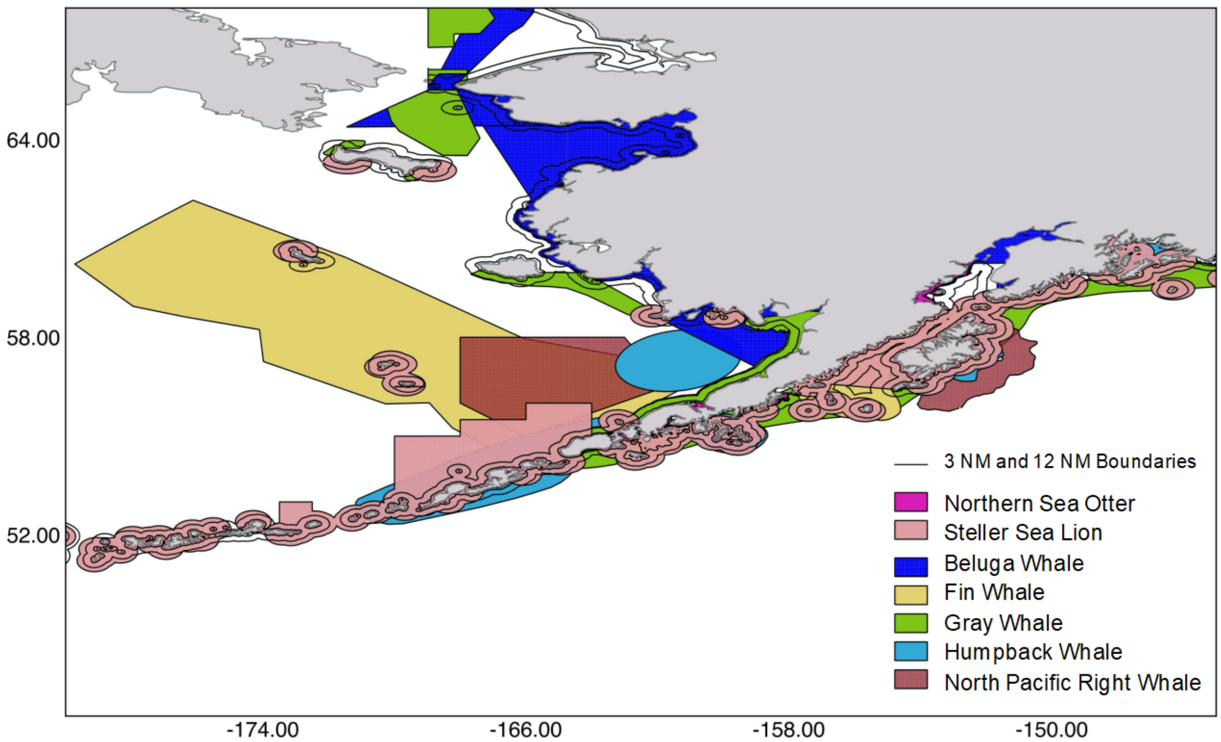

Figure 6.1. Habitat of ESA-listed marine mammals in Southwest Alaska. (Note: Data for blue whales, sei whales, and sperm whales were not available.)

6.1.1.1 Beluga Whale

All beluga whale populations are protected under the Marine Mammal Protection Act (MMPA). The beluga whale distinct population segment (DPS) in Cook Inlet is one of five populations of beluga in Alaska and is listed as endangered under the ESA. The Cook Inlet stock is also designated as depleted under the MMPA. Beluga whales are usually found in shallow coastal waters during the summer months. During other seasons, they inhabit deep water areas. Belugas also seasonally inhabit estuaries and large river deltas. They return to their birth areas along the coast each summer to hunt, breed, and calve.

6.1.1.2 Humpback Whale

In the North Pacific, there are four populations of humpback whales. The Mexico DPS breeds along the Pacific coast of Mexico and feeds between California and the Aleutian Islands (Alaska). The Central American DPS breeds along the coast of Central America and feeds off the west coast of the United States and British Columbia (Canada). The Hawaii DPS breeds off Hawaii and feeds in Southeast Alaska and British Columbia. Finally, the western North Pacific DPS breeds off the coast of west Asia and feeds in the west Bering Sea and off the coast of Russia and the Aleutian Islands. The Mexico DPS, the Central America DPS, and the western North Pacific DPS are listed as endangered under the ESA. Humpback whales are protected under the MMPA throughout their range. The western North Pacific stock, central North Pacific stock, and California/Oregon/Washington stock are designated as depleted.

In Alaska, although humpback whales may be seen at any time of the year, most individuals spend the winter in temperate or tropical waters. In the spring, they migrate back to Alaska to feed. In Southwest Alaska, humpback whales are mainly located around Kodiak, the Barren Islands at the mouth of Cook Inlet, and around the Aleutian Islands (**Error! Reference source not found.**).

6.1.1.3 North Pacific Right Whale

North Pacific right whales are believed to feed during summer in high latitudes and migrate toward temperate regions during winter. In Alaska, the population off the west coast is represented by only a few individuals. They are protected and also designated as depleted under the MMPA. In 2006, critical habitat was designated for the species, which includes a large area in the Bering Sea and a relatively small area in the Gulf of Alaska just south of Kodiak Island (**Error! Reference source not found.**).

6.1.1.4 Fin Whale

Fin whales are protected and also designated as depleted under the MMPA. Fin whales feed in Alaska waters during the spring and summer and migrate toward warmer water breeding and calving areas in fall and winter. In Alaska, fin whales are found in the western Chuckchi Sea, the Bering Sea, and throughout the Gulf of Alaska.

6.1.1.5 Gray Whale

Gray whales are protected under the MMPA throughout their range. They are only found in the North Pacific Ocean. The eastern North Pacific population of gray whale was listed as endangered under the ESA until 1994. The western North Pacific DPS is listed as endangered under the ESA and depleted under the MMPA. Gray whales are mainly distributed in shallow waters. In summer, the eastern population of gray whales feed in the northern Bering and Chukchi Seas and along the United States west coast.

6.1.1.6 Steller Sea Lion

In Alaska, Steller sea lions are protected throughout their range under the MMPA. The western DPS is listed as endangered under the ESA and designated as depleted under the MMPA. The population of the western DPS has decreased approximately 77 to 81% from the 1970s to early 2000s. They mainly live around the coasts of the Aleutian Islands and Bering Sea (**Error!**

Reference source not found.). During the non-breeding season, they also inhabit deeper continental slope and pelagic waters.

6.1.1.7 Blue Whale

Blue whales are protected and designated as depleted under the MMPA throughout their range. Blue whales inhabit all the oceans except the Arctic Ocean. They migrate in summer toward their feeding grounds and winter toward their breeding grounds. Along the west coast of United States, they are observed off the coasts of Mexico and Central America in winter, and off the west coast and in the Gulf of Alaska in summer.

6.1.1.8 Sei Whale

Sei whales are protected and designated as depleted under the MMPA throughout their range. They typically are observed in deep waters off the coast. In summer, they are observed from California to the Gulf of Alaska, and, in winter, from central California to the equator.

6.1.1.9 Sperm Whale

Sperm whales are protected and designated as depleted under the MMPA throughout their range. They spend most of the time in deep waters and inhabit all the oceans. Their migration patterns are not well understood. Sperm whales inhabiting mid-latitudes generally move toward the poles in summer.

6.1.2 Critical Habitats

Critical habitats are specific areas within the spatial distribution of species that contain physical or biological characteristics essential for their conservation, or specific areas outside of their spatial distribution that are deemed essential for conservation.

In southwestern Alaska, critical habitats are described for three species of marine mammals: Steller sea lion, beluga whale, and North Pacific right whale (see Figure 6.2).

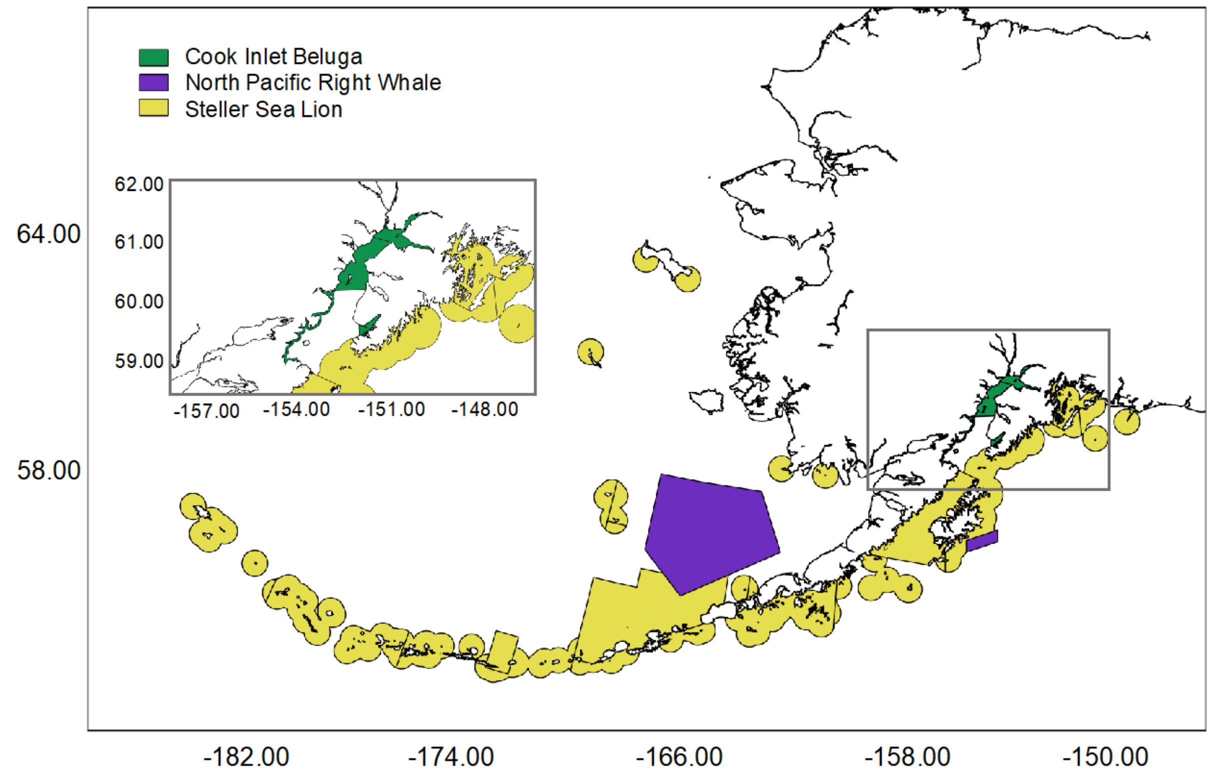

Figure 6.2. Designated critical habitats for Steller sea lion, beluga whale, and North Pacific right whale in Southwest Alaska, U.S.

6.2 Essential Fish Habitat

Essential fish habitat (EFH) is defined by the Magnuson-Stevens Fishery Conservation and Management Act (MSA) as "waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." EFHs have been identified in the southwestern Alaska for the following groups:

- salmon – juveniles and adults,
- scallop – all life stages,
- king and Tanner crabs – all life stages, and
- groundfish – all life stages.

Habitat Areas of Particular Concern (HAPCs) are smaller habitat areas within EFH and are priority areas for conservation and management efforts. HAPCs within southwestern Alaska include the following:

- the Alaska Seamount Habitat Protection Areas,
- the Bowers Ridge Habitat Conservation Zone, and
- the Gulf of Alaska Coral Habitat Protection Areas.

EFH and HAPCs are mapped in Figure 6.3.

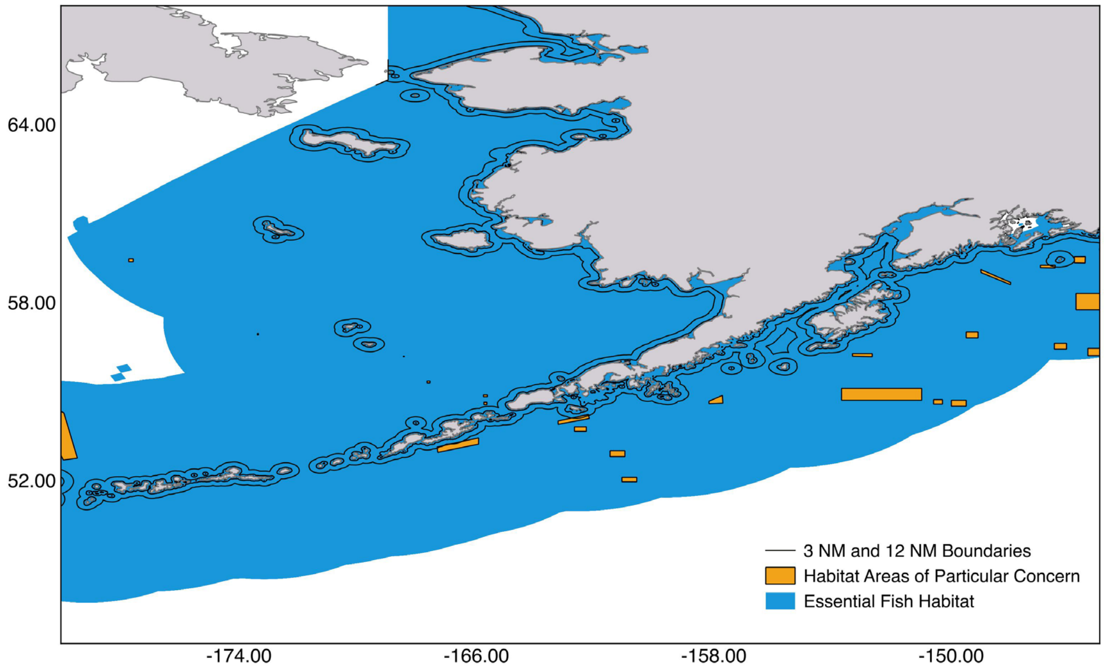

Figure 6.3. Essential fish habitat and habitat areas of particular concern in Southwest Alaska, U.S.

6.2.1 Salmon

Five species of Pacific salmon are present in Southwest Alaska: Chinook (*Oncorhynchus tshawytscha*), coho *(Oncorhynchus kisutch)*, pink *(Oncorhynchus gorbuscha)*, Sockeye (*Oncorhynchus nerka*), and chum *(Oncorhynchus keta)*. Areas that are relevant to consider for kelp harvesting are the ones important for ocean rearing of juveniles, and for juvenile and adult migration. All species feed in the entire water column.

6.2.2 Scallop

Relevant EFH to consider for kelp harvesting are habitats where all scallop (weathervane scallops [*Patinopecten caurinus*], pink or reddish scallops [*Chlamys rubida*], spiny scallops [*Chlamys hastata*], and rock scallops [*Crassadoma gigantea*]) life stages are found. Eggs and larvae of scallops are planktonic, and the larval dispersal duration is about 1 month. Settlement of larvae occurs in the bottom of the water column. Juveniles and adults have low mobility.

6.2.3 King and Tanner Crabs

Species of interest in the Bering Sea/Aleutian Islands area include red king crab (*Paralithodes camtschaticus*), blue king crab (*P. platypus*), golden (or brown) king crab (*Lithodes aequispinus*), Tanner crab (*Chionoecetes bairdi* and *C. opilio*).

King and Tanner crabs inhabit shallow inshore areas (less than 50 m depth) during reproduction and mating. The larval stage is planktonic, and larvae are generally distributed in the upper 30 m of the water column. The settlement of larvae occurs on the bottom of the water column and in shallow areas. Important locations for king crab spawning and juvenile rearing in Southwest Alaska include the area north and adjacent to the Alaska Peninsula (Unimak Island to Port

Moller), the eastern portion of Bristol Bay, and nearshore areas of the Pribilof and Saint Matthew Islands.

6.2.4 Groundfish of the Gulf of Alaska

Groundfish species in Southwest Alaska consist of walleye pollock (*Gadus chalcogrammus*), Pacific cod (*Gadus macrocephalus*), sablefish, flatfish, rockfish, Atka mackerel (*Pleurogrammus monopterygius*), skates, sculpins, sharks, and octopuses. Forage fish species, grenadiers, and squids are also included in this group. All life stages of groundfish inhabit the water column of pelagic waters throughout the Gulf of Alaska. Juvenile and adult stages are generally located in the lower portion of the water column along the entire shelf.

6.3 Use of Kelp Habitat

Kelp forests are highly productive habitats and are found on rocky reefs. Kelps are composed of blades (leaves), stipes (stems), and holdfasts (roots, attached to submerged rocks), and provide shelter and food for many species such as invertebrates, fish, and marine mammals

6.3.1 Aquatic Resources Using Kelp Habitat

Johnson et al. (2003) studied fish assemblages in kelp habitat of southeastern Alaska from 1998 to 2000. Kelp habitat was found to support high biodiversity and to be an important nursery habitat for juveniles of many commercially important or forage fish species. Several species included within either salmon or groundfish groups in Alaska were observed in kelp habitat. This includes commercial species, such as rock sole (*Lepidopsetta bilineata*), quillback rockfish (*Sebastes maliger*), yellowtail rockfish (*Sebastes flavidus*), chum salmon, and pink salmon, as well as forage species, such as Arctic shanny (*Stichaeus punctatus*), Pacific herring (*Clupea pallasii*), and Pacific sandfish (*Tricodon tricodon*).

Although Johnson et al.'s (2003) study occurred in southeastern Alaska, similar fish assemblages are observed in southwestern Alaska as shown by Dean et al.'s (2002) study conducted in Prince William Sound. The most common species observed in kelp habitat were chum salmon, shiner perch (Cymatogaster *aggregata*), crescent gunnel (*Pholis laeta*), Pacific herring, and Pacific sand lance (*Ammodytes hexapterus*). All are key forage species for other species of fish such as salmon, birds, and marine mammals.

The following species use kelp as spawning or nursery habitat in Alaska:

- Pacific herring spawn between March and June and also use kelp as rearing habitat.
- Canary rockfish (*Sebastes pinniger*) spawn during winter.
- Rockhead (*Bothragonus swanii*) spawn in winter and spring and in nearshore habitats. Eggs are attached to kelp holdfasts.
- Yelloweye rockfish (*Sebastes ruberrimus*).
- Giant kelpfish (*Heterostichus rostratus*) spawn year-round with spawning peaking from February to April. Eggs are found on floating kelp filaments.
- Kelp clingfish (*Rimicola muscarum*). Eggs are attached on the blades of kelp beds.
- Kelp greenling (*Hexagrammos decagrammos*) spawn between October and November.

Marine mammals such as sea otters, seals, sea lions, and whales are known to use kelp habitat to feed or escape from predators. Sea otters play a particularly important role for kelp as they prey on sea urchins. While sea urchins graze kelp and large populations of sea urchins can decimate an entire kelp forest, sea otters help keep kelp forests thriving by feeding on sea urchins, thereby helping to control their population.

6.3.2 Potential Environmental Effects of Kelp Harvesting

The habitat function of wild vs. cultivated kelp populations is not well understood. Although kelp cultivation would create new habitat and have positive effects on biodiversity (Hasselström et al. 2018), it could also induce the displacement of local fish and invertebrate species from their natural habitat to a new artificial habitat, and potential changes in benthic communities. The long-term consequences of these changes on the ecosystem are unknown.

Effects on the environment of harvesting wild or cultivated kelp are likely similar. Lorentsen et al. (2010) investigated the environmental consequences of harvesting kelp along the coast of central Norway. They found that the number of juvenile gadid fish, an important commercial species in Norway, was lower (up to 92%) in harvested kelp areas than in un-harvested areas. This low abundance was also correlated to a lower foraging yield in harvested areas for great cormorants (*Phalacrocorax carbo*), one of the main predators of gadid fish. Although experimental, this study demonstrated direct (decrease of preys associated with habitat removal) and indirect (decrease of foraging yield) effects of kelp harvesting on the environment.

Because kelp has high growth rates and is able to rapidly recover after removal, kelp harvesting may be possible if properly managed (Mineur et al. 2015). Some examples of management practices could be acceptable levels of kelp removal related to the kelp recovery rate and the effects on ecosystems. These effects would first need to be quantified and are largely species-specific, depending on the use of kelp habitat by the species of interest (Bertocci et al. 2015).

Changes in the environment caused by kelp harvesting may also be combined with the effects of other human activities and natural processes. Fisheries, energy development, and climate change are other important processes to consider when evaluating the effects on the environment. With climate change, kelp populations are expected to decline or spatially shift (Raybaud et al. 2013), and the ecological consequences of these changes are not known. A better understanding of the effects of kelp harvesting is needed to mitigate cumulative effects on the environment.

6.4 Conceptual Framework to Assess Aquatic Resources

The conceptual framework shown in Figure 6.4. Conceptual framework for determining the aquatic resources that may be affected by the harvesting of kelp. can be used to determine the aquatic resources that may be affected by the harvesting of kelp. The framework summarizes the key biological and ecological processes developed in the previous sections.

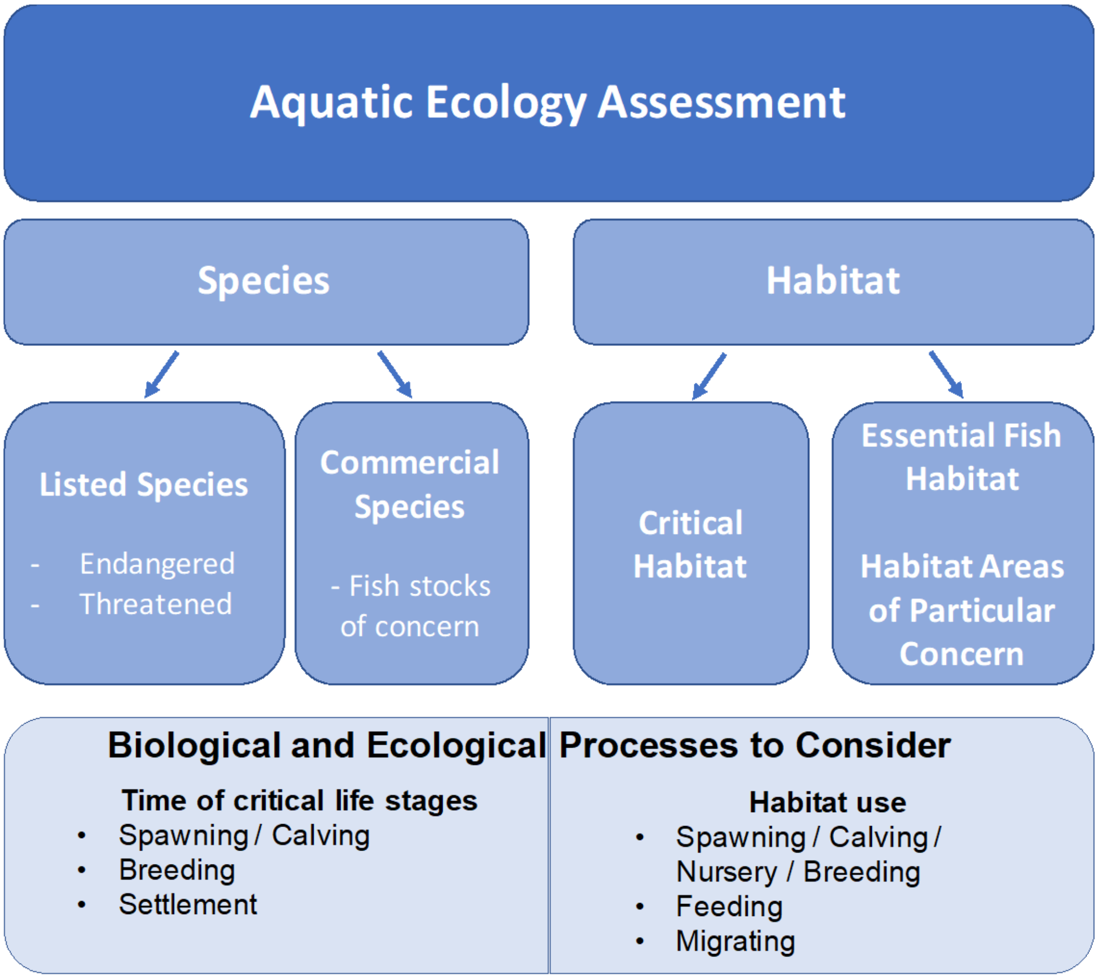

Figure 6.4. Conceptual framework for determining the aquatic resources that may be affected by the harvesting of kelp.

6.5 Conclusion

Table 6.1. ESA-listed species of marine mammals including MMPA status, critical habitat, and seasonality in Southwest Alaska. provides an overview of ESA-listed species, their critical habitats, and their temporal distribution (seasonality) in Southwest Alaska. Beluga whale, Steller sea lion, and northern sea otter are present all year around in Southwest Alaska. Other species are mainly observed there in spring and/or summer.

Table 6.1. ESA-listed species of marine mammals including MMPA status, critical habitat, and seasonality in Southwest Alaska.

Species	Status	Critical Habitat	Seasonality
Humpback whale (*Megaptera novaeangliae*)	MMPA protected		Spring and Summer
Mexico DPS	Endangered		
Western North Pacific DPS			

Species	Status	Critical Habitat	Seasonality
	Endangered, MMPA depleted		
Beluga Whale (*Delphinapterus leucas*) Cook Inlet DPS	MMPA protected Endangered, MMPA depleted	X	All year
North Pacific Right Whale (*Eubalaena japonica*)	Endangered, MMPA protected and depleted	X	Summer
Fin Whale (*Balaenoptera physalus*) – Alaska Northeast Pacific	Endangered, MMPA protected and depleted		Spring and Summer
Gray Whale (*Eschrichtius robustus*) Western North Pacific DPS	MMPA protected Endangered MMPA depleted		Summer
Blue Whale (*Balaenoptera musculus*)	Endangered, MMPA protected and depleted		Summer
Sei Whale (*Balaenoptera borealis*)	Endangered, MMPA protected and depleted		Summer
Sperm Whale (*Physeter macrocephalus*)	Endangered, MMPA protected and depleted		Summer
Steller Sea Lion (*Eumetopias jubatus*) western DPS	MMPA protected Endangered, MMPA depleted	X	All year
Northern Sea Otter (*Enhydra lutris kenyoni*)	Threatened, MMPA		All year

6.6 References

35 FR 18319 - Endangered and Threatened Wildlife and Plants; Identification of 14 Distinct Population Segments of the Humpback Whale and Revision of Species-Wide Listing. Federal Register / Vol. 81, No. 245 / Wednesday, December 21, 2016 / Rules and Regulations.

35 FR 12222 - Clarification of the Practice for Requiring Additional Information in Petitions Filed in Patent Applications and Patents Based on Unintentional Delay. Federal Register / Vol. 85, No. 41 / Monday, March 2, 2020 / Rules and Regulations.

64 FR 14052 - Endangered and Threatened Species; Regulations Consolidation. Federal Register / Vol. 64, No. 55 /Tuesday, March 23, 1999 /Rules and Regulations.

73 FR 12024 - Endangered and Threatened Species; Endangered Status for North Pacific and North Atlantic Right Whales. Federal Register / Vol. 73, No. 45 / Thursday, March 6, 2008 / Rules and Regulations.

73 FR 19000 - Endangered and Threatened Species; Designation of Critical Habitat for North Pacific Right Whale. Federal Register / Vol. 73, No. 68 / Tuesday, April 8, 2008 / Rules and Regulations.

73 FR 62919 - Endangered and Threatened Species; Endangered Status for the Cook Inlet Beluga Whale. Federal Register / Vol. 73, No. 205 / Wednesday, October 22, 2008 / Rules and Regulations.

74 FR 51988 - Endangered and Threatened Wildlife and Plants; Southwest Alaska Distinct Population Segment of the Northern Sea Otter (Enhydra lutris kenyoni): Availability of Recovery Plan. Federal Register / Vol. 78, No. 173 / Friday, September 6, 2013 / Notices.

76 FR 20179 - Endangered and Threatened Species: Designation of Critical Habitat for Cook Inlet Beluga Whale. Federal Register / Vol. 76, No. 69 / Monday, April 11, 2011 / Rules and Regulations.

79 FR 46392 - Endangered and Threatened Species; Designation of Critical Habitat for Steller Sea Lions; Public Meeting. Federal Register / Vol. 79, No. 153 / Friday, August 8, 2014 / Proposed Rules.

81 FR 62259 - Endangered and Threatened Species; Identification of 14 Distinct Population Segments of the Humpback Whale (Megaptera novaeangliae) and Revision of Species-Wide Listing. Federal Register / Vol. 81, No. 174 / Thursday, September 8, 2016 / Rules and Regulations.

83 FR 4032 - Proposed Information Collection; Comment Request; Weather Modification Activities Reports. Federal Register / Vol. 83, No. 19 / Monday, January 29, 2018 / Notices.

Bertocci I, R. Araújo, P. Oliveira, and I Sousa-Pinto. 2015. Review: Potential effects of kelp species on local fisheries. Journal of Applied Ecology 52, 1216-1226.

Dean TA, L. Haldorson, DR Laur, SC Jewett, and A Blanchard. 2000. The distribution of nearshore fishes in kelp and eelgrass communities in Prince William Sound, Alaska: associations with vegetation and physical habitat characteristics. Environmental Biology of Fishes 57, 271-287.Endangered Species Act of 1973, as amended. 16 U.S.C. ch. 35 § 1531 et seq.

Hasselström L, W Visch, F Gröndahl, G Nyland, and H Pavia. 2018. “The impact of seaweed cultivation on ecosystem services – a case study from the west coast of Sweden”. Marine Pollution Bulletin 133, 53-64.

Johnson SW, ML Murphy, DJ Csepp, PM Harris, and JF Thedinga. 2003. A survey of fish assemblages in eelgrass and kelp habitats of southeastern Alaska. NOAA Technical Memorandum NMFS-AFSC-139.

Lorentsen S-H, K Sjøtun, and D Grémillet. 2010. “Multi-trophic consequences of kelp harvest.” *Biological Conservation* 143, 2054-2062.

Magnuson-Stevens Fisheries Conservation and Management Act of 1976. 16 U.S.C. ch 38 § 1801 et seq.

Mineur F, F Arenas, J Assis, A Davies, et al. 2015. “European seaweeds under pressure: Consequences for communities and ecosystem functioning”. *Journal of Sea Research* 98, 91-108.

Raybaud V, G Beaugrand, E Goberville, G Delebecq, C Destombe, M Valero, D Davoult, P Morin, F Gevaert. 2013. “Decline in Kelp in West Europe and Climate.” *PLoS ONE* 8(6): e66044

7.0 Kelp Asset World Survey

Kelps are a group of conspicuous, large brown macroalgae in the Class Phaeophyta and Order Laminariales. Kelps commonly grow in areas ranging from temperate to subpolar regions as shown in Figure 7.1, and do not naturally exist in waters warmer than 20°C. Although not considered to be a diverse group with around 30 genera, their ecological importance cannot be understated. Kelps grow in large groups, ranging in size and density, however, the kelp beds of the giant kelp *Macrocystis pyrifera* can extend for many kilometers and be dense enough to act as a natural wave break, with individual thalli, analogous to the stems of plants, reaching up to 30 m (Mondragon 2003). The value of such an ecosystem service is difficult to calculate because its presence is so integral to the function of the diverse ecosystem that develops around it. Numerous species of fish, invertebrates, marine mammals, and other macroalgae use these ideal conditions.

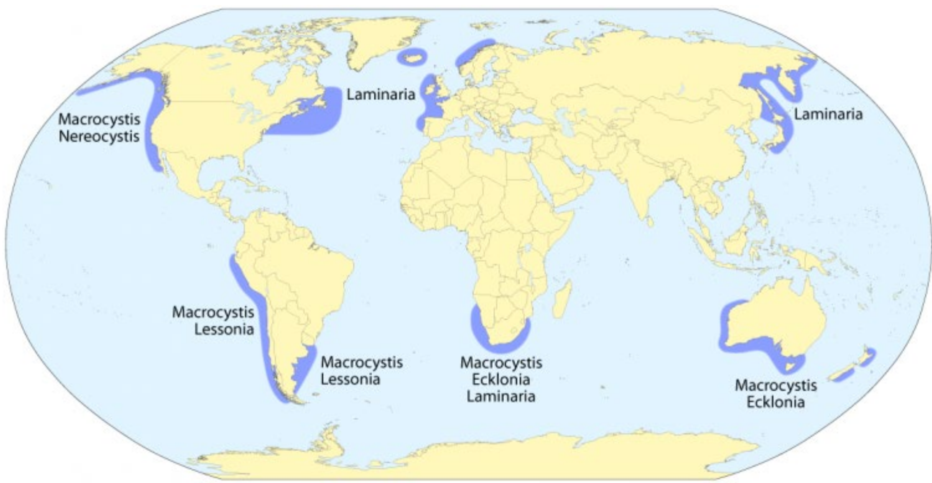

Figure 7.1. The global distribution of kelp species with some of the primary genera that occupy those locations. (Courtesy of Maximilian Dörrbecker)

7.1 Background

The historical uses of kelp are extensive. Some evidence shows that kelp and other seaweeds were dried and preserved by early humans in the Neolithic Era around 20,000 years ago (Dillehay et al. 2008). Existing historical records show that seaweeds were held in high regard in Japanese and Chinese cultures—only the ruling class could eat them. Around the year 3600 BC, the Chinese discovered that goiters could be treated by having the afflicted person ingest kelp. Kelps are natural bioaccumlators of iodine, and can concentrate the essential mineral by 30,000x the concentration of the seawater in which they live (Zava 2011). In Europe, kelps and other seaweeds were commonly used to feed livestock or spread onto fields to act as a natural fertilizer before commercial fertilizers were available.

Industrial uses for kelps did not develop until around the 16th century when it was discovered that seaweed could be burned to produce sodium salts (soda) and potassium salts (potash) and that, compared to other seaweeds, kelps produced the most soda and. The soda and potash obtained from the burning of kelps were used to produce glass, fertilizers, and eventually, gunpowder. Elemental iodine was accidentally discovered in 1811 when a French chemist mixed kelp-derived potash with sulfuric acid, which produced a purple vapor and was recognized as a new substance and named iodine. Once the useful properties of iodine were discovered, such as its role as an antiseptic and as a treatment for goiter, iodine was produced from kelp potash at a commercial scale. When World War I began, Germany, the single largest producer of potash for fertilizer, placed an embargo on all exports of potash. This prompted the United States Government to begin to intensively research the kelp resources on its, which led to the commercial scale harvesting of the *Macrocystis* beds along the coast of California.

Although the harvest of various seaweeds and kelps has been taking place for thousands of years, the intentional farming of kelp is a fairly recent practice. *Saccharina japonica* was accidentally introduced to the shores of China in the early 20th century, but its presence was embraced and capitalized on. In Japan, kelp harvesters would throw rocks into the water around kelp beds, providing more substrate on which juvenile kelps could attach and grow. The same practice was applied around the introduced kelp thalli in China to firmly establish the species in the area. In the mid-20th century, the Chinese developed the methods by which *S. japonica* could be cultivated on a rope culture.

A great deal of research went into learning how to exploit their alternation of heteromorphic generations to harvest the large, blade-like diploid stage and use the microscopic haploid stage to seed the lines. While the industry was still in its infancy, strain selection was initiated to develop superior strains that would grow larger, and for a longer season, in order to increase their yields and extend the growing season to provide kelp for an extended time period. Today, China, Japan, the Republic of Korea, and the Democratic Republic of Korea all use their own cultivars.

Cultivation methods have evolved as better products have come onto the market. In the 1950s, kelp seedlings were cultivated on ropes made of twisted palm or straw fibers and held afloat with sections of large-diameter bamboo that acted as floats. The bamboo floats were replaced with glass floats, and palm ropes were replaced with nylon ropes. Today, plastic floats and nylon ropes are the standard in the industry. As the practices of kelp cultivation have spread around the world, the methods have not changed much. Largely, kelp is grown very similarly to the ways it is done in the main eastern Asian countries with long lines suspended from floats with weights on the grow out lines to keep the kelp at the appropriate depth for optimum growing conditions. The kelp is attached to the main grow out line via the smaller diameter seedstring, or the spores are directly seeded onto the main line. These modern methods have allowed for the rapid expansion of kelp industries in eastern Asian countries. The global industry is dominated by the four pivotal countries: China, South Korea, North Korea, and Japan (Ferdouse et al. 2018), as shown in Figure 7.2.

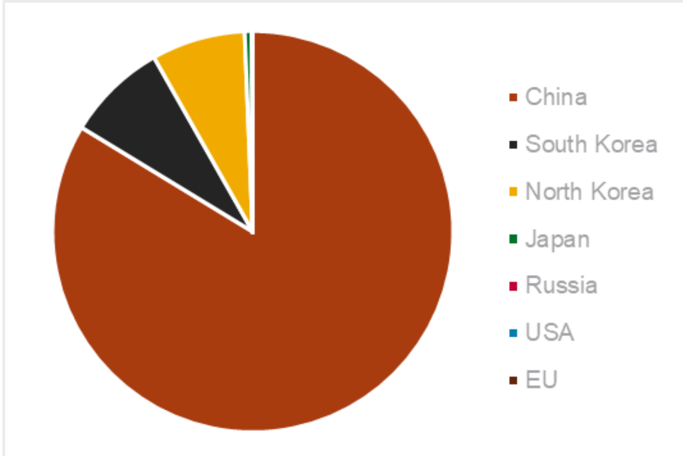

Figure 7.2. Chart of the major kelp producers in the world showing their proportion of the global supply of kelp.

Sometimes in China, kelp seedlings are reared in seawater until they reach a suitable length at which time, they are removed from the seed string and spliced into the main grow out line at appropriate intervals. This prevents overcrowding and produces larger thalli, because there is less competition for light and nutrients. This is especially true for kelp grown specifically for human consumption where a higher-quality crop is needed. When kelp is grown for the hydrocolloid industry or for aquaculture feed for abalone or sea cucumbers, no thinning occurs because quality is less of a concern compared to the need to maximize biomass production.

The uses for kelp are wide and varied. Kelp, especially *S. japonica* and *U. pinnatifida*, has been an important source of food for humans along coastal areas in Eastern Asia. Kombu, the common name for *S. japonica* and a few other related species that originated in Japan, was an important trading commodity that made its way to the interior of China and was eaten as a winter vegetable. I's high vitamin and mineral content made it an important source of nutrients in times when fresh vegetables were impossible to access. The reason *S. japonica* cultivation was so heavily invested in initially was that a significant proportion of Chinese citizens were afflicted with goiters due to iodine deficiency. Hence, the Government encouraged the cultivation of *S. japonica* to make the kelp widely available to improve the health of the country's inhabitants.

Today, kelp is still a valuable commodity. Kombu is sold for around $2,800/T (dried), and *Undaria* or wakame is sold for around $6,900/T (dried) (McHugh 2003). In western countries where *Saccharina latissima* and *Alaria esculenta* are the cultivated species, prices differ. In Norway, *S. latissima* sells for about $399/T and *A. esculenta* sells for about $1,099/ton (wet weight) (Stévant et al. 2017). Although the prices appear to be significantly different, the discrepancy arises because of the presence or absence of water, or wet weight vs dry weight. In reality, western kelp sells for more money than the mass-produced kelps grown in eastern Asia. Differences in prices can vary significantly due to kelp applications and availability. The large difference in prices between *A. esculenta* and *S. latissima* is thought to be in part due to the lack of *A. esculenta* on the market, making it more of a specialty product. Additionally, *S. latissima* has a broader range of applications on the market.

Specific information about the kelp industry is often difficult to come by, and the reasons for this vary by region. In the West, the kelp industries are very young. Research is still ongoing regarding which methods are needed for kelp to be grown successfully. Many farms are little more than experiments or trial runs to investigate the plausibility of a larger-scale operation, and for that reason, the data about the sizes or harvest amounts are nonexistent at times. In other places, the industry is not as valuable as other fisheries or enterprises that are managed within a given agency, and for that reason, the data about the number, size, and production values are not readily available, simply because no one has taken the time to look. In these areas, someone with knowledge and connections in each area would be needed to contact individual companies or growers in order to compile a comprehensive view of the industry.

In the Asian countries where the kelp industry is well-established, as shown in the aerial photo of South Korea's Sisan Island (Figure 7.3), specific information regarding the sizes, locations, and operators of kelp farms is not readily available either. Expansive networks of lines covering thousands of hectares are common sights along the productive coasts of China, the Korean Peninsula, and Japan. South Korea seems to have the most academic papers available regarding their industry, but most information is about selective breeding practices or overall production. China's kelp industry is by far the most substantial because they produce more kelp than the rest of the world combined. However, specific information regarding their farming practices is lacking. Similarly, intentional effort would need to be invested in each country's industry in order to gain a better understanding of the specifics of for each region. A great deal of effort and integral connections would be necessary to elucidate the intricacies of the substantial industry in eastern Asian countries.

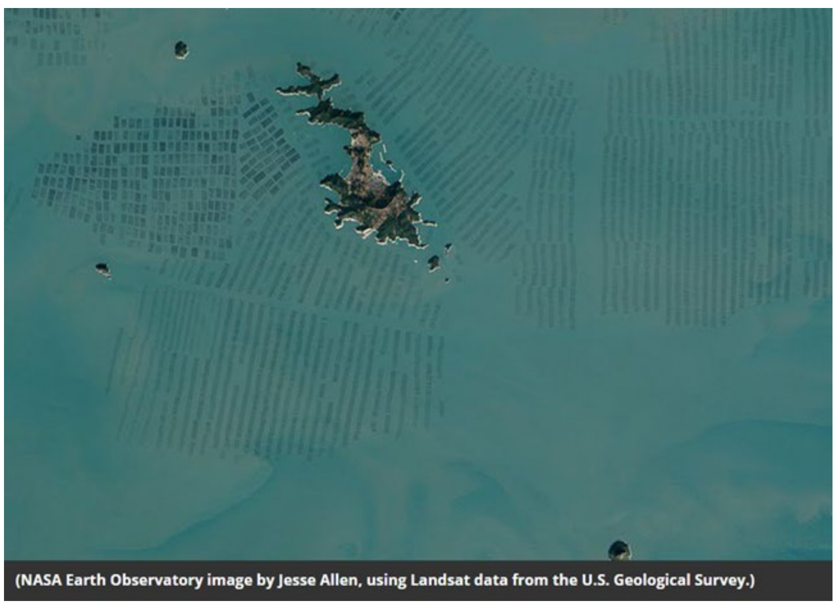

Figure 7.3. Aerial photograph of Sisan Island, South Korea, and the kelp farms that surround it. (The large island is 4.83 km long.)

7.2 China

7.2.1 History

China was producing kelp pre-1950 by relying on wild stocks and patches of kelp that were tended to much like garden plots. Their production peaked in 1949 with a total mass of approximately 40.3 T dry weight. The floating rope or raft culturing methods were being developed during the following two years, allowing for 114.7 T to be harvested in 1953. By 1958, China was producing 6,253.3 T of kelp, an increase of more than 154 times the production in just a span of 8 years (Zeng [Tseng] 1984). The development of these methods of seeding onto an artificial substratum set the stage for the industry in China to scale up the production of kelp extremely rapidly. As seen in Figure 7.4, production levels have continued to grow rapidly, and today, China produces most of the kelp in the world (Ferdouse et al. 2018). Combinations of numerous factors have allowed the production seen today, but the development of rope culture and genetic strain selection are arguably most responsible for the increases in production.

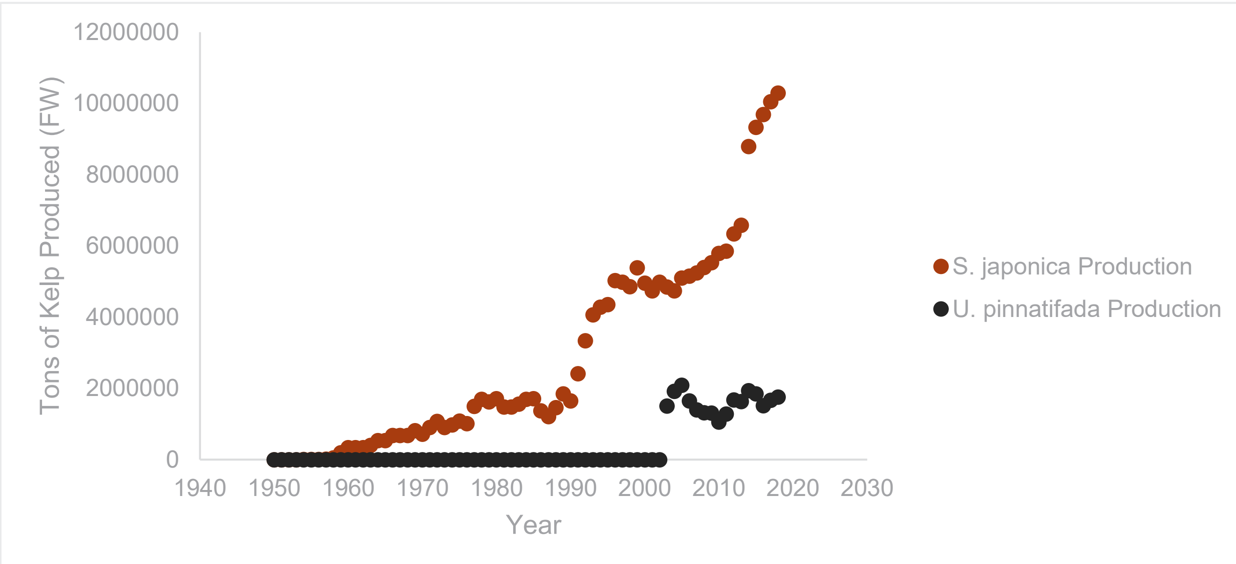

Figure 7.4. China's production of *S. japonica* and *U. pinnatifida*.

7.2.2 Environmental Conditions

China has a long coastline that ranges between latitudes 18° N and 54° N, meaning that the climate changes significantly as one surveys across these latitudes. The northern areas that border Siberia are subboreal, whereas the southern latitudes are quite warm and tropical. This significant transition in temperatures creates variation in the algal species that naturally occur along the coast of China. Kelp species prefer colder water, as is found in China's more northern provinces such as Shandong and Liaoning, where water temperatures stay within kelp's optimal temperatures of 5–10°C. However, experiments in 1956 showed that sufficient growth could still occur in water temperatures above 10°C, so industrial cultivation of *Undaria* and *Saccharina* species spread to China's warmer southern provinces of Zhejiang, Fujian, and Guangdong.

7.2.3 Kelp-Seeding Methods

The methods developed for the seeding of kelp onto an artificial substratum are scalable, meaning that a farmer could have a series of lines that occupy less than a single hectare, or, as seen today, a major company could have a series of lines and floats that covers more than 6,700 ha (Zhang 2015). This ability to adjust the efforts invested based upon the space available has allowed kelp farming practices to spread across much of China's eastern coast. The practices were initiated in the northern province of Liaoning in the city of Dalian. Farms quickly spread to the provinces of Shandong and Jiangsu, both of which have water temperatures in the optimum growing range for the kelp, between 5 and 10°C. Kelp farming in China is a large enterprise, and it represents a significant range in effort invested by each company or farmer. Farms as large as 6,000 ha are managed by major corporations, which represent the majority of the kelp farming effort seen in China. These company farms generally range in size between 3,000 and 6,700 ha and are described as being situated in offshore, open-sea areas. These expansive farms rely on seasonal workers to do the outplanting in the fall and the harvesting in the late spring and early summer. Although large farms represent the majority of kelp farming efforts, the sizes of farms, and the effort that is invested in them varies. In the northern provinces of Shandong and Liaoning, large company farms dominate the available areas. But in the southern provinces, especially in Fujian, smaller family operations still exist, deploying and maintaining lines that occupy a few hundred hectares (Zhang 2015). No major differences in the size or amount of effort exists between farms dedicated to farming different species of kelp.

Although the southern provinces of Zhejiang and Fujian have warmer water temperatures outside of the optimum range, experiments were soon taking place to determine whether Japanese kelp, or kombu, could be grown at a commercial scale. With water temperatures sometimes reaching 20°C and very turbid water, expectations were low. The results of the experiments eventually did show that a sufficient biomass could still be grown, even though the warmer water temperatures cut the growing season significantly shorter than those seen in the northern provinces. The solution to adapting to the turbid water was to simply raise the grow out lines closer to the surface of the water. Once the Zhejiang and Fujian provinces were deemed suitable for kelp cultivation, large-scale farms were soon established there. These farms continue to produce a significant proportion of China's kelp harvest. The expansion of kelp farming in Fujian and Guangdong is closely associated with the expansion of abalone aquaculture (Hwang et al. 2019). Abalone farming has been rapidly expanding in the last several years, and abalone need to be fed fresh feed, much of which is provided through the widespread cultivation of S*accharina* and *Undaria* species. Farms in these southern regions provide a significant portion of the all the kelp grown in China, but many smaller farms also operate in this region. Many of the farms are associated with other larger aquaculture operations to provide feed for other components of integrated multi-trophic aquaculture integrated multi-trophic aquaculture facilities.

7.2.4 Cultivar Development

China's cultivar breeding program originated early in the kelp industry's development. An ideal cultivar can be bred for different purposes. Nearly always, disease resistance is required, because numerous bacterial and pathogenic diseases can severely affect a kelp farm's yield (Fang 1983). Because yields need to be maximized, individual kelp plants are grown tightly together, making entire crops susceptible to outbreaks of disease. Aside from that, cultivars can be bred to increase yields by maximizing the length or thickness of the blades, or they can be bred to have better nutritional quality by having higher vitamin and mineral contents. When iodine was more intensively produced from kelp, a cultivar was bred to improve the levels of iodine that was concentrated with in the kelp tissue. Beginning in 1970, scientists began crossing and breeding *S. japonica* thalli from across all the provinces. While the thalli were maturing, the distal portion of the blade was cut off and tested for iodine levels. The remaining portion of the thalli continued to mature. Using the results from the iodine analysis and growth measurements, individuals were selected for increased growth rates and high iodine contents. The study resulted in two strains that result in larger biomasses and higher iodine contents. Later a hybrid was created by crossing the two strains, and the hybrid reportedly had higher yields than either of the parent strains (Fang 1983). The targeted market will generally dictate which cultivar a farmer will use on their farm. Strains exhibiting higher concentrations of hydrocolloids are better suited for the alginate industry, whereas kelp for human food needs to have superior nutritional qualities and would place a higher priority on appearance.

Many cultivars have been developed in China over the several decades as the industry has progressed. The various strains have been created by individual farms, industries, or researchers (Pang et al. 2015). However, only 10 cultivars have been officially registered with the Chinese Ministry of Agriculture. Of those, there are three types:

- Type one is created by interspecific crossing, meaning that two different cultivars are crossed (Zhang et al. 2011).
- Type two is created by crossing *S. japonica* with an individual of *S. longissima,* and then crossing the hybrid offspring with another *S. japonica* (Li et al. 2008).
- Type three is created by crossing individuals of *S. japonica* that have been geographically isolated (Li et al. 2016).

The whole process is tedious and requires careful tracking of gametophyte parents and corresponding sporophyte offspring. It generally takes 6 years or more for the strain to stabilize on the desirable characteristics (Hwang et al. 2019).

Undaria pinnatifida is the other important kelp species undergoing active cultivation in China. China has native populations of *U. pinnatifida* and has been growing the species since the 1950s. The strains that are grown in the main kelp-growing provinces are believed to have been introduced from Japan, which represents China's main export market (Hwang et al. 2019). Japanese buyers had rigid requirements for the products they were willing to buy, so Japanese strains were introduced to Chinese farms in order to satisfy those requirements. Today, China has two registered strains of *U. pinnatifida* that have been developed in their country. The two cultivars were developed such that one strain matures earlier than the other. This gives enough time in the harvesting season to completely harvest and process the early maturing strain before beginning to harvest the later maturing strain. The staggered harvest times also provide fresh product to consumers for a longer period of time.

Figure 7.5 shows the various provinces in China where kelp is produced, and Table 7.1 lists the kelp strain and recent production for each province. Each color in Table 7.1 corresponds to its placement on the map in Figure 7.5. Cooler colors correspond to cooler water temperatures.

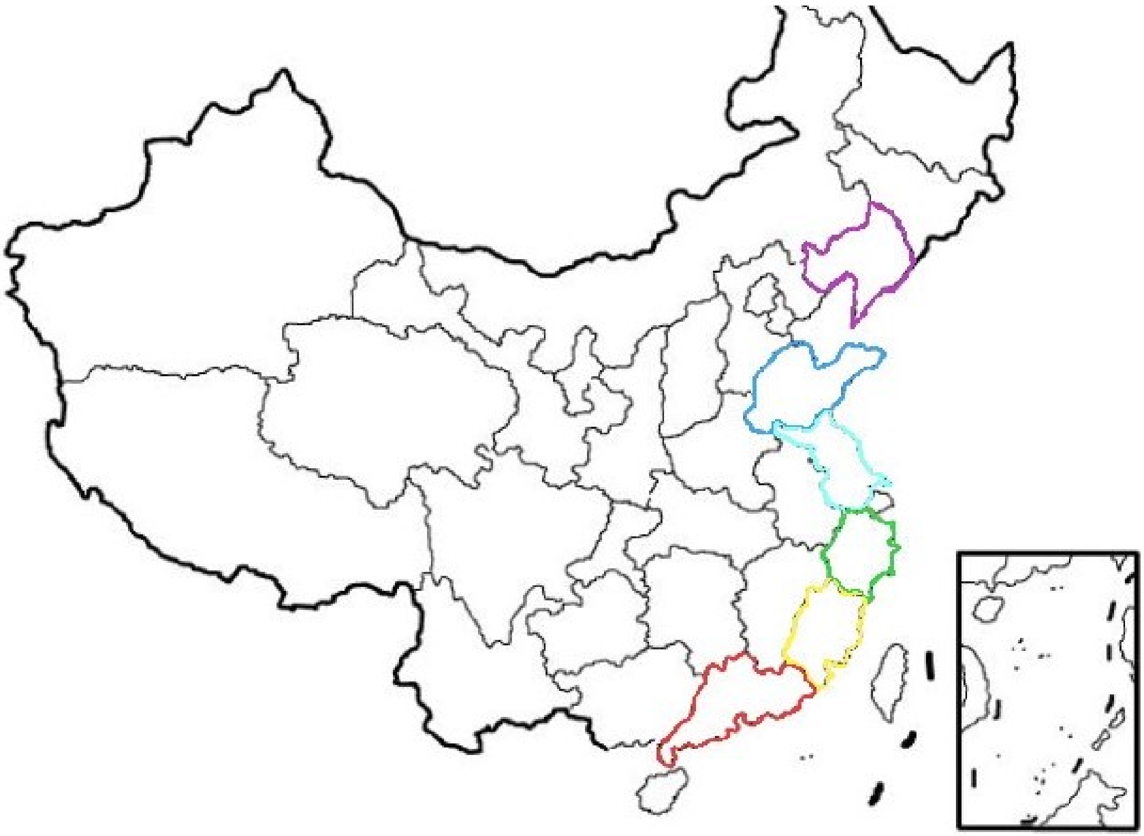

Figure 7.5. Kelp-producing provinces of China. (Data from Hwang et al. 2019.)

Table 7.1. Kelp strain and recent production by province in China. (Data from Hwang et al. 2019.)

Provinces	***S. japonica*** (tons dw)	***U. pinnatifida*** (tons dw)
Liaoning	218,704	106,855
Shandong	533,439	43,961
Jiangsu	300	4
Zhejiang	10,363	–
Fujian	693,533	–
Guangdong	4719	1029

7.3 The Korean Peninsula

7.3.1 History

The two nations on the Korean Peninsula both actively produce kelp at an industrial level. Although more information is available regarding South Korea's history on the subject, both countries primarily produce *S. japonica* and *U. pinnatifida. U. pinnatifida* occurs naturally all along the coastlines of the peninsula and has been cultured commercially for several decades. *S. japonica* was introduced to the area from Japan in the 1970s.

In South Korea, both species are grown extensively for human food, as well as for abalone feed, although a cultural preference for *Undaria* exists for human consumption. The total production for both species represents more than 1.1 million tons of biomass, roughly two-thirds of all seaweed produced in South Korea. South Korea is different from China in that they grow more *U. pinnatifida* than *S. japonica*. In 2018, 622,613 T (fresh weight) of *Undaria* was grown, whereas only 542,285 T of *Saccharina* was grown (Ministry of Oceans & Fisheries 2018). South Koreans have traditionally consumed more *Undaria* than *Saccharina,* so that could explain the difference in cultivation efforts. Upwards of 90% of all the kelp grown in South Korea is grown along its southwestern coast in the province of Jeollanam and the surrounding area (Sohn1998).

S. japonica was actively farmed at a much smaller scale in South Korea until the abalone industry began to expand in a significant way, beginning in the early 2000's. Since then, cultivation efforts have multiplied several times, and now, more than 9,000 ha are dedicated to farming *S. japonica* for both human food, and more importantly, for abalone feed (Hwang et al. 2019). The autumn sporeling-rearing technique was pivotal for developing a cultivar that would suit the needs of the abalone farmers (Sohn 1998). The normal life cycle of kelp generally has a growing season in the winter, and by early summer the blades are badly deteriorated and not suitable for use as food or feed. The autumn sporeling-rearing technique postpones the sporing out process in the early fall until several weeks later. This delay extends the growing season into the early summer and allows the kelp to be harvested much later and provides feed for the abalone farmers into the summer months when feed is more difficult to acquire.

7.3.2 Environmental Conditions

Water temperatures vary along the Korean Peninsula and are influenced mainly by two currents. The North Korean Cold Current branches off the Liman Cold Current and runs along the west coast of the peninsula, which lowers the average water temperatures in the northern regions of the Korean Peninsula. In the winter, the minimum temperatures hover around 2–3°C, but temperatures can exceed 25°C during the summer in some areas. The peninsula as a whole is more influenced by the Kuroshio Warm Current that flows up from the south (Sohn1998).

Figure 7.6 shows a map of South Korea's main kelp-producing region, the province of Jeollanam (outlined in red). Wando County (outlined in blue) is especially central to South Korea's kelp and abalone industry.

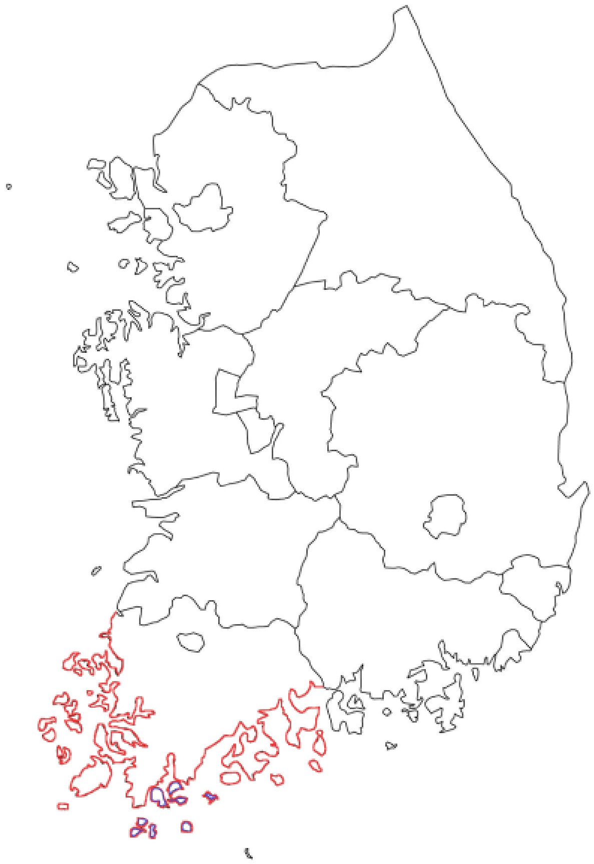

Figure 7.6. Map of South Korea's primary kelp-producing region.

7.3.3 Cultivar Development

Extending the growing season even further is one of the main priorities of the breeding program in South Korea. As of 2018, five cultivars of *Undaria* and one of *Saccharina* have been registered for variety protection. These cultivars have been developed either by hybridization or consecutive selection. For example, Hwang et al. (2012) examined the growth of a hybrid of *U. pinnatifata* and *U. peterseniana* and found that it had better growth and performance than either of its parent species. Figure 7.7 shows the growth of kelp production in South Korea from 1950 to the present (Ferdouse et al. 2018).

The Food and Agricultural Organization (FAO) of the United Nations reports that North Korea produced an estimated 572,600 T of *S. japonica* and 515,600 T of *U. pinnatifida* in 2018 (Ferdouse et al. 2018). That is all the information available regarding the kelp industry in North Korea.

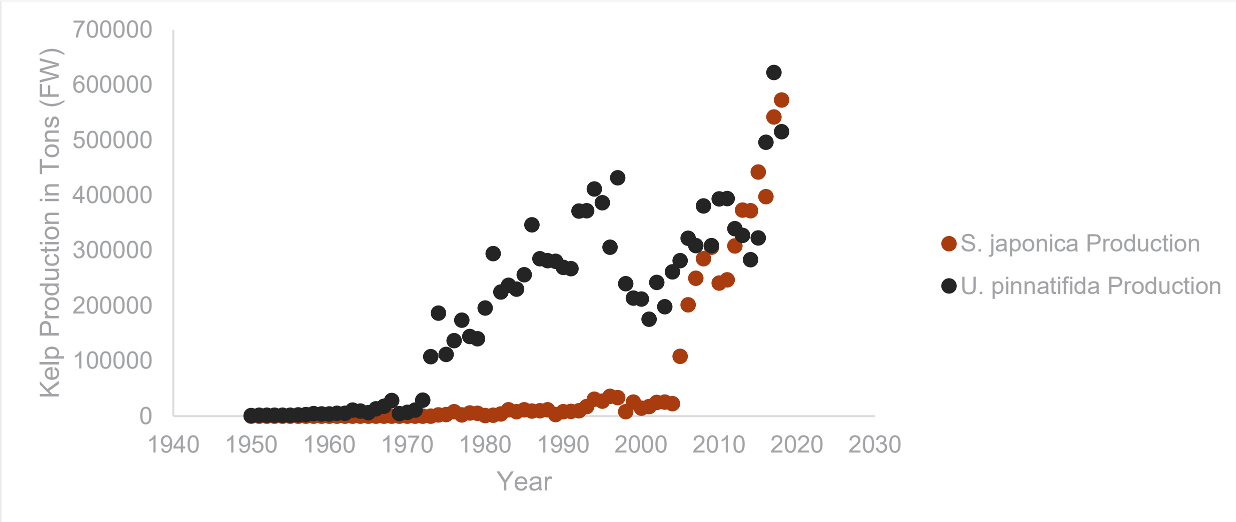

Figure 7.7. Kelp production in South Korea from 1950 to the present.

7.4 Japan

7.4.1 History

Japan has been harvesting their wild kelp bed resources for hundreds of years, but intensive farming of *S. japonica* did not begin until 1969. The farming began because the natural kelp beds were in decline and could no longer produce enough biomass to adequately supply the industry (Kawashima 1984). However, *Undaria* had been farmed commercially for several years prior to 1969. Production for *Undaria* began to sharply increase in the mid-1960s and continued to increase into the 1970s. Production plateaued for several years but has since continued to decline to the present. *Saccharina* cultivation saw steep increases in production following its initiation in 1969, and its highest levels of production in the early 1990s, but since then it has slowly but steadily declined into its current production levels. In 2018, Japan produced 33,300 T of *S. japonica* and 49,800 T of *U. pinnatifida* (FAO 2018). The primary kelp-producing prefectures of Japan, including from north to south are Hokkaido, Miyagi, Iwate, and Tokushima, as shown in Figure 7.8.

Figure 7.8. Primary kelp-growing prefectures of Japan.

7.4.2 Environmental Conditions

The country of Japan is made up of a unique archipelago of four main islands of Hokkaido, Honshu, Shikoku, and Kyushu (northernmost to southernmost) and an additional 4,000 more smaller islands among them. Their environment and water temperatures are strongly influenced by the water currents that move around the islands. The Oyashio current flows to Japan from the north and brings very cold water out of the Arctic, keeping the water around Hokkaido very temperate; temperatures average 16–18°C in the summer and are as low as -1°C in the winter (Ohno and Largo 1998). This cold-water current creates suitable conditions for kelp growth in Northern Japan.

7.4.3 Uses of Kelp

The majority of kelp grown in Japan is consumed within the country. Japan consumes the largest amount of seaweed per capita, and its consumption has been linked by some to their overall good health and longevity. Japan does not grow enough kelp to completely supply itself with enough kelp; significant volumes are imported from China and South Korea.

Japan also produces alginate, although cultivated *S. japonica* and *U. pinnatifida* are generally too expensive to use as a raw material for that application. The alginate that is produced in Japan is sourced from raw materials that are imported from mostly Chile and South Africa, which harvest wild Durvillea and Ecklonia kelps for export (Ohno and Largo 1998). Kelp production in Japan from 1950 to present is shown in Figure 7.9 (Ferdouse et al. 2018).

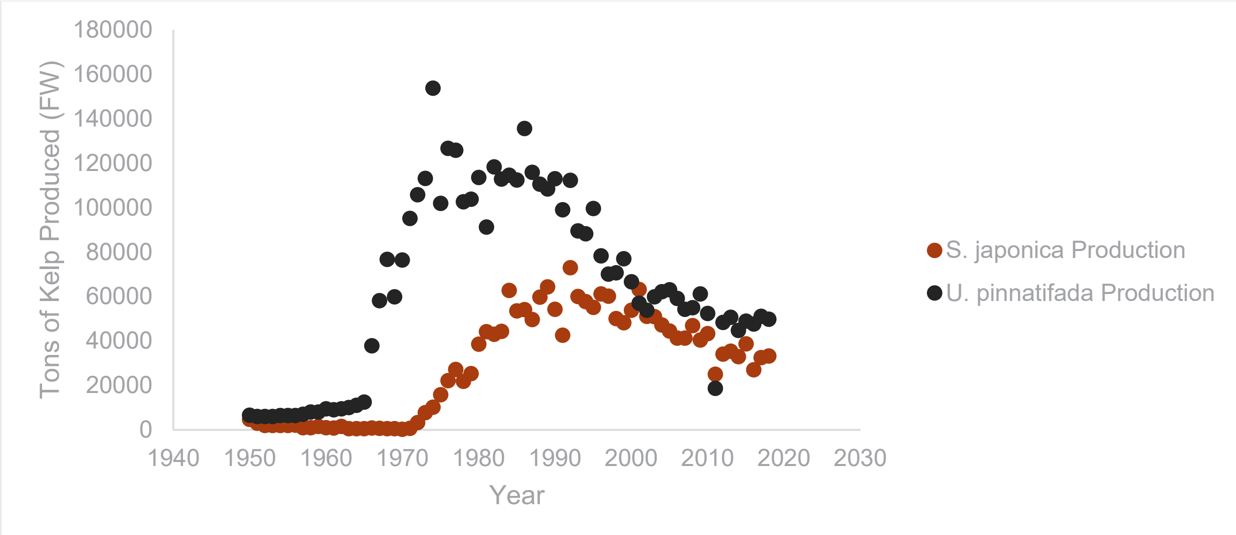

Figure 7.9. Kelp production in Japan from 1950 to the present.

7.5 Europe

7.5.1 History

The European Union (EU) has a long history of exploiting its natural resources in the ocean, especially with activities like capture fisheries for finfish and shellfish, and there is a burgeoning interest in aquaculture. Aquaculture practices for growing salmon and trout are well-established in the Northern EU, in countries like Sweden, Scotland, and France, and interest in kelp aquaculture is growing as well, with the species *Saccharina latissima* being the main target for cultivation, because studies have shown its potential for generating large biomasses (Handå et al. 2013). Several countries also have long histories of exploiting wild stands of kelp, usually for industrial applications.

7.5.2 Norway

Norway has been harvesting its natural kelp beds for around 50 years (Stévant et al. 2017). Norwegians were quick to recognize the value of their fast growing and renewable resources along the coastline and were among the first countries to establish harvesting guidelines and criteria to maintain ecosystem diversity. The main kelp species harvested is *Laminaria hyperborea*, and it is harvested from specialized boats using trawling equipment that removes the kelp's holdfast from their rocky substrate. The regulations and management of the wild harvest of Norwegian kelp beds is considered to be among the most thorough in the world. Harvest limits are set for each area, and once a bed has been harvested, a minimum of 4-year waiting period is required before the area can be harvested again. This allows the kelp bed to regenerate, and for the ecosystem it supports to restabilize.

In 2019, Norway harvested just under 163,000 T of brown algae, most of which was *Laminaria hyperborea* or *Laminaria digitata* (Norwegian Directorate of Fisheries). Most of this harvest is processed for hydrocolloid extraction (alginates). Although wild harvest of kelps has been well-established for many years, it became apparent that wild harvest would soon no longer be able to support the demand for kelp biomass. To avoid the overharvesting of algal resources like that seen in France and Morocco, alternative sources had to be evaluated. Experimental farms were deployed in 2005 to determine the feasibility of kelp aquaculture in Norway. Due to its established finfish aquaculture systems and the resulting nutrient discharge from waste and uneaten food, kelp aquaculture seemed to be a logical answer to address the problems of eutrophication and generate a valuable biomass simultaneously (Wang et al. 2012).

Commercial kelp farming permits were first issued in 2014 once the Government established a temporary permitting process to certify commercial applicants (Stévant et al. 2017). Little information was available prior to the establishment of the permitting process. Although Norway has a strong history of wild harvest, kelp aquaculture is a very recent endeavor. Permits have been granted for the farming of *L. digitata* as well, but it has not yet been harvested in significant volumes. The number of permits granted has been on the rise ever since 2014, and the Norwegian Government has been allocating larger areas for macroalgae farming. In 2014, 54 licenses were granted for kelp farming, and that number had risen to 475 in 2019 (Norwegian Directorate of Fisheries). Many of these farms are in startup phases, and production values will continue to grow as more companies actively grow kelp on their permitted sites. Kelp production in Norway is shown in Figure 7.10.

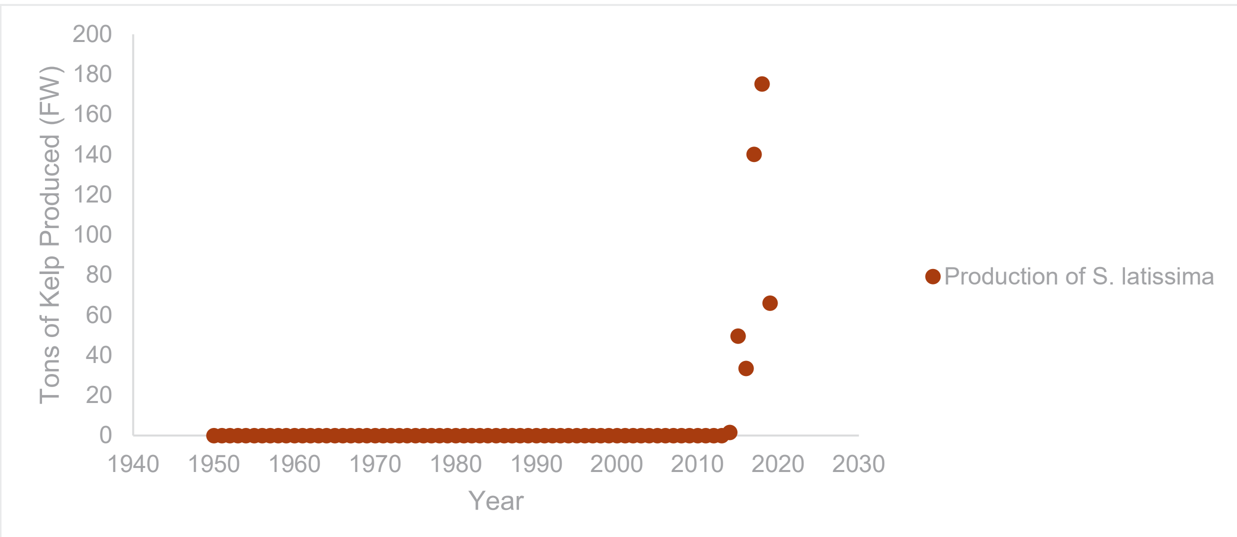

Figure 7.10. Kelp production in Norway.

EU interest in kelp cultivation continues to grow, just as it does in Norway. Even prior to Norway's exploration into *S. latissima* cultivation, several other countries in the EU, including France, Germany, Scotland, and Ireland, had conducted their own experiments and obtained promising results (Stévant et al. 2017). The list of countries in the EU that are actively researching the possibilities of growing kelps at industrial scales continues to grow. Today, Sweden, the Netherlands, Denmark, and Great Britain all have kelp farming companies in their economic zones. Although kelp is being grown in these locations, they are still operating at a small scale and represent a very small fraction of a percent relative to the global production scale. The website www.phyconomy.net provides open-source data on the numerous companies and enterprises involved in the growing, harvesting, processing, and marketing of kelp and other algal species around the world, but especially in Europe. This represents a valuable resource when evaluating the investment European countries are making to work toward a more environmentally focused economy and future.

7.5.3 France

It is worth noting that France has a long history of wild kelp harvesting. It has a well-established fishery that targets wild kelp beds of *L. hyperborea* and, to a greater extent, *L. digitata*. Mechanical harvest from large vessels began in the late 1960s when the "scoubidou" was developed. The scoubidou is a large iron hook attached to the arm of a crane that is used to twist up the thalli of mainly *L. digitata. L. hyperborea* is harvested from boats using a large rake that is pulled through kelp beds, which pulls up the holdfasts. The kelp is then sent to factories where it is processed for alginate extraction by Dupont-Danisco and Lannilis for global food corporation Cargill (Mesnildrey et al. 2012). Between 40,000 and 60,000 T of *L. digitata* and around 11,000 T of *L. hyperborea* are harvested each year (Mesnildrey et al. 2012).

In addition to their wild harvest landings, France also produces approximately 50 T of kelp on aquaculture facilities. *S. latissima* and *U. pinnatifida* are both farmed. There are only seven farms—four in North Brittany, two in South Brittany, and one in Vendée (Mesnildrey et al. 2012). However, France is at the forefront of research efforts to develop new uses and applications for cultured kelp. For example, the company C-Weed Aquaculture has its own culture and processing facilities and develops a wide range of products. In addition, all their products have Bureau Veritas (FR BIO 10) organic certification (Ferdouse et al. 2018). Both companies work to find new uses and presentations for incorporating kelp into western diets and lifestyles.

7.5.4 Innovations

Innovation is continually pursued as markets and products are developed and promoted, and technology is designed and implemented to make industrial-scale kelp production a competitive practice in the EU. MACROSEA, a program run by SINTIF in Norway, is acting as a common area for everything pertaining to industrial-scale cultivation of kelp. Research is conducted in every step of the process, including seed quality, sea cultivation, and genetic studies, as well as 3-D modeling efforts to optimize kelp farming practices (MACROSEA, www.sintef.no/projectweb/macrosea/; Broch et al. 2019).

Several technologies have been tested to evaluate their effectiveness in keeping kelp farming equipment intact in offshore locations. The advantages of growing kelp offshore are many and are mostly represented by a decrease in user conflicts and an abundance of unoccupied space. Grandorf et al. (2018) tested the Macroalgae Cultivation Rig (MACR) and showed that it effectively held the kelp cultivation equipment in place even when subjected to offshore waves. Another method also evaluated the effect of multiple partial harvesting on the overall cost of production. By conducting four partial harvestings over a 2-year period, the cost of production per kilogram of kelp was reduced from € 36.73 to € 9.27 (Grandorf et al. 2018).

Seaweed Solutions (formally Seaweed Energy Solutions) has patented a method of cultivating kelp on a setup known as the Seaweed Carrier, shown in Figure 7.11. The Seaweed Carrier is designed to be deployed in offshore environments. Its construction is similar to that of a kelp thallus, with a single "holdfast" anchor connected to the floating cultivation site via a single cable. This construction should allow for enough movement in order for the carrier to remain stable during extreme weather events and prevent catastrophic losses (www.seaweedsolutions.com).

Creating technologies that increase production and improve efficiencies will be imperative for the successful implementation of industrial-scale production of kelp in Europe.

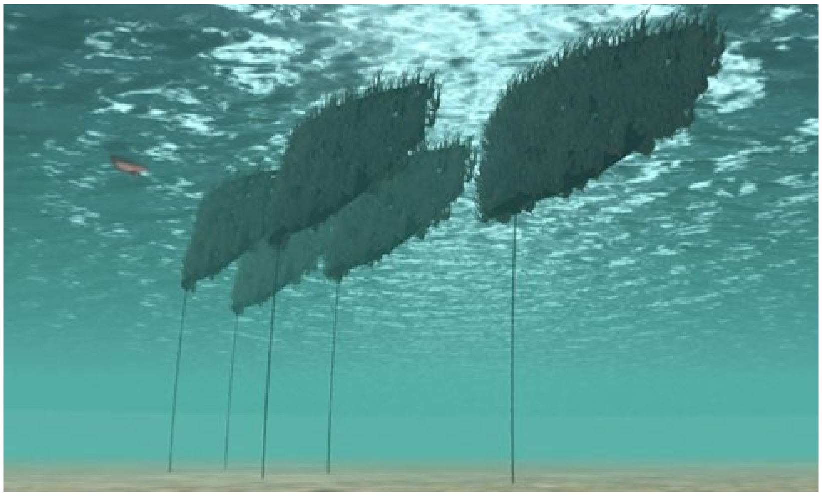

Figure 7.11. The Seaweed Carrier patented by Seaweed Solutions.

7.6 United States of America

7.6.1 History

The kelp industry in the United States of America (U.S.) is still in its infancy. The first kelp farm was founded in Casco Bay, Maine, in 2010 (Flavin et al. 2013). The cofounders wrote a book called the *Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters* that continues to be an invaluable resource for American kelp farmers that are getting started in the industry. Although interest is growing in a few areas, production levels are still relatively small, and the infrastructure required to do anything with the generated biomass has yet to be sufficiently developed. Harvesting aquatic species from the wild has an extensive history in North America, involving both algal species, as well as finfish and shellfish. However, relative to other countries, the extensive coastline has been underused relative to aquaculture efforts. The United States continues to be the top importer of fishery-related products, and the fifth largest exporter of fishery products. Production values for both wild harvest and aquaculture efforts have remained stable for the last several years. The production of any aquatic plants is not included in the official statistics from the FAO, demonstrating how minute current production levels are (Ferdouse 2019).

Although efforts are currently limited, interest continues to grow. Currently, kelp is being grown at either a commercial or a research level in the following states: Maine, New Hampshire, Connecticut, Rhode Island, Massachusetts, New York, Washington, and Alaska.

7.7 Kelp Industry Challenges

Compared to the kelp industries of Eastern Asia, kelp farms in the United States are miniscule. Kelp farms in the United States undergo an extensive permitting process that often requires permits from several agencies. Issues involving competition from other stakeholders in the farm area often create significant push back from the community. Additionally, finding markets for the harvested biomass once a farm has been established also represents a challenge, making profitability difficult to achieve. These challenges make it more difficult for the kelp industry in the United States to grow and expand into something to be recognized at the global scale.

In terms of regulations, there is much concern surrounding the potential to damage the surrounding ecosystems into which kelp farms are placed. Much of the permitting process involves doing risk assessments of the impacts on other species or ecosystems of concern, such as eel grass beds (*Zostera marina*). Another significant concern is contaminating the gene pools of wild kelp beds. Several studies from East Asian countries already have found evidence of gene flow between wild and farmed kelp that occupy similar spaces. Due to kelp's reproductive strategies, individual spores are able to be carried by currents, greatly increasing their dispersal potential. The ADFG has written the regulations for sourcing parent plants to prevent the contamination of wild gene pools. ADFG dictates that 50–60 parent plants sourced from the wild must be used to seed the lines that are out planted onto a farm. This farmed diversity is expected to help maintain the total diversity present in the environment.

7.7.1 Maine and Alaska

Most of the kelp grown in the United States is grown in Maine and Alaska. Both of these states have extensive coastlines, as well as existing infrastructure related to extracting marine resources. Having a population that is familiar with working on the water is important for the establishment of a kelp farm and having an abundance of coastline decreases concerns regarding user conflicts. In both states, more permits are being issued, and existing operations are expanding.

The main kelp species of interest in the United States is *S. latissima*, and it is grown on both the East and West Coast. On the East Coast, *Saccharina angustata, Alaria marginata, and Laminaria digitata* are also cultivated. Until recently, *S. angustata* was considered to be a unique variety of *S. latissima* because the blade is much narrower, but enough genetic differences were found to consider it its own distinct species. On the West Coast, in addition to *S. latissima*, *Nereocystis luetkeana* and *Alaria marginata* are cultivated in large quantities.

Although Alaska does not allow for the use of intensively bred strains of kelp, the Advanced Research Projects Agency–Energy (ARPA-E) program of the U.S. Department of Energy has awarded Woods Hole Oceanographic Institute a grant to continue a selective breeding program to develop superior strains of kelp that can be grown in U.S. waters (ARPA-E 2017). To grow a biomass large enough to create an adequate supply for biofuel applications, a number of aspects of the entire production chain will need to be optimized, including the genetics of the kelp that will be grown, thereby maximizing the yield per unit of effort invested. Other grants from the ARPA-E Mariner program have been awarded for research into other aspects of kelp product in U.S. waters. This strong investment from the Government and changing the public views on kelp will help ensure that the U.S. kelp industry continues to grow and becomes a profitable component of the U.S. economy and future.

7.8 Kelp Processing and Uses

As mentioned previously, kelp was first exploited for industrial purposes as a source of potash used glass production, beginning in the 17th Century (Mesnildrey et al. 2012). Prior to that, kelps had been used for millennia as a source of food and other herbal remedies in Eastern countries. Food for humans represents the most common use for farmed kelp, but the processing that is required to convert raw kelp into a marketable product can vary significantly.

A few aspects of kelp must be considered when developing protocols for the processing of kelp. Because all kelp species are aquatic, the vast majority of their biomass is water, ranging from 70–90% (Jensen 1993). This poses potential problems for the logistics of transporting large volumes of biomass and for processing large quantities of kelp for its valuable elements. Additionally, fresh kelp biomass quickly begins to microbially decompose, which also poses logistical problems related to the processing kelp (Enríquez et al. 1993). Drying kelp halts that microbial decomposition but can also alter the nutritional qualities of the kelp (Gupta et al. 2011). Processing techniques must be tailored to obtain the desired outcome for each specific end product. Intuitively, kelp that is allocated for human food will be treated differently than kelp allocated for hydrocolloid extraction.

7.8.1 Kelp for Human Food

Kelp allocated for human food will undergo a series of steps to arrive at a safe, marketable product. Traditionally, kelp was either consumed raw or in a sun-dried form. Kelp can still be purchased raw in a fish market or similar environment during the seasons that the kelp is being harvested, and sun-drying kelp is still an extremely common practice. When dealing with the astounding volumes of kelp that are harvested in China, Korea, and Japan, a variety of methods are employed to use the maximum proportion of the biomass harvested before it degrades. In very large operations, multiple strains of a species with varying maturation rates are planted. The staggered timing of maturation gives harvesters the opportunity to stagger the harvest, instead of having the whole crop reach maturation simultaneously.

After the kelp is harvested, it is transported to a processing facility, with the exception of kelp that is to be dried. Sun-drying kelp is still a common practice in China, Korea, and Japan. Kelp is laid out on the beach, in unoccupied agriculture fields, or on long racks made of bamboo or steel specially built for kelp drying. Debris can stick to the kelp when it is laid on the ground, and the extent of the associated contamination will impact the value of the kelp. Dried kelp is widely available as a food product. It can be sold in large pieces for a wholesale market or cut down into smaller manageable pieces that are more common for products directly marketed to single households. Sometimes, dried kelp is shredded to a consistency similar to tea leaves, which are then used to brew a hot beverage in a fashion similar to brewing tea. Dried kelp can also act as a feedstock for alginate extraction. In South Korea, dried *Undaria* is widely available, and is often included in many processed food, snack, and well-being products to use *Undaria's* natural nutritional value (Hwang and Park 2020).

Kelp used for human food undergoes a pretreatment process that involves a series of seawater or freshwater rinses to remove debris and salt content, respectively. The next step in the pretreatment process is to either blanch it or boil it. Cooking the kelp effectively stabilizes it, and extends it shelf life. For some products, a green dye is added to the boiled kelp, turning it a vibrate green color, and that would occur right after the boiling process. Once the kelp is boiled, it is salted and placed in cold storage to await its transfer to a food processor.

7.8.2 Processing Equipment

Once pretreated kelp arrives at a seafood processing factory, it can be transformed into many different forms, such as dried, semi-dried, wet, salted, non-salted, or sliced, and then into any number of food products, including seasoning products, kelp sauce, kelp noodles, or kelp soup-mate (Zhang 2018). The final product packaging can vary in sizes and shapes. Machines involved in the processing of kelp products include, but are not limited to, washing tanks or tunnels, kitchen cookers or blanchers, dewatering machines, cutting/slicing machines, drying tunnels, cooling fans, heavy metal sensors, scales, packing machines, vacuum packing machines, and many other types of equipment. Heavy metal detectors are especially important when processing kelp that may have been grown in waters polluted by anthropogenic activities.

Processing lines must be specialized for the product that is being produced, and specialized equipment often must be custom built in order to produce a novel product.

7.8.3 Kelp for Industrial Uses and Feed

Kelp that is not being used for human food can be used two broad categories: animal feed and industrial uses (hydrocolloid extraction).

7.8.3.1 Kelp for Animal Feed

For animal feed, the necessary processing of the kelp will vary depending on the animal to which it will be fed. In China and Korea especially, kelp represents a significant source of feed for abalone and sea cucumber farms. For this application, little to no processing is required; pieces of fresh kelp are simply placed in the cages with the animals at regular intervals. Growing *S. japonica* exclusively for use as abalone feed caused the area used for *S. japonica* in South Korea to increase by 671% between 2001 and 2015, and it now occupies 9,147 ha (Hwang et al. 2019). This simple example demonstrates the importance that this application holds in the industry.

Kelp is a common component of other kinds of animal feeds, such as feed for higher trophic levels in aquaculture like finfish or crustaceans. For these applications, the kelp is generally dried and then pulverized into a powder that can then be added to other ingredients. Kelp can serve as a source of plant-derived protein, which will become more and more important as the world's population grows and there are more people to feed. *U. pinnatifida* can be around 16.3% crude protein, and *S. japonica* and *L. digitata* can contain roughly 6.2% crude protein (Misurcova 2011). Using animal protein in animal feeds is sometimes viewed as using food to make food. Using algae-based proteins circumvents that problem by using protein from lower trophic levels. The generation of algae-based proteins is also attractive because no freshwater or farmland is used. Many other plant-based proteins are derived from soy, which reintroduces the problem of using food to grow food. However, the protein content is not the only reason using kelp in animal feeds is useful because of the micro- and macronutrients found in kelp tissue. Supplementing normal feed with kelp is common in the organic farming sector, which significantly reduces the additives that can be administered to farm animals. Some studies have seen improvements in body condition and overall health in pigs and cattle when kelp is added to their diets.

7.8.3.2 Hydrocolloid Extraction

The industrial uses for kelp are broad, and there are ongoing research efforts to discover more uses for the bioactives that are contained in kelp tissue. The hydrocolloid industry has been a dominant component in the kelp industry since alginate was discovered and has had its useful properties applied to its myriad of applications. Alginate, or alginic acid, is a structural component of all the seaweeds in the Phylum Phaeophyceae and is the most widely produced polysaccharide (Brownlee et al. 2005). Although it occurs in other brown algae, kelps are unique because of their large size and ability to grow in thick beds. This allows the resource to be very accessible, because a large biomass can be harvested for an alginate extraction facility.

Alginate's most useful property is its ability to form gels. It is used at industrial scales in a variety of industries including the processed food industry, textile industry, pharmaceutical industry, dental and medical fields, cosmetic industry, and many others, as research is always being conducted on how to bring new, innovative products to market using this versatile component.

For example, alginates are used in emulsifiers, firming agents, flavor enhancers, flavor adjuvants, formulation aids, processing aids, stabilizers, thickeners, surface-active agents, and texturizers (Truong et al. 1995). Alginate is used in the textile industry to aid in the dying of fibers and the process of printing onto materials. In the paper industry, it is added to the pulp mixture to the paper's smoothness, aid in ink adherence, and help resist crumpling. It stabilizes colors in paints and dyes and is used in the manufacturing of welding rods. In medical fields, alginates are used to make dental impressions, and are common components of pharmaceutical products. In addition, various fibers can be made with alginates, and their uses include wound dressings, facial masks, fire protective cloth, and static proof cloth (Zhang 2018). Alginate in its numerous forms will continue to be involved in the many facets of modern society as researchers continue to find new ways to incorporate its useful properties.

The most common form of alginate is extracted as sodium alginate, although other chemical forms of alginate are available, including propylene glycol alginate, potassium alginate, calcium alginate, and ammonium alginate (Zhang 2018). Figure 7.12 shows the steps taken to extract sodium alginate via two different pathways, the calcium alginate process and the alginic acid process (Hernández-Carmona et al. 1998). Both processes begin with wet, chopped seaweed to which sodium carbonate solution is mixed in. This dissolves the alginate into solution, and the residual solids are strained out. To get the alginate out of the solution, either calcium chloride or an acid is added, depending on which process is being used. The calcium chloride reacts to form fibers of calcium alginate, which can be strained out of solution. To remove the calcium, an acid is added to displace the calcium cations, forming alginic acid fibers. Sodium carbonate is added to form sodium alginate. For the alginic acid process, an acid is added to the original sodium alginate solution. This forms an alginic acid gel that can be strained out of the solution. Sodium carbonate is added to the alginic acid gel, which then forms sodium alginate. Sodium alginate is commonly sold in powdered or pelletized form.

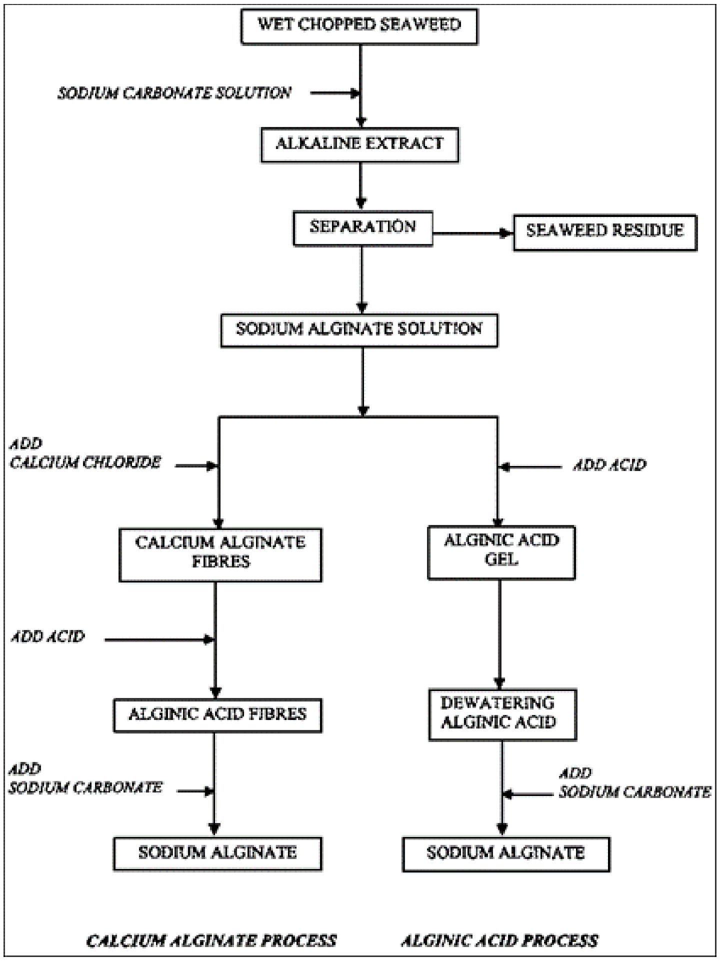

Figure 7.12. Flow chart displaying the steps required to produce sodium alginate from brown algae via two different methods (from Hernández-Carmona et al. 1998).

Alginate is not the only useful compound contained in kelp; several other chemicals are actively extracted from kelps. Kelps commonly contain, in varying degrees, compounds such as phlorotannin, fucoidan, mannitol, and laminarin. All these compounds have useful properties, especially for pharmaceutical applications as indicated in Table 7.2 (Zhang et al. 2020).

Table 7.2. Common chemicals found in kelp and their useful applications.

Biomaterial	Applications
Alginate	Drug delivery, wound healing, heavy metal sequestration, gelling agent
Phlorotannin	Antioxidant, anticancer agent, antidiabetic, anti-HIV agent, anti-allergic agent
Fucoidan	Anticoagulant and antithrombotic agent, antiviral agent, antitumor agent, antioxidant, anti-inflammatory
Mannitol	Biofuel feedstock
Laminarin	Anticancer agent, anti-microbial agent, antioxidant, biofuel feedstock

7.8.4 Biorefinery Model

The presence of these useful compounds, and the developing methods for extracting them, are important for application of a biorefinery model for processing kelp. A kelp biorefinery process would extract a number of useful and valuable components of kelp, and as a result, would decrease the amount of waste that is generated and increase the number of products at the end of the process, thereby making the end result more economically feasible. A current and popular component of the conversation surrounding kelp is the possibility of generating biomass feedstock to produce biogas or other biofuels. Kelps are attractive for this application because they have a significant proportion of polysaccharides that would serve as the primary energy source. Additionally, kelps lack the structural component of lignin, which is used by land-based plants, and generally makes them more difficult to break down (Zhang et al. 2020).

In addition, kelps do not require any freshwater or arable land, which gives kelp biomass a significant advantage over other sources of biomass for biofuel like corn, soybeans, or sugarcane. However, a serious disadvantage to generating biofuel with kelp is the negative net-energy balance, meaning that it takes more invested energy to produce a smaller amount of energy contained by the biofuel (Clarens et al. 2010). The result is that biofuel can be produced using algal biomass, but at a net loss of total energy. This reality necessitates additional products to enable the processing of algal biomass to be economical.

Figure 7.12 (Zhang et al. 2020) shows an example of the process of applying a biorefinery model to extract pigments, mannitol, phlorotannins, and alginate from kelp biomass. These compounds would first be removed from the kelp, leaving a residual mass that can then be fed into a bioreactor for the generation of biofuel. This process reduces waste and increases the number of marketable products from the same processed kelp biomass.

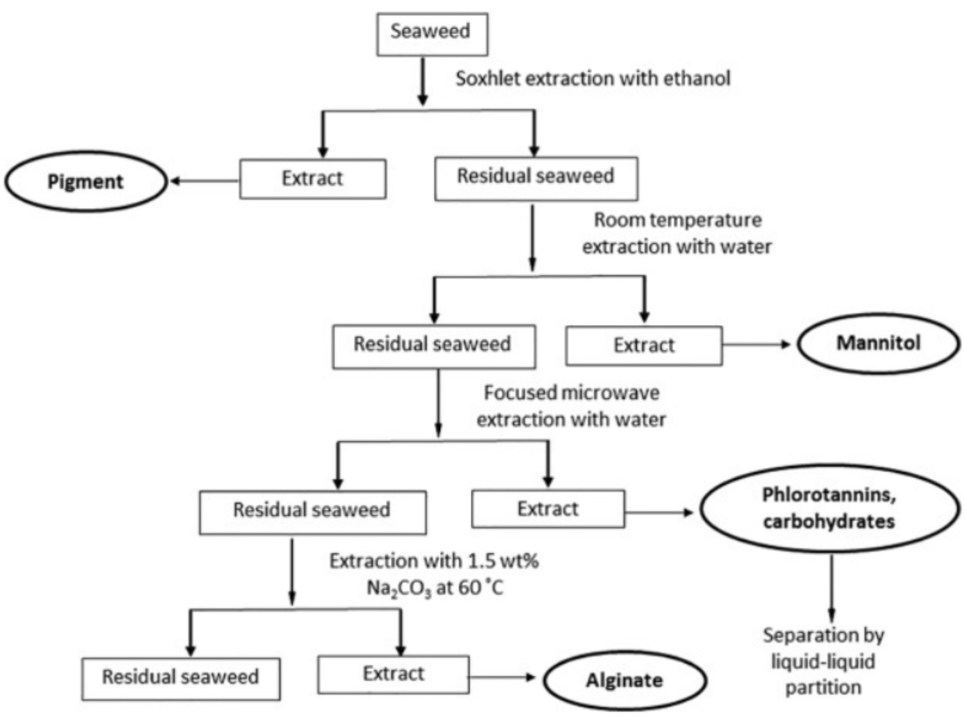

Figure 7.13. Biorefinery model for extracting valuable compounds from kelp.

The extraction, marketing, and utilization of these additional compounds will help to create an ecosystem of sorts for the use of kelp-derived products from farmed kelp species. Such an ecosystem is well-established in East Asian countries, but anything of the sort needs substantial support in the West.

7.9 Kelp and Renewable Energy Sources

Kelp could be an important component of the world’s economy as cultivation practices expand around the globe. However, numerous factors are involved when evaluating the impact that large-scale kelp cultivation will have at its numerous steps of production. One significant concern is the amount of energy required in the preparation, maintenance, harvesting, and processing for a large-scale kelp farm. Consuming energy produced by fossil fuels in the course of producing kelp for any application could significantly offset the benefits of using kelp. The ideal scenario would be to use a renewable source of energy during production of kelp. In this way, the two renewable sources could work synergistically, as the world works toward achieving a decarbonized state.

All emerging and major kelp-producing countries have signed the Paris Agreement, promising to work toward reducing the carbon emissions of their countries. Country investments into renewable energy varies in extent and forms. Additionally, depending on the source of renewable energy, generated renewable energy may not be available to activities related to kelp production. The following sections provide an overview of renewable energy production in each major kelp-producing country.

7.9.1 China

China is of particular interest in this conversation because it is responsible for more than 20% of the world’s total carbon emissions, and also produces most of the kelp in the world. The energy invested in processing kelp, everything from the primary processing to hydrocolloid extraction to enable other advanced uses of it, is significant. If all kelp were to be processed solely with renewable energy, the greatest impact on the world would come from China, simply because they are growing, processing, and marketing incredible volumes of kelp.

China is actively growing their renewable energy resources. In fact, they are the world’s leader in the manufacturing and deployment of wind and solar energy production plants. Of all the solar panel manufacturing companies in the world, China has the six largest, as well as the largest company for manufacturing wind turbines (Slezak 2017). However, this heavy investment is based on a clear need. A study by the Asian Development Bank found that 7 out of 10 of the world’s most polluted cities were in China (Staedter 2013). This reality has pushed the Chinese Government to make drastic investments in cleaner sources of energy to reduce the country’s reliance on fossil fuels, especially coal. Before the push for renewables, China had nearly exclusively generated all of its power for its enormous populous with coal-fired power plants. Since 2011, China has burned more coal than all other countries combined (O’Meara 2020). In 2019, China produced about 9% of its power from wind and solar sources (Hove 2020).

Energy generated from renewable sources cannot always be used by the kelp industry. Although there are several offshore wind farms, the bulk of the wind and solar energy generated in China is produced in remote provinces in the western portion of the country, such as the Tibetan Plateau. These regions are very dry and have little cloud cover, making them very suitable for solar power generation. In addition, the landscape is quite flat and has little to block the path of wind, making these area’s suitable for wind farms as well. The kelp farms, however, are located on China's eastern coast, far away from the abundance of power generated by solar panels and wind turbines. One significant roadblock for renewable energy in China is the lack of high-voltage transfer infrastructure, which prevents energy generated in remote locations from reaching the main power grid where it can be used in population centers. This inability to transfer renewable power has led to the waste of more than 1.75 TWh of wind energy (Reuters 2015). This reality shows that China has the technology to generate large amounts of energy from renewable sources, but still has obstacles to overcome before they more completely use their current potential.

7.9.2 South Korea

South Korea is the world's second largest producer of kelp, and hence devotes a significant amount of energy to the processing and packaging of kelp products. The country is extremely reliant on fossil fuels to supply energy to their power grid and has very limited capabilities of generating power through renewable resources. South Korea is among the top countries for the importation of both liquified natural gas and coal, and the burning of fossil fuels represents approximately 69% of the country's generated electricity (EIA 2020). South Korea has set ambitious goals as a signing member of the Paris Agreement, and has promised funds dedicated to increasing the proportion of renewable energy within their country. Already, emissions are being reduced. In 2014, the burning of fossil fuels produced 83.9% of the country's electricity (KEEI 2016). As of 2016, South Korea's current renewable energy production was about 4.54%, but the Government has announced that 20% of the country's energy will come from renewable sources by 2030 (KNREC 2016). Government incentives have been issued to promote the development of the necessary infrastructure needed to reach that goal. New projects for solar, onshore wind, offshore wind, geothermal, and biomass burning are all be evaluated for their feasibility for power generation. The largest proportion of renewable energy is projected to come from wind power.

The kelp industry could benefit from wind power generation, because of its proximity to the coast. Offshore wind farms could be introduced in areas unsuitable for kelp cultivation, and the generated power could be supplied to kelp processing plants, kelp seedling nurseries, and the surrounding infrastructure necessary for kelp production. Biomass burning seems to be a favorite alternative in the short term because of its low cost and the fact that little needs to be done to modify coal-burning power plants to accept biomass sources. However, several problems with biomass energy must be addressed to make it sustainable. The main concern stems from the source of the biomass, whether it is forest residue associated with deforestation, or a crop that is grown and harvested for energy production, which will be competing with crops for human and animal feed for arable land and water resources. Developments in technology to enable the use of kelp biomass for energy production would help solve many of these problems.

7.9.3 Japan

Japan has sourced energy for electricity generation from several sources in the last few decades. Like many other nations, the majority of energy produced is derived from fossil fuels, especially coal, liquified natural gas, and petroleum, which together account for about 87% of the country's energy production (ANRE 2020). In the recent past, a more significant proportion of Japan's energy was derived from nuclear reactors. After the Fukushima Daiichi Accident in March 2011, in which a 15 m tsunami caused by an earthquake hit the nuclear power plant and caused the melt down of three reactors, Japan's use of nuclear reactors was essentially halted. Japan underwent a more than 14-fold reduction in nuclear power generation and went from producing 29% of power from nuclear reactors in 2010 to just 2% in 2012. However, after an extended period of safety inspections, Japan's reactors are beginning to come back online. Currently, about 17% of Japan's energy needs are supplied with renewable energy sources and Japan has pledged to increase that to 22–24% by 2030 (WSA 2020).

Because an archipelago makes up the country of Japan, kelp cultivation areas are relatively close to areas where renewable energy is harvested. The largest island in Japan, Honshu, is only 230 km at its widest point, meaning that renewable energy should always be available around its extensive coastline. Recent increases in efforts to expand renewable resources have been disproportionately focused on solar energy, although wind power will need to be expanded to reach Japan's goal or 22–24% renewable by 2030 (Yamazaki 2018).

7.9.4 European Union

As mentioned previously, several EU countries have strong and growing interests in kelp aquaculture for one or several of its numerous applications. While East Asian countries are more focused on kelp as a source of human or animal feed, countries in the EU are generally more interested in what can be extracted from kelp. Eating kelp is growing in popularity but is still a niche market compared to the popularity experienced by kelp in East Asian countries.

However, processing kelp for the extraction of its components has significant energy demands, as well as a need for a great deal of freshwater. In the coming years when more renewable energy will be needed, and freshwater will be in short supply, countries and companies must be prepared to adapt to less than ideal conditions while using an important resource.

The EU has been on the forefront of efforts to decarbonize modern society, and those efforts should integrate well with the processing of kelp as kelp mariculture becomes more widespread. Across the EU as a whole, 18.9% of their gross energy production came from renewable resources in 2018. That figure is up from 9.6% in 2004, showing that renewable energy production has more than doubled in just 14 years (EUROSTAT 2020). A few countries that are active in pioneering kelp mariculture in the EU are also integral to increasing the proportion of renewable energy they use; 54.6% of all the energy consumed in Sweden is derived from renewable sources, and renewable energy sources represent 36.1% of all energy consumed in Demark.

Although not an EU member, Norway also derives an impressive proportion of its energy from renewable resources—98% of all the electricity produced in Norway comes from renewable resources. Of all the electricity produced by renewable resources, hydropower represents the largest proportion of production at 96.1%, followed by thermal power and wind power at 2.5% and 1.4%, respectively (MPE 2016). Although areas other than electricity generation, such as the transportation and shipping sector, need to be considered when evaluating a country's reliance on fossil fuels, electricity generation remains a key component when evaluating the intersection of the kelp industry and the reduction of fossil fuel use. Overall, Norway consumes fossil fuels in other areas, and their CO_2 emissions have increased by 31.2% since 1990 (IEA 2020). More efforts need to be made to ensure that the kelp industry can thrive in a way helps solve the problem of climate change instead of exacerbating it.

7.9.5 United States of America

Although the kelp industry in the United States is still in development stages, the renewable energy sector is growing and developing right along with it. The United States is creating more infrastructure and working to better use alternative power sources. In 2018, the United States generated nearly 765,000 GWh, and when evaluating metrics such as total amount of renewable energy generated, the United States takes second place; only China uses more renewable energy (IRENA 2018). However, when the proportion of renewable energy to total energy used is surveyed, the United States as a whole, ranks much lower. However, 2020 is expected to see record growth in installations of renewable energy facilities, despite the numerous associated challenges.

As is true for China, the large size of the United States and its numerous power companies means that renewable energy can be captured in remote, sparsely populated areas located in the nation's interior, but have no way of getting to areas where the kelp industry is operating. Alaska and the New England states have the most established kelp industry in the United States, so it would be most pertinent to survey renewable energy projects in these states.

New England states are characterized by large population centers and extensive developments along the coastline. Their high concentration of working waterfront and cool water temperatures makes their coastlines ideal locations for kelp mariculture, and there are several viable options for the implementation of infrastructure for renewable energy capture. The first offshore windfarm to ever be built in the United States was constructed in the coastal waters of Rhode Island in 2016, a facility that produces 30 MWh per year (https://us.orsted.com/wind-projects). Although its capacity is small, Rhode Island was able to establish a precedent that other New England states can follow. Currently, several projects are under way that will increase the production of clean energy from offshore wind farms that are several times larger than the first windfarm in Rhode Island. Massachusetts has two proposed projects that, when completed, will each produce more than 800 MWh of power (https://www.vineyardwind.com/, https://www.mayflowerwind.com/). Maine, the New England state that grows the most kelp, does not have any plans for offshore wind, but instead is looking to incorporate renewable energy from other sources. Hydroelectric power generates approximately 31% of Maine's electricity, and land-based wind power provides an additional 24% of generated power (EIA Maine 2020). These are only a few examples of the New England states' efforts to move toward renewable energy sources. The continued development of these projects will ensure that the budding kelp industry in the area will be able to use renewable resources to keep environmental impacts low.

Alaska does not have the population centers that are widespread in the New England states and, as such, has very different energy needs. Although it is the largest state by landmass, it has the lowest population density. The state features tiny population centers separated from one another by long distances and rugged geographic features. These realities make any kind of standardized, state-wide power grid as employed in the continuous 48 states an impossibility. Due to the discontinuities between communities, independent petroleum-powered generators are ideal. Where possible, hydroelectric dams are also used to provide the needed electricity to a community. About 30% of electricity is generated from renewable resources in the state, and hydroelectric facilities account for most of that energy; a few minor wind fields provides some electricity as well (EIA Alaska 2020).

Additional renewable resources should be evaluated to best incorporate renewable energy sources with the processing and other needs of the burgeoning kelp industry. Areas with abundant rainfall should be ideally set up for hydroelectric facilities. Wind farms could be used in areas that feature sufficient wind speeds. The extreme tides that occur along the coast could be harnessed for tidal power production. All sources of renewable energy should be evaluated to determine the ideal power source for each region.

7.10 Gene Flow

Gene flow has been documented for both *S. japonica* and *U. pinnatifida* between farmed populations and wild populations. Using microsatellite markers, evidence of genetic connectivity became clear. Wild may not be the best word to describe "not farmed" populations of *S. japonica* in China because the species as a whole was believed to be introduced from Japan in the 1920s. A genetic analysis of individuals of *S. japonica* from China and Japan showed evidence of founder's effect in the populations in China, which limits the maximum amount of genetic diversity that is possible (Shan et al. 2017). When the genetics of wild and farmed populations of *S. japonica* were compared, the evidence provided by 10 microsatellite markers suggested that gene flow was occurring, and that farmed populations had a higher level of genetic diversity than the "wild" populations. Even though gene flow was occurring, genes did not seem to be exchanged at an equal rate. Evidence suggested that the wild populations passed more of their genes to the farmed populations than vice versa (Shan et al. 2017). A very similar situation was seen with wild and farmed populations of *U. pinnatifida*—the wild populations were more likely to spread their genes into farmed populations than vice versa (Shan et al. 2018). This demonstrates that if a kelp is being cultivated in the natural range of its wild counterparts during a reproductively active season, gene flow is inevitable, and the genetics of both the farmed and wild populations will change. Research must be conducted to evaluate the long-term effects of the exchanges, and to attempt to prevent the mutual contamination of both gene pools.

7.11 Climate Change Considerations

Kelp aquaculture is often brought up in conversations about climate change. Anthropogenic activities have raised the concentration of CO_2 and other greenhouse gases within Earth's atmosphere. These significant alterations of global conditions have been suggested to contribute to several widespread phenomena such as ocean acidification, a global rise in average temperatures, an increased frequency of harmful algal blooms (HABs), and an increased frequency of severe storm events.

Kelp could be an important component in helping to alleviate many of the problems associated with the changing climate. All kelps are primary producers, meaning that they consume CO_2 while growing in a way similar to land plants. Additionally, kelps take up excess nutrients in the water column that could contribute to eutrophication events and HABs. Studies from Connecticut showed that *S. latissima* could remove 38–180 kg of nitrogen per hectare from nearshore waters (Kim et al. 2015). In China's nearshore aquaculture zones, several studies have shown that cultivating another type of algae, *G. lemaneiformis* and *P. yezoensis*, has significantly reduced the prevalence of HABs (Wu et al. 2015; Yang et al. 2015). It has also been hypothesized that kelp cultivation could create a "halo effect" of alkalinization. The reduced acidity of the water around kelp farms would be beneficial to shell-forming organisms in the vicinity (Ling et al. 2020). Although the scale at which the reduction of acidity occurs is still being evaluated, several factors like weather conditions, wave action, and current speeds would all affect the extent to which a kelp farm could deacidify an area.

Climate change is raising the average temperatures seen all over the world, including the temperature of its oceans. Because most of the kelps in the world is farmed in the ocean, these rising temperatures are affecting their habitat, and hence affecting where kelps can be grown. This poses a significant problem for the world's top kelp-producing countries: China, the Koreas, and Japan. These countries are on the edge of temperate and tropical zones. As the temperature of the world's oceans increases, the countries that produce nearly all of the world's kelp are at risk of losing hospitable habitat for their aquatic crops to heat stress, because the cooler water temperatures kelp need to thrive in will only be found at higher latitudes.

In preparing to adapt to a warmer ocean, governments involved with kelp production are looking to develop heat-resistant strains of kelp that can be deployed in warmer waters than those in which natural populations are found (Hwang et al. 2019). In each of the breeding programs of eastern Asian countries, developing heat-resistant cultivars has been identified as a top priority for the future kelp industry. Other options may be to move cultivation to more hospitable waters toward the poles, but that could be complicated by Exclusive Economy Zones. Technology currently being developed uses drones to move kelp farms up and down in the water column in hopes of increasing growth by cycling between getting enough light during the day and going to the nutrient-rich waters found at depth during the night. Perhaps the same technology can be used to move kelp farms according to suitable temperature areas (Kim et al. 2019).

Finally, countries' access to more northern latitudes that are interested in growing kelp should anticipate a change in the market as countries adapt to the changing climate. Countries that traditionally have provided significant proportions of raw products may not be able to grow the same amounts as they had historically. Countries with cool, nutrient-rich waters, where the effects of climate change will not be manifested until later, could expand their industries locally to make up for the lack of kelp biomass on the global market.

7.12 Conclusion

Worldwide, the significance of kelp is often overlooked. The most common place an average person interacts with kelp in their day-to-day lives is probably walking past it on the beach where it washed up during a recent storm. In reality, kelps are invaluable to the ecosystems they occupy, and they help create and continue to become more and more valuable to humans. With the global population set to reach nine billion people by the mid-century, kelp is quickly becoming more integral to the entire population. Conventional farming practices will be unable to produce enough to feed everyone, and most capture fisheries are either at capacity or are overfished. Aquaculture will be part of the solution.

Kelp biomass has the versatility that will be needed for the uncertain future ahead. Kelp exists in a variety of forms as food for humans. It can be eaten fresh or cooked, dried or salted. It can be ground and included in processed foods to improve a product's nutritional quality. Kelp biomass is also a good source of feed for a variety of animals, including those in aquaculture and conventional agriculture. Animals in aquaculture, like sea cucumbers, sea urchins, and others, would eat kelp in their natural environment, making it an obvious choice for sourcing feed. Kelp meal is also included in food formulas for commercial finfish and shrimp feed. Kelp meal provides important macro- and micronutrients and protein, providing the critical nutritional needs for these valuable sources of food and income for the human populace.

The industrial uses for kelp are also expansive and growing. Kelp produces a number of useful chemicals that are commonly extracted for applications ranging from the medical field to the food industry. Alginate, perhaps the most common of these chemicals, is used in the production of textiles, welding rods, and gelatinous foods. Applications for these chemicals are actively studied and new uses will continue to be discovered.

Kelp cultivation is concentrated in eastern Asia, and especially China. China, North and South Korea, and Japan account for more than 99% of all the kelp grown in the world. However, efforts elsewhere in the world are growing. Several countries in Europe are looking to grow a few species of kelp, and interest is growing in the United States. Asian countries have used a head start to cement themselves in a leading role in the development of the industry, but other countries can use what they have learned to advance their regional industries. In addition, it is difficult to prepare for the changes that will result from the changing climate. Warming ocean temperatures and changes in the chemical equilibrium of the ocean could alter the locations traditionally used for kelp cultivation, which could lead to major shifts in the production of kelp and kelp products.

Research and development efforts should be invested in making kelp production more efficient and using renewable energy sources to a greater extent. The renewable resources in each region are unique and incorporating them into kelp production efforts will require specialized tailoring in each situation. Using renewable energy to produce this valuable resource will simultaneously remove carbon from the global cycle, while not contributing more greenhouse gases to the atmosphere. Additional focused efforts will be required to maximize the effectiveness of this synergistic relationship.

7.13 References

Broch OJ, MO Alver, T Bekkby, H Gundersen, S Forbord, A Handå, J Skjermo, and K Hancke. 2019. "Kelp Cultivation Potential in Coastal and Offshore Regions of Norway." *Front. Mar. Sci.* 5:529

Brownlee I, J Pearson, and P Dettmar. 2005. "Alginate as a Source of Dietary Fiber." *Critical Reviews in Food Science and Nutritio*n. 45 (6) 497- 856.

Clarens A, E Resurreccion, M White., L Colosi. 2010. Environmental life cycle comparison of algae to other bioenergy feedstocks. Environmental Science and Technology. 44: 1813-1819.

EUROSTAT. 2020. Renewable energy statistics. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Renewable_energy_statistics#Share_of_renewable_energy_almost_doubled_between_2004_and_2018

Fanq ZX. 1983 A summary of the genetic studies of Laminaria japonica in China. In Proceedings of the Joint China-U.S. Phycology Symposium, edited by C.K. Tseng. Beijing, Science Press, pp. 123-36.

Ferdouse F, S Holdt, R Smith, P Murúa, Z Yang. 2018. "The global status of seaweed production, trade, and utilization." *FAO Globefish Research Programme* 124:1-124.

Flavin K, N Flavin, B Flahive. 2013. Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters. https://static1.squarespace.com/static/52f23e95e4b0a96c7b53ad7c/t/52f78b0de4b0374e6a0a4da8/1391954701750/OceanApproved_KelpManualLowRez.pdf

Grandorf Bak U, A Mols-Mortensen, and O Gregersen. (2018). Production method and cost of commercial scale offshore cultivation of kelp in the Faroe Islands using multiple partial harvesting. Algal Research, 33, 36-47. https://doi.org/10.1016/j.algal.2018.05.001

Gupta S, S Cox, N Abu-Ghannam (2011) Effect of different drying temperatures on the moisture and phytochemical constituents of edible Irish brown seaweed. Food Sci Technol-LEB 44(5):1266–1272

Handå A, S Forbord, X Wang, et al. (2013) Seasonal- and depth-dependent growth of cultivated kelp (*Saccharina latissima*) in close proximity to salmon (Salmo salar) aquaculture in Norway. Aquaculture 414-415:191–201.

Hernández-Carmona, G, DJ McHugh, DL Arvizu-Higuera. et al. Pilot plant scale extraction of alginate from Macrocystis pyrifera. 1. Effect of pre-extraction treatments on yield and quality of alginate. Journal of Applied Phycology 10, 507–513 (1998). https://doi.org/10.1023/A:1008004311876

Hove, Anders. 2020. Trends and Contradictions in China's Renewable Energy Policy. Columbia, Center on Global Energy Policy. https://www.energypolicy.columbia.edu/research/commentary/trends-and-contradictions-china-s-renewable-energy-policy#_edn2

https://www.eia.gov/state/?sid=AK .

Hwang EK, YG Gong, and CS Park. 2012. Cultivation of a hybrid of free-living gametophytes between Undariopsis peterseniana and Undaria pinnatifida: morphological aspects and cultivation period. Journal of Applied Phycology 24: 401–408. DOI:10.1007/s10811-011-9727-7.

Hwang E and C Park. 2020. Seaweed cultivation and utilization of Korea. Algae. 35: 107-171.

Hwang E, N Yotsukura, S Pang, L Su, T Shan. 2019. Seaweed breeding programs and process in eastern Asian countries. Phycologia. 58: 484-495.

International Energy Agency (IEA). 2020. Norway. https://www.iea.org/countries/norway

Japan Agency for Natural Resources and Energy (ANRE). 2020. Japan's Energy 2019. Ministry of Economy, Trade, and Industry. https://www.enecho.meti.go.jp/en/category/brochures/pdf/japan_energy_2019.pdf

Jensen A. 1993. Present and future needs for algae and algal products. In: Chapman ARO, Brown MT and Lahaye M (ed) Fourteenth International Seaweed Symposium. Springer Netherlands. 85: 15–23.

Kawashima S. 1984. Kombu cultivation in Japan for human foodstuff. Japanese Journal of Phycology 32: 379–394.

Kim J, G Kraemer, and C Yarish. 2015. Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. Mar. Ecol. Prog. Ser., 531:155-166.

Kim J, M Stekoll, and C Yarish. 2019. Opportunities, challenges, and future directions of open-water seaweed aquaculture in the United States. Phycologia. 58: 446-461.

Korea Energy Economics Institute (KEEI). Yearbook of Energy Statistics 2015; KEEI: Ulsan, Korea, 2016; p. 4.

Korea New and Renewable Energy Center (KNREC). New & Renewable Energy Statistics 2015; Korea Energy Agency: Yongin, Korea, 2016.

Li X, Y Cong, S Qu, Z Zhang, H Dai, S Luo, X Han, S Huang, Q Wang, and G Liang. 2008. Breeding and trial cultivation of Dongfang No. 3, a hybrid of Laminaria gametophyte clones with a more than intraspecific but less than interspecific relationship. Aquaculture 280: 76–80.

Li X, Z Zhang, S Qu, G Liang, N Zhao, J Sun, S Song, Z Cao, X Li, and J Pan. 2016a. Breeding of an intraspecific kelp hybrid Dongfang no. 6 (Saccharina japonica, Phaeophyceae, Laminariales) for suitable processing products and evaluation of its culture performance. Journal of Applied Phycology 28: 439–447.

Ling S, C Cornwall, B TilbrooK, and C Hurd. 2020. Remnant kelp bed refugia and future phase-shifts under ocean acidification. PLoS ONE. 15: 1-16.

Marine Mammal Protection Act of 1972. 16 U.S.C. ch 31 § 1361 et seq.

McHugh D. 2003. A guide to the seaweed industry. FAO Fisheries Technical Paper, No. 441: 1-105.

Mesnildrey L, M Lesueur, C Jacob, and K Frangoudes. (2012). Seaweed industry in France. Report. Interreg program NETALGAE, Les publications du Pôle halieutique AGROCAMPUS OUEST.

Slezak M. “China cementing global dominance of renewable energy and technology,” The Guardian, January 6, 2017, https://www.theguardian.com/environment/2017/jan/06/china-cementing-global-dominance-of-renewable-energyand-technology

Ministry of Oceans & Fisheries. 2018. Fisheries statistics. https://portal.fips.go.kr searched on 25 July 2018.

Ministry of Petroleum and Energy (MPE). 2016. Renewable energy production in Norway. https://www.regjeringen.no/en/topics/energy/renewable-energy/renewable-energy-production-in-norway/id2343462/

Misurcova L. 2011. Chemical Composition of Seaweeds. Handbook of Marine Macroalgae. 171-192.

Mondragon J. 2003. Seaweeds of the Pacific Coast: common marine algae from Alaska to Baja California. Sea Challengers, Monterey, CA. 97 p.

O’ Meara S. 2020. China’s plan to cut coal and boost green growth. Nature. 26 August, 2020.

Pang SJ, F Liu, QS Liu, JQ Wang, and CB Sun. 2015. Breeding and genetic stability evaluation of the new Saccharina variety “205”. China Fisheries 10: 59–60.

Rueters. "China installed wind power capacity hits 7 pct of total in 2014." Reuters.com. 12 February 2015.

Shan T, S Pang, X Wang, J Li, and L Su. 2018. Assessment of the genetic connectivity between farmed and wild populations of Undaria pinnatifida (Phaeophyceae) in a representative traditional farming region of China by using newly developed microsatellite markers. Journal of Applied Phycology 30: 2707–2714. DOI: 10.1007/s10811-018-1449-7.

Shan T, N Yotsukura, and S Pang. (2017). Novel implications on the genetic structure of representative populations of Saccharina japonica (Phaeophyceae) in the northwest pacific as revealed by highly polymorphic microsatellite markers. J. Appl. Phycol. 29, 631–638. doi: 10.1007/s10811-016-0888-882

Sohn CH. 1998. The seaweed resources of Korea. In: Seaweed resources of the world (Ed. by A.T. Critchley & O. Masao), pp. 15–33. Japan International Cooperation Agency, Yokosuka, Japan.

Staedter T. “7 of 10 Most Air-Polluted Cities Are in China,” Seeker, January 16, 2013, https://www.seeker.com/7-of-10-most-air-polluted-cities-are-in-china-1766374196.html.

Stévant P, C Rebours, and A Chapman. (2017). Seaweed aquaculture in Norway: recent industrial developments and future perspectives. Aquaculture International, 25: 1373–1390.

Truong VD, WM Walter, and FG Giesbrecht. "Texturization of Sweetpotato Puree with Alginate: Effects of Tetrasodium Pyrophosphate and Calcium Sulfate." Journal of Food Science, 1995: 1054-59.

US EIA. 2020. Country Analysis Executive Summary: South Korea. US Energy Information Administration. https://www.eia.gov/international/content/analysis/countries_long/South_Korea/south_korea.pdf

US. Energy and Information Administration. 2020. State Profile and Energy Estimates, Maine. https://www.eia.gov/state/?sid=ME.

US. Energy and Information Administration. 2020. State Profile and Energy Estimates, Alaska.

Wang X, LM Olsen, KI Reitan, et al. (2012) Discharge of nutrient wastes from salmon farms: environmental effects, and potential for integrated multi-trophic aquaculture. Aquac Environ Interact 2(3):267–283.

World Nuclear Association (WSA). 2020. Fukushima Daiichi Accident. https://www.world-nuclear.org/information-library/safety-and-security/safety-of-plants/fukushima-daiichi-accident.aspx

Wu H, Y Huo. J Zhang, Y Liu, Y Zhoa, and P He. 2015. Bioremediation efficiency of the largest scale artificial Porphyra yezoensis cultivation in the open sea in China. Marine Pollution Bulletin. 95: 289-296.

Yamazaki T. 2018. Japan’s Renewable Energy Policy. Renewable Energy Division Agency for Natural Resources and Energy. 1-14.

Yang Y, Z Chai, Q Wang, W Chen, Z He, and S Jiang. 2015. Cultivation of seaweed Gracilaria in Chinese coastal waters and its contribution to environmental improvements. Algal Research. 9: 236-244

Zava TT, and DT Zava. 2011. Assessment of Japanese iodine intake based on seaweed consumption in Japan: A literature-based analysis. Thyroid Research 4: 14. https://doi.org/10.1186/1756-6614-4-14

Zeng C. 1984. Phycological research in the development of the Chinese seaweed industry. Hydrobiologia, 116/117:7-18

Zhang J, Y Liu, D Yu, HZ Song, JJ Cui, and T Liu. 2011. Study on high-temperature-resistant and high-yield Laminaria variety “Rongfu”. Journal of Applied Phycology 23: 165–171. DOI:10.1007/s10811-011-9650-y.

Zhang J. 2018. Seaweed industry in China. Innovation Norway China. www.submariner-network.eu/images/grass/Seaweed_Industry_in_China.pdf

Zhang R, A Yuen, R de Nys, A Masters, and T Maschmeyer. 2020. Step by step extraction of bio-actives from the brown seaweeds, Carpophyllum flexuosum, Carpophyllum plumosum, Ecklonia radiata and Undaria pinnatifida. Algal Research. 52: 102092.

8.0 Kelp Compositional Analyses

With the growing need to increase the efficacy of renewable energy in order to maximize energy production and reduce our carbon footprint, scientists aim to identify innovative ways to use the byproducts produced throughout a given process. Finding uses for byproducts not only encourages a step toward a sustainable biobased economy, but also identifies useful and marketable alternatives for materials that would otherwise go to waste. Among these marketable alternatives are products in health care and valuable trace metal elements. While major advancements have been made by the DOE to improve energy resiliency, more research is necessary to reduce costs associated with biofuel production through valorization of coproducts.

In recent years, algae have become a promising source of renewable energy because they possess the ability to capture CO_2, one of the most important GHGs because of its impact on climate change. By using algae-derived biofuels, CO_2 emissions can be greatly reduced and can promote a longer-term, sustainable source of fuels for the United States (Chen et al. 2015). Microalgae have taken the spotlight in terms of renewable energy research because of its potential to be a high-yield source of biofuels and a greener alternative to fossil fuels. On the other hand, macroalgae are preferred over microalgae because of their ability to be harvested easily from natural environments. However, macroalgae generally do not contain the high amounts of lipids that microalgae contain, which are necessary to produce the lipid-based fuels. Instead, carbohydrates that are present at high concentrations in macroalgae are suitable for conversion to ethanol and butanol via fermentation and to methane via anaerobic digestion.

Carbohydrates are any large group of organic compounds in foods and tissues such as sugars, starches, and fibers. The sugar units that link by glyosidic bonds form a macromolecule called a polysaccharide. The two primary polysaccharides widely known to be abundant in specific types of macroalgae are alginate and fucoidan. They are specific to brown types of macroalgae such as *Saccharina latissima* and *Alaria esculenta*. Such carbohydrates have also found plenty of uses in health care due to their natural neuroprotective properties.

In this chapter, we report on the concentrations of alginate, fucoidan, rare-earth and other trace elements that were measured in 14 commercial (brown, green, and red) seaweeds as well as 16 Alaska kelp samples obtained from Blue Evolution and Seagrove Kelp.

8.1 Material and Methods

8.1.1 Source of Macroalgae

8.1.1.1 Commercial Seaweed

The following seaweeds were obtained in air-dried form from commercial suppliers with all stipes and holdfasts removed for food-grade products (Table 8.1 in Section 8.1.2):

- *Saccharina latissima* fronds were harvested from two Pacific sites (Alaska, USA and Vancouver BC, Canada) and an Atlantic site (Hancock, Maine, USA).
- *Alaria esculenta* fronds were also harvested from both a Pacific site (Alaska, USA) and an Atlantic site (Hancock, Maine, USA).
- *Nereocystis luetkeana*, *Macrocystis pyrifera,* and *Laminaria digitata* fronds were harvested from a Pacific site (Vancouver BC, Canada).

- *Ulva lactuca* fronds were harvested from a Pacific site (Hawaii, USA) and two Atlantic sites (Hancock, Maine, USA).
- *Porphyra umbilicalis* fronds were harvested from the East China Sea and an Atlantic site (Maine, USA).
- *Palmaria palmata* fronds were harvested from an Atlantic site (Hancock, Maine, USA).

8.1.1.2 Alaska Kelp Samples from Blue Evolution and Seagrove Kelp

Freshly harvested Alaska kelp samples were obtained from Blue Evolution and Seagrove Kelp as indicated in Table 8.2 (in Section 8.1.2). The samples from Blue Evolution consisted of sugar kelp (*Saccharina latissima*) and winged kelp (*Alaria esculenta*) harvested initially in 2019, and later at their offshore farms at Popov Island in April 2020, and Woody Island in April, May, and June 2020. All May and June harvest samples were received frozen, while all April harvest samples (SA-P-4, SA-W-4, AL-P-4, and AL-W-4) were received air-dried, following forced air-drying by Blue Evolution in an oven at ca. 50°C for 8–10 hours to achieve a final moisture content of 7–8%. Prior to freezing or air-drying, none of the samples was washed or rinsed in freshwater, i.e., they are “as is” out of the ocean. The samples from Seagrove Kelp were received frozen.

8.1.2 Freeze-Drying of Macroalgal Samples

All commercial seaweed samples as seen in Table 8.1 were weighed to obtain an initial weight, freeze-dried for 1 week, weighed again to obtain a dry weight, and ball milled at 1,725 rpm in 100 mL plastic vials containing two to four 10 mm diameter glass beads until they turned into a fine powder. Leftover samples were kept and stored in a cool and dry environment. All Alaska kelp samples (frozen or air-dried) received from Blue Evolution and Seagrove Kelp were freeze-dried for 1 to 2 weeks, following the same procedure as that the commercial samples.

Table 8.1. List of commercially sourced macroalgae and respective sample codes used in subsequent analyses.

Common Name	Genus	Phylum/ Division	Reason for Inclusion	Sources	Code Name	Supplier
Sugar Kelp/ Atlantic Kombu	Saccharina	Ochrophyta	Potential as a PNW-Alaska crop	Bamfield BC, Canada	SA-BC	Canadian Kelp Resources (https://canadiankelp.com/)
				Hancock, Maine	SA-HME	Maine Coast Sea Vegetables (www.seaveg.com)
Bull Kelp	Nereocystis			Bamfield BC, Canada	NE-BC	Canadian Kelp Resources (https://canadiankelp.com/)
Winged Kelp/ California Wakama	Alaria			Hancock, Maine	AL-HME	Maine Coast Sea Vegetables (www.seaveg.com)
Giant Kelp	Macrocystis			Bamfield BC, Canada	MA-BC	Canadian Kelp Resources (https://canadiankelp.com/)
Kombu	Laminaria		Large global commercial production/ PNW-Alaska crop	China	LA-CHI	Great Eastern Sun (www.great-eastern-sun.com)
				Bamfield BC, Canada	LA-BC	Canadian Kelp Resources (https://canadiankelp.com/)
Sea Lettuce	Ulva	Chlorophyta	Rapid growth rate/high protein content (20-30%)	Honolulu, Hawaii	UL-HA	Hawaii Pharm (www.hawaiipharm.com)
				Maine	UL-ME	VitaminSea Seaweed (www.vitaminseaseaweed.com)
				Hancock, Maine	UL-HME	Maine Coast Sea Vegetables (www.seaveg.com)
Nori/Laver	Porphyra	Rhodophyta	High protein content (up to 50%)/ large commercial market/high value	China	PO-CHI	Great Eastern Sun (www.great-eastern-sun.com)
				Maine	PO-ME	VitaminSea Seaweed (www.vitaminseaseaweed.com)
Dulse	Palmana	Rhodophyta	High protein content (up to 50%)/ Oregon State research crop/high value	Hancock, Maine	PA-HME	Maine Coast Sea Vegetables (www.seaveg.com)
				Oregon State	PA-OSU	Oregon State University (Dr. Christopher Langdon)

Table 8.2. List of Alaska kelp samples received from Blue Evolution and Seagrove Kelp and respective sample codes used in subsequent analyses.

Count	Common name	Genus	Phylum/Division	Havest Location and Date	Sources:	Code Names:
1	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Alaska, 2019	Blue Evolution	SA-AL
2	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Popov Island, Alaska, April 2020	Blue Evolution	SA-P-4
3	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Woody Island, Alaska, April 2020	Blue Evolution	SA-W-4
4	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Woody Island, Alaska, May 2020	Blue Evolution	SA-W-5
5	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Woody Island, Alaska, June 2020	Blue Evolution	SA-W-6
6	Alaska Winged Kelp	*Alaria*	Ochrophyta	Alaska, 2019	Blue Evolution	AL-AL
7	Alaska Winged Kelp	*Alaria*	Ochrophyta	Popov Island, Alaska, April 2020	Blue Evolution	AL-P-4
8	Alaska Winged Kelp	*Alaria*	Ochrophyta	Woody Island, Alaska, April 2020	Blue Evolution	AL-W-4
9	Alaska Winged Kelp	*Alaria*	Ochrophyta	Popov Island, Alaska, May 2020	Blue Evolution	AL-P-5
10	Alaska Winged Kelp	*Alaria*	Ochrophyta	Popov Island, Alaska, June 2020	Blue Evolution	AL-P-6
11	Five-ribbed kelp	*Costaria*	Ochrophyta	July 2020	Seagrove Kelp	CO-SG
12	Sea Cabbage	*Hedophyllum*	Ochrophyta	July 2020	Seagrove Kelp	HE-SG
13	Badderlocks	*Alaria*	Ochrophyta	July 2020	Seagrove Kelp	AL-SG
14	Bull Kelp	*Nereocystis*	Ochrophyta	July 2020	Seagrove Kelp	NE-SG-S
15	Giant Kelp	*Macrocystis*	Ochrophyta	July 2020	Seagrove Kelp	MA-SG
16	Sugar Kelp/ "Atlantic Kombu"	*Saccharina*	Ochrophyta	July 2020	Seagrove Kelp	SA-SG

8.1.3 Extraction Process for Alginates and Fucoidans

To extract alginate and fucoidan fractions, procedures were modified from Lorbeer et al. (2015). A flow chart of the polysaccharide extraction and fractionation procedures can be found in Figure 8.1. Dried and milled alga samples (10 g) were first extracted twice with 100 mL of anhydrous ethanol and left to stir constantly in a shaking incubator for 3 hours under room temperature to remove proteins and other undesirable components. The samples were then strained via vacuum filtration (55 mm Whatman® filter paper) and dried overnight at 42°C. All samples were weighed to obtain a dry weight.

The extracts (Extract A) were discarded while the residual seaweeds (Residue A) were placed in 150 mL of a warm, aqueous HCl solution and extracted in a shaking incubator (0.1 M HCl, 2.5 hours, 42°C). After extraction, the mixture was immediately placed in a cooler filled with ice. Using several pH strips, 2 M NaOH was slowly added dropwise to neutralize the mixture. The mixture was centrifuged and the supernatants (Extract B) were transferred to 500 mL high density polyethylene (HDPE) bottles where it was stored in a freezer at -70°C for further use.

The precipitates (Residue B) were then transferred to 250 mL HDPE bottles to which 150 mL of a 0.2 M Na_2CO_3 solution was added. The mixture was placed in a 45°C shaking incubator for 2 hours for extraction. After extraction, the mixture was transferred to a 500 mL HDPE bottle and diluted with deionized water to a total volume of 600 mL. The final seaweed residues (Final Residue) were removed via low-speed centrifugation (4,000 rpm, 10 min), washed with deionized water and freeze-dried for 3 days. Final residue dry weights were obtained after subsequent freeze-drying. Concurrently, one volume of anhydrous ethanol was added to the extract (Extract C) in a 1 L glass jar and left to precipitate the alginates overnight at 4°C. The precipitates were then collected via methods of centrifugation, washed twice with 50% ethanol, and freeze-dried for 3 days. Final alginate dry weights were obtained subsequently after freeze-drying.

Extract B was subsequently thawed overnight. The following day, two volumes of anhydrous ethanol were added to the extract liquor (Extract B). Extract B was then left overnight at 4°C to allow for the precipitation of polysaccharides. The precipitate was then removed via methods of centrifugation (7,000 rpm, 15 min, 4°C), washed twice with a 70% ethanol solution, and freeze-dried for several days to obtain fucoidan. Final fucoidan-rich dry weights were obtained subsequently after freeze-drying. Because of PNNL's laboratory restrictions related to the COVID-19 pandemic, the analyses for half of the fucoidan samples were left incomplete.

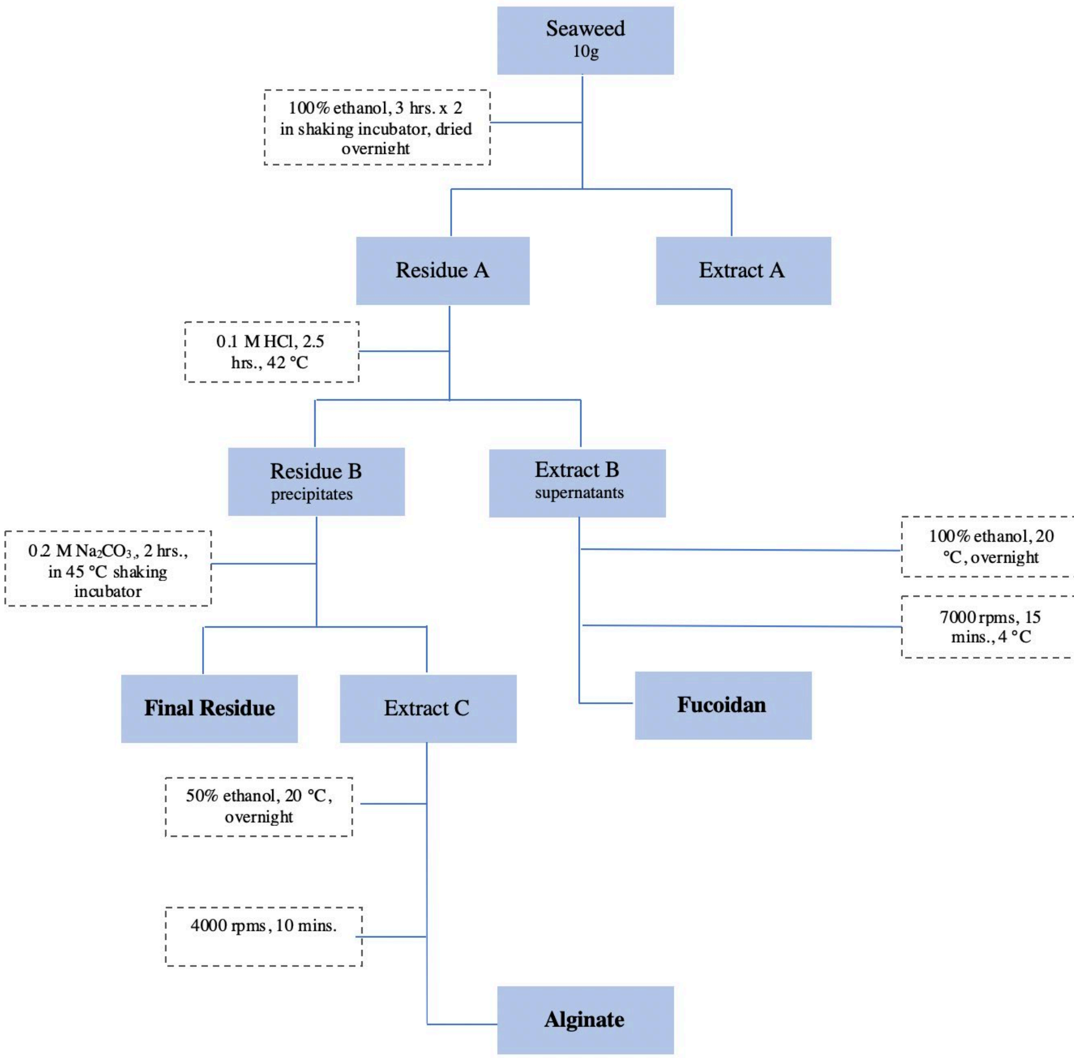

Figure 8.1. Flow chart of the polysaccharide extraction method.

8.1.4 Trace Element Analysis

8.1.4.1 Digestion of Seaweed Samples

Freeze-dried samples were digested using alternating treatments of Fisher 30% American Chemical Society (ACS)-certified hydrogen peroxide, ultrapure deionized water (with resistivity no less than 18 MΩ-cm) and 4M Fisher OPTIMA grade nitric acid. First, enough hydrogen peroxide was added to cover the sample (5 mL) and then it was dried down at 90°C using a WATLOW 120V 8A digestion block, after which the same amount of deionized water (>18 MΩ-cm) was added and then dried down. This procedure was repeated at least three times until the sample ceased reacting with the hydrogen peroxide. Following this, the same amount of 4M nitric acid was added and then dried down. This procedure was repeated at least three times until sample digestion was complete. Samples were brought back into solution in 5% Fisher OPTIMA grade nitric acid for analysis.

8.1.4.2 Analysis of Cations

Major cations (As, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Sn, Sr, Ti, V, and Zn) were analyzed quantitatively using a PerkinElmer OPTIMA 8300 dual-view inductively coupled plasma-optical emission spectrometer (ICP-OES) with a PerkinElmer S-10 auto-sampler interface. The instrument was calibrated using standards made by the High-Purity Standards Corporation to generate calibration curves. The range of the calibration curves was 50 ppb to 50 ppm. This calibration was verified immediately with an initial calibration verification (ICV) and during sample analysis with a continuing calibration verification (CCV), which is run every 10 samples at a minimum in accordance with Hanford Analytical Quality Assurance Requirements Document (HASQARD) requirements (see also: http://www.hanford.gov/page.cfm/AnalyticalServices). Calibration blanks were also analyzed after each calibration verification to ensure background signals and potential carryover effects were not a factor. The calibration was independently verified using standards made by Inorganic Ventures. All calibration verification values must be within ±10% of the target concentrations to comply with the quality assurance/quality control (QA/QC) requirements as defined in the HASQARD document, Volumes 1 and 4 (Note: *Conducting Analytical Work in Support of Regulatory Programs* is the name of the document that PNNL uses to remain in compliance with HASQARD). A 1 ppm Lu, Sc, and Y solution was added as an online internal standard to all samples, standards, and blanks to demonstrate the stability of the instrument and sample introduction system.

Method Detection Limits (MDLs) were established by running the lowest calibration standard (0.05 ppb) seven consecutive times and multiplying the standard deviation of those seven replicates by 3.143 (student t-test value) to establish an Instrument Detection Limit (IDL) and then multiplying that number by 5 to get the MDL. This process was repeated three times on non-consecutive days and averaged to establish a working MDL in parts per billion.

All samples and standards were diluted with 2% Fisher Scientific OPTIMA trace metal grade nitric acid and twice deionized water with resistivity no lower than 18.0 MΩ-cm. The ICP-OES operating conditions were plasma Ar flow = 10 L/min, auxiliary Ar flow = 0.2 L/min, nebulizer Ar flow = 0.60 L/min, RF power = 1,400 watts, and peristaltic pump rate = 0.5 mL/min.

8.1.5 Analysis of Rare-Earth and Other Elements

Elements of interest (Sc, Cu, Y, Rh, Pd, Ag, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Re, U) were analyzed using a Thermo Scientific X-Series II quadrupole Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) and an Elemental Scientific SC4 DX *FAST* auto-sampler interface. The instrument was calibrated using standards made by the High-Purity Standards Corporation to generate calibration curves. The seven calibration standards range from 0.05 ppb to 5 ppb. This calibration was verified immediately with an ICV and during sample analysis with CCVs, which are run every 10 samples at a minimum in accordance with HASQARD requirements. Calibration blanks were also analyzed after each calibration verification to ensure background signals and potential carryover effects were not a factor. The calibration was independently verified using standards made by Inorganic Ventures. All measured calibration verification values must be within ±10% of their known concentrations to comply with the QA/QC requirements as defined in the HASQARD document (cited above). A 10 ppb Cs, Sb, Ta and Tl solution was added as an online internal standard to all samples, standards, and blanks during the analysis to demonstrate the stability of the instrument and sample introduction system.

MDLs were established by running the lowest calibration standard (0.05 ppb) seven consecutive times and multiplying the standard deviation of those seven replicates by 3.143 (student t-test value) to establish an IDL and then multiplying that number by 5 to get the MDL. This process was repeated three times on non-consecutive days and averaged to establish a working MDL in parts per billion.

All samples and standards were diluted with 2% Fisher Scientific OPTIMA trace metal grade nitric acid and twice deionized water with resistivity no lower than 18.0 MΩ-cm. The ICP-MS operating conditions were plasma Ar flow = 14 L/min, auxiliary Ar flow = 0.8 L/min, nebulizer Ar flow = 0.75 L/min, RF power = 1,400 watts, and peristaltic pump rate = 0.9 mL/min.

8.2 Results

8.2.1 Alginate Content

8.2.1.1 Commercial Seaweed

Alginate was extracted and isolated from *Saccharina latissima*, *Alaria esculenta*, *Ulva lactuca*, *Nereocystis luetkeana*, *Macrocystis pyrifera*, *Laminaria digitata*, *Palmaria palmata*, and Porphyra *umbilicalis*. To find the highest alginate content dependent on location and type of macroalgae, the alginate yield was calculated by dividing the final alginate mass (g) by the final residue mass (g). Among the various tested macroalgae, brown macroalgae, such as *Saccharina latissima*, *Alaria esculenta*, *Nereocystis luetkeana*, *Macrocystis pyrifera*, and *Laminaria digitata*, contained higher percentages of alginate than their green and red macroalgae counterparts (Table 8.3 and Figure 8.2). Harvested from the Northern Pacific Ocean, *Saccharina latissima* from Bamfield BC, Canada (SA-BC) contained 20.56% alginate. On the other hand, *Saccharina latissima* harvested from the Northern Atlantic Ocean off the coast of Hancock, Maine, USA (SA-HME) contained slightly higher alginate, i.e., 23.9%. *Alaria esculenta* harvested in the Northern Pacific Ocean off the coast of Hancock, Maine, USA (AL-HME) contained alginate at 25.50%. The three other types of brown macroalgae were each harvested from the Northern Pacific Ocean off the coast of Bamfield BC, Canada, and contained the following alginate content: *Nereocystis luetkeana* (NE-BC) 16.89%, *Macrocystis pyrifera* (MA-BC) 22.32%, and *Laminaria digitata* (LA-BC) 20.65%. *Laminaria digitata* from another harvest location in the Northern Pacific Ocean off the coast of the East China Sea (LA-CH), had a similar alginate content of 20.02% (Table 8.3 and Figure 8.2).

The alginate contents of green and red macroalgae were observably lower compared to the alginate contents of brown macroalgae (Table 8.3 and Figure 8.2). *Palmaria palmata*, a red macroalga harvested from the Northern Atlantic Ocean off the coast of Hancock, Maine, USA (PA-HME), had an alginate content of only 3.61%. Also harvested off the coast of Maine, USA, the red seaweed *Porphyra umbilicalis* (PO-ME) contained only 0.11% of alginate. Green macroalgae had low alginate contents similar to red macroalgae. Both green types of macroalgae, *Ulva lactuca*, were harvested from the Northern Atlantic Ocean off the coast of Maine (UL-ME, UL-HME) and were shown to contain 0.43% and 1.94% of alginate, respectively.

Table 8.3. Weight percentages of alginate and fucoidan in commercial seaweed samples.

Count	Common name	Genus	Phylum/Division	Harvest Location	Code Names	Alginate (%wt)	Fucoidan (%wt)
1	Sugar Kelp/ "Atlantic Kombu"	*Saccharina*	Ochrophyta	Bamfield BC, Canada	SA- BC	15.78	3.92
				Hancock, Maine	SA- HME	23.90	
2	Bull Kelp	*Nereocystis*	Ochrophyta	Bamfield BC, Canada	NE-BC	16.90	
3	Winged Kelp/ "California Wakame"	*Alaria*	Ochrophyta	Hancock, Maine	AL-HME	25.50	5.44
4	Giant Kelp	*Macrocystis*	Ochrophyta	Bamfield BC, Canada	MA- BC	22.32	3.84
5	Kombu	*Laminaria*	Ochrophyta	China	LA- CH	20.02	2.02
				Bamfield BC, Canada	LA- BC	20.65	
6	Sea Lettuce	*Ulva*	Chlorophyta	Honolulu, Hawaii	UL-HA		
				Maine	UL-ME	0.43	2.96
				Hancock, Maine	UL- HME	1.94	
7	Nori/Laver	*Porphyra*	Rhodophyta	China	PO- CH		
				Maine	PO- ME	0.11	
8	Dulse	*Palmaria*	Rhodophyta	Hancock, Maine	PA- HME	3.61	
				Oregon State	PA-OSU		

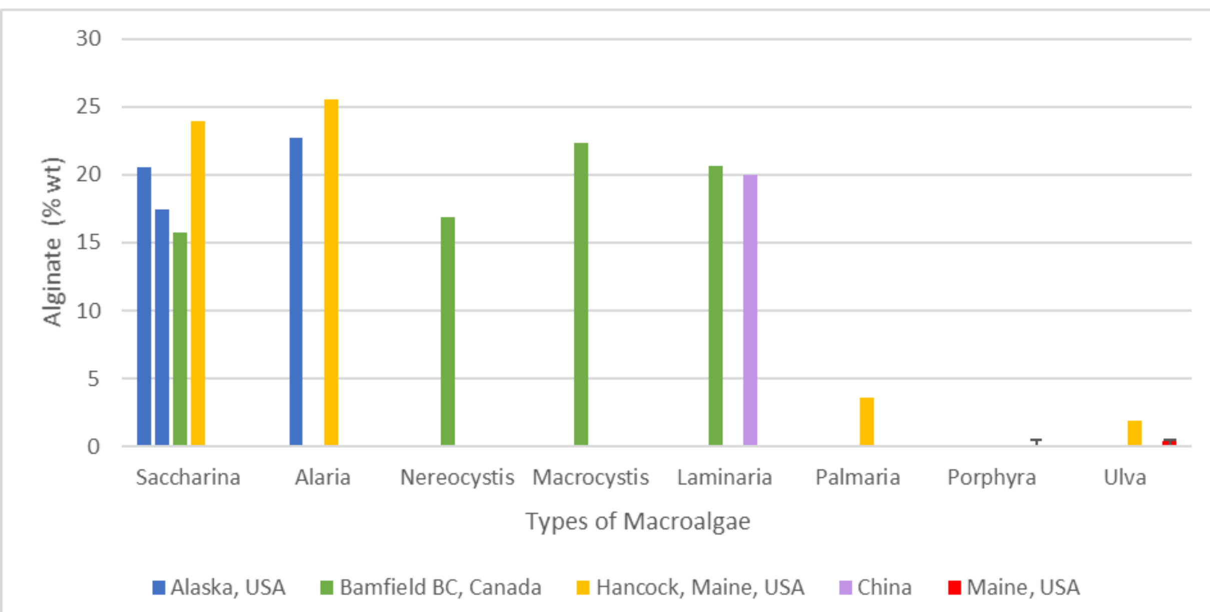

Figure 8.2. Alginate content (%) in various types of commercial seaweed harvested at different locations.

8.2.1.2 Alaska Kelp

Duplicate samples of *Saccharina latissima* (SA-AL#1, SA-AL#2), a green macroalga harvested by Blue Evolution in 2019 from the Northern Pacific Ocean, off the coast of Alaska, had alginate contents of 17.40% and 20.56%, respectively (Table 8.4). *Alaria esculenta*, another green seaweed harvested by Blue Evolution in 2019 from the Northern Pacific Ocean off the coast of Alaska, USA (AL-AL), contained 22.72% alginate (Table 8.4). Subsequent samples of *Saccharina latissima* (SA-P-4, SA-W-4, SA-W-5, and SA-W-6) harvested by Blue Evolution from two locations (Popov and Woody island, Alaska) in April, May, and June 2020 had significantly lower alginate contents, ranging from 1.8 to 6.7% and increasing with harvesting time (i.e., the plants' maturity). Similarly, samples of *Alaria esculenta* (AL-P-4, AL-W-4, AL-W-5, and AL-W-6) harvested at the same times from these two locations had also much lower alginate contents, ranging from 5.3 to 9%. The reason for these much lower alginate contents is not entirely clear. One possible explanation is that alginate may have degraded during the air-drying procedure employed by Blue Evolution. However, only samples from the April 2020 harvests were air-dried prior to shipment, while all others were received frozen and intact, thus this explanation is unsatisfactory. Another possibility is "operator error." The Blue Evolution samples from the 2019 harvests were analyzed for alginate by one lab technician, while the samples from the 2020 harvests were analyzed by another. However, the exact same protocols were used and both technicians measured similar fucoidan contents in the 2019 and 2020 samples (see next section), making this explanation also unsatisfactory.

Table 8.4. Weight percentages of alginate and fucoidan in Alaska kelp samples.

Count	Common name	Genus	Phylum/Division	Havest Location and Date	Sources	Code Names	Alginate (%wt)	Fucoidan (%wt)
1	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Alaska, 2019	Blue Evolution	SA-AL #1	17.40	3.86
2	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Alaska, 2019	Blue Evolution	SA-AL #2	20.56	4.84
4	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Popov Island, Alaska, April 2020	Blue Evolution	SA-P-4	1.81	3.12
5	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Woody Island, Alaska, April 2020	Blue Evolution	SA-W-4	3.62	2.34
6	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Woody Island, Alaska, May 2020	Blue Evolution	SA-W-5	6.29	4.40
7	Alaska Sugar Kelp	*Saccharina*	Ochrophyta	Woody Island, Alaska, June 2020	Blue Evolution	SA-W-6	6.71	4.14
3	Alaska Winged Kelp	*Alaria*	Ochrophyta	Alaska, 2019	Blue Evolution	AL-AL	22.72	
8	Alaska Winged Kelp	*Alaria*	Ochrophyta	Popov Island, Alaska, April 2020	Blue Evolution	AL-P-4	9.04	3.40
9	Alaska Winged Kelp	*Alaria*	Ochrophyta	Woody Island, Alaska, April 2020	Blue Evolution	AL-W-4		
10	Alaska Winged Kelp	*Alaria*	Ochrophyta	Popov Island, Alaska, May 2020	Blue Evolution	AL-P-5	5.33	4.22
11	Alaska Winged Kelp	*Alaria*	Ochrophyta	Popov Island, Alaska, June 2020	Blue Evolution	AL-P-6	5.30	5.93

8.2.2 Fucoidan Content

8.2.2.1 Commercial Seaweed

Fucoidan was extracted and isolated from *Saccharina latissima, Alaria esculenta, Ulva lactuca, Macrocystis pyrifera,* and *Laminaria digitata*. To find the highest fucoidan content dependent on location and type of macroalgae, the fucoidan yield was calculated by dividing the final fucoidan mass (g) by the final residue mass (g). The *Saccharina latissima* harvested from Bamfield BC, Canada(SA-BC) contained 3.92% of fucoidan while *Alaria esculenta* from Hancock, Maine, USA (AL-HME) contained 5.44% of fucoidan (Table 8.3 and Figure 8.3). The two other types of brown macroalgae for which fucoidan was measured were both harvested from the Northern Pacific Ocean. *Macrocystis pyrifera* (MA-BC) and *Laminaria digitata (*LA-CH), both of which were harvested from the Northern Pacific Ocean, contained 3.84% and 2.02% fucoidan, respectively. Finally, the green macroalga *Ulva lactuca* (UL-ME), contained 2.96% of fucoidan (Table 8.3 and Figure 8.3).

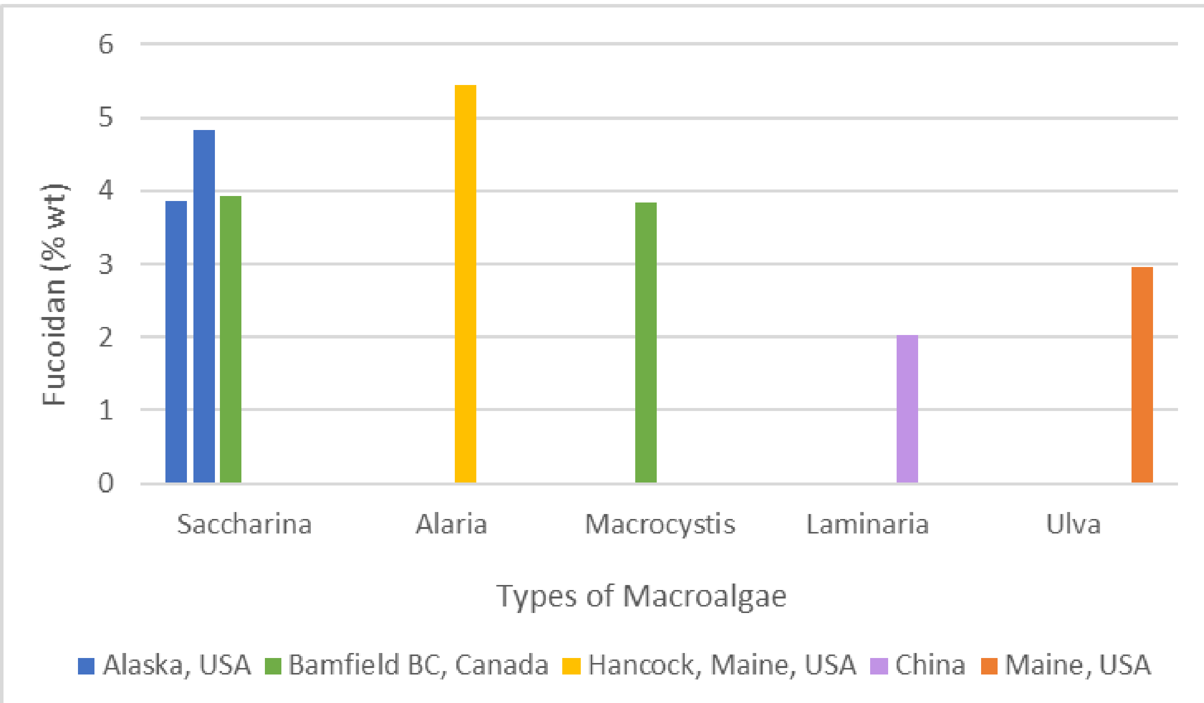

Figure 8.3. Fucoidan content (%) in various types of commercial seaweed harvested at different locations.

8.2.2.2 Alaska Kelp

Duplicate samples of *Saccharina latissima* (SA-AL#1, SA-AL#2), a green macroalga harvested by Blue Evolution in 2019 from the Northern Pacific Ocean, off the coast of Alaska, had fucoidan contents of 3.86% and 4.84%, respectively (Table 8.4). Subsequent samples of *Saccharina latissima* (SA-P-4, SA-W-4, SA-W-5, and SA-W-6) and of *Alaria esculenta* (AL-P-4, AL-W-4, AL-W-5, and AL-W-6) harvested by Blue Evolution from two locations (Popov and Woody island, Alaska) in April, May, and June 2020 had similar fucoidan contents, ranging from 2.3 to 5.9%.

8.2.3 Elemental Analysis

8.2.3.1 Commercial Seaweed

The concentrations of rare-earth and other trace elements for the commercial seaweed samples, including concentration averages, standard deviations, and minimum/maximum values, are shown in Table 8.5. The sum of concentrations (ug/kg) of rare-earth and other elements ranges more than 10-fold, from 317 ug/kg (NB-BC) to 3720 ug/kg (PO-ME), as shown in Figure 8.4. An example of the concentrations (ug/kg) of specific rare-earth and other elements in commercial *Ulva* (from Maine) is shown in Figure 8.5. It is noteworthy that scandium, a rare-earth element of high commercial value at more than hundred dollars per gram, is present at high concentration (i.e., ca. 600 ug/kg) in this green macroalga. The concentrations of cations in commercial *Ulva* (from Maine) are shown in Figure 8.6 and Figure 8.7. Additional research is needed to determine whether the concentrations of some of these elements, such as arsenic and cadmium, are below concentration limits required for food safety.

Table 8.5. Concentrations (ug/kg) of elements in commercial seaweed samples. Concentrations below the detection limit are marked as *. Concentration averages, standard deviations, and minimum/maximum values are shown the four right columns.

Element	Analyte		SA-AL	SA-HME	AL-AL	AL-HME	NE-BC	MA-BC	LA-BC	UL-HA	UL-HME	PO-ME	PA-HME	Average	Stdev	Min	Max
			Saccharina Alaska	*Saccharina* Maine	*Alaria* Alaska	*Alaria* Maine	*Nereocystis* Bamfield, BC	*Macrocystis* Bamfield, BC	*Laminaria* Banfield, BC	*Ulva* Hawaii	*Ulva* Maine	*Porphyra* Maine	*Palmaria* Maine				
			Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)
Scandium	45Sc	ppb	170.38	15.56	**503.47**	316.32	*	39.98	20.42	339.19	**591.33**	216.18	103.06	231.59	202.92	15.56	591.33
Copper	65Cu	ppb	506.34	291.72	863.31	629.91	187.31	312.43	1571.56	1350.50	1483.57	2877.53	883.16	996.12	790.96	187.31	2877.53
Yttrium	89Y	ppb	41.96	18.78	70.34	98.73	10.41	15.35	18.83	68.14	**118.63**	**225.62**	72.97	69.07	63.23	10.41	225.62
Rhodium	103Rh	ppb	8.58	7.99	14.81	12.50	8.16	10.46	13.95	*	*	*	*	10.92	2.85	7.99	14.81
Palladium	108Pd	ppb	16.63	16.31	8.10	**30.37**	37.18	44.53	11.64	4.99	7.78	**45.82**	4.94	20.75	15.82	4.94	45.82
Silver	109Ag	ppb	*	*	17.22	17.92	*	*	26.08	8.69	15.56	51.13	17.06	21.95	13.83	8.69	51.13
Lanthanum	139La	ppb	129.87	62.66	79.04	134.95	*	*	*	171.34	311.59	60.66	112.15	132.78	81.86	60.66	311.59
Cerium	140Ce	ppb	89.77	104.36	66.32	146.21	4.67	26.13	8.53	184.20	326.28	52.31	64.55	97.57	93.84	4.67	326.28
Praseodymium	141Pr	ppb	8.32	4.67	7.14	18.51	*	*	*	20.60	39.33	8.69	14.06	15.16	11.27	4.67	39.33
Neodymium	146Nd	ppb	34.66	18.89	36.75	70.45	3.43	4.88	3.59	**87.83**	**146.85**	38.95	70.66	47.00	44.06	3.43	146.85
Samarium	147Sm	ppb	7.78	4.35	10.68	18.08	*	*	*	**21.68**	**26.88**	16.10	15.40	15.12	7.38	4.35	26.88
Europium	153Eu	ppb	2.84	*	4.29	5.26	*	*	*	4.94	7.99	4.13	*	4.91	1.73	2.84	7.99
Gadolinium	157Gd	ppb	8.32	4.40	3.43	18.35	*	*	*	**20.71**	**34.29**	**21.94**	17.22	16.08	10.35	3.43	34.29
Terbium	159Tb	ppb	*	*	1.61	2.79	*	*	*	2.84	4.83	3.92	2.41	3.07	1.14	1.61	4.83
Dysprosium	163Dy	ppb	6.44	2.63	9.66	15.94	*	*	*	9.44	**16.74**	**24.36**	12.77	12.25	6.78	2.63	24.36
Holmium	165Ho	ppb	*	*	1.93	3.17	*	*	*	2.79	3.49	4.99	2.31	3.11	1.08	1.93	4.99
Erbium	166Er	ppb	3.54	*	5.96	9.34	*	*	*	3.76	**10.03**	**14.27**	5.96	7.55	3.88	3.54	14.27
Thulium	169Tm	ppb	*	*	*	*	*	*	*	*	1.72	1.77	*	1.74	0.04	1.72	1.77
Ytterbium	172Yb	ppb	3.00	*	5.69	9.98	*	*	*	7.35	**11.43**	6.49	4.13	6.87	3.02	3.00	11.43
Lutetium	175Lu	ppb	*	*	*	1.66	*	*	*	*	1.72	5.85	*	3.08	2.40	1.66	5.85
Rhenium	185Re	ppb	4.51	3.06	5.96	10.73	6.81	*	3.54	*	*	*	*	5.77	2.82	3.06	10.73
Uranium	238U	ppb	30.96	73.08	175.40	184.47	59.40	100.60	290.81	26.93	27.85	39.70	16.47	93.24	87.76	16.47	290.81
Arsenic	As 193.696	ppb	60743.48	57896.52	57300.80	50954.41	52572.19	71679.44	43360.51	4201.20	4649.56	21885.67	5286.69	39139.13	25296.31	4201.20	71679.44
Calcium	Ca 317.933 R	ppb	6574157.50	5861730.72	8391694.27	7062995.73	4356836.26	6616779.46	7329299.11	1862359.54	2379814.06	1208617.68	571418.86	4746882.11	2782547.04	571418.86	8391694.27
Cadmium	Cd 226.502	ppb	1396.93	989.24	279.59	1753.35	2656.56	2874.54	531.89	*	91.22	2406.34	59.82	1303.95	1079.36	59.82	2874.54
Cobalt	Co 228.616	ppb	*	24.44	25.97	125.19	2.55	*	2.13	51.41	**190.10**	123.75	58.09	67.07	65.13	2.13	190.10
Chromium	Cr 267.716	ppb	426.50	77.68	429.79	610.10	49.68	199.08	129.92	537.63	815.66	404.73	119.00	345.43	249.72	49.68	815.66
Iron	Fe 259.939	ppb	219877.07	48666.82	174886.86	384013.58	11699.71	30095.23	10712.10	292474.18	506291.24	100093.86	85818.66	169511.76	165258.16	10712.10	506291.24
Potassium	K 766.490 R	ppb	142346422.37	65163248.37	58534461.95	44957748.29	73853967.03	59765718.08	37760891.62	14112457.50	19740336.66	21315268.31	47660626.90	53201013.37	35481490.97	14112457.50	142346422.37
Lithium	Li 610.362 R	ppb	*	*	*	*	*	*	*	*	*	-47.29	*	-47.29		-47.29	-47.29
Magnesium	Mg 285.213	ppb	4669842.94	5572589.10	5715971.84	5002625.00	4918959.84	4967365.98	4843490.54	7791268.96	7272246.62	3262575.23	1406534.24	5038497.30	1727751.08	1406534.24	7791268.96
Manganese	Mn 257.610	ppb	9140.51	3349.37	8271.36	8007.28	1733.84	3527.21	2431.87	6696.71	**16732.88**	16990.86	7128.22	7637.28	5209.49	1733.84	16990.86
Molybdenum	Mo 202.031	ppb	*	268.62	*	*	*	*	*	323.57	245.00	648.88	298.63	356.94	165.88	245.00	648.88
Sodium	Na 589.592 R	ppb	29282976.28	38263936.00	32624800.58	24325507.50	35305713.02	30639240.46	25753941.82	18226349.75	21551080.14	22087495.95	9372750.03	26130344.69	8293745.40	9372750.03	38263936.00
Nickel	Ni 231.604	ppb	1074.64	3039.06	870.08	3226.15	4291.91	11934.63	3793.25	**19108.71**	3868.21	3005.73	9793.24	5818.69	5562.55	870.08	19108.71
Tin	Sn 189.927	ppb	49806.53	57603.66	59071.97	53835.66	52991.94	52284.73	54021.77	77762.92	71526.26	41332.82	21958.96	53836.11	14556.51	21958.96	77762.92
Strontium	Sr 421.552 R	ppb	573610.44	382767.07	795713.67	638518.09	376869.59	483255.34	592097.07	24331.74	30632.31	22413.96	9631.61	357258.26	289949.63	9631.61	795713.67
Titanium	Ti 334.940	ppb	7882.56	764.15	6249.77	4874.54	*	1174.64	*	6633.43	10194.52	*	1545.51	4914.89	3463.88	764.15	10194.52
Vanadium	V 290.880	ppb	629.44	298.29	18.21	394.17	79.84	1055.57	*	406.01	815.93	904.67	35386.30	3998.84	11033.75	18.21	35386.30
Zinc	Zn 206.200	ppb	15672.69	8597.01	14588.14	20894.91	5366.98	5563.39	14197.74	5144.18	5722.92	27993.21	8378.11	12010.84	7459.54	5144.18	27993.21
SUM - REE (ug/kg)			1073.91	628.46	1891.11	1755.63	317.37	554.37	1968.96	2335.93	3187.88	3720.43	1419.28				
SUM - TE (mg/kg)			183813.66	115425.85	106384.63	82516.08	118943.79	102652.75	76408.90	42430.11	51595.25	48112.11	59196.79				

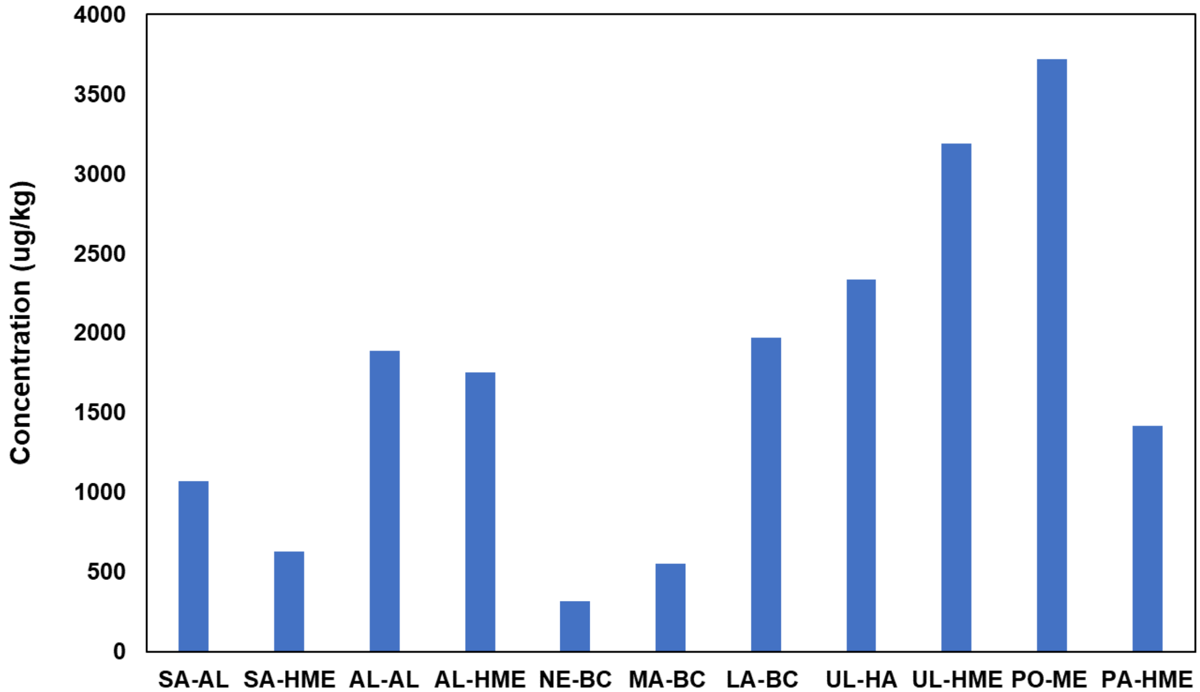

Figure 8.4. Sum of concentrations (ug/kg) of rare-earth and other elements in commercial seaweed samples.

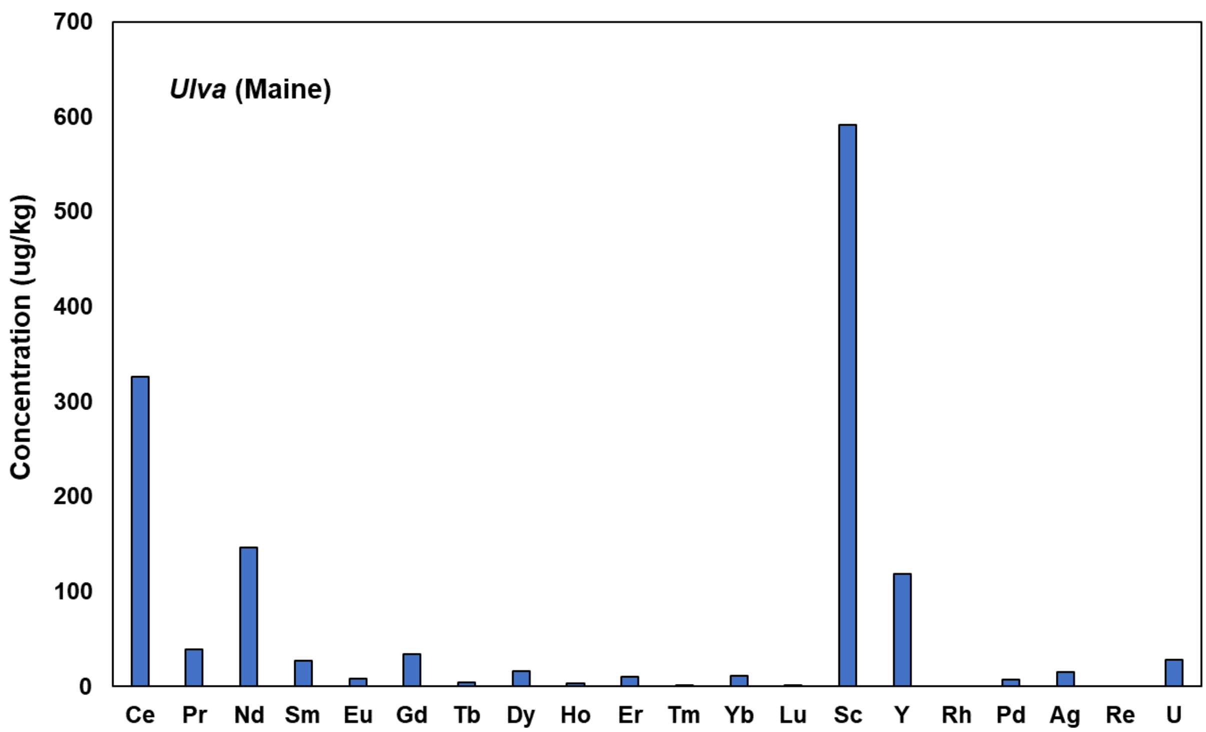

Figure 8.5. Concentrations (ug/kg) of rare-earth and other elements in commercial Ulva (from Maine).

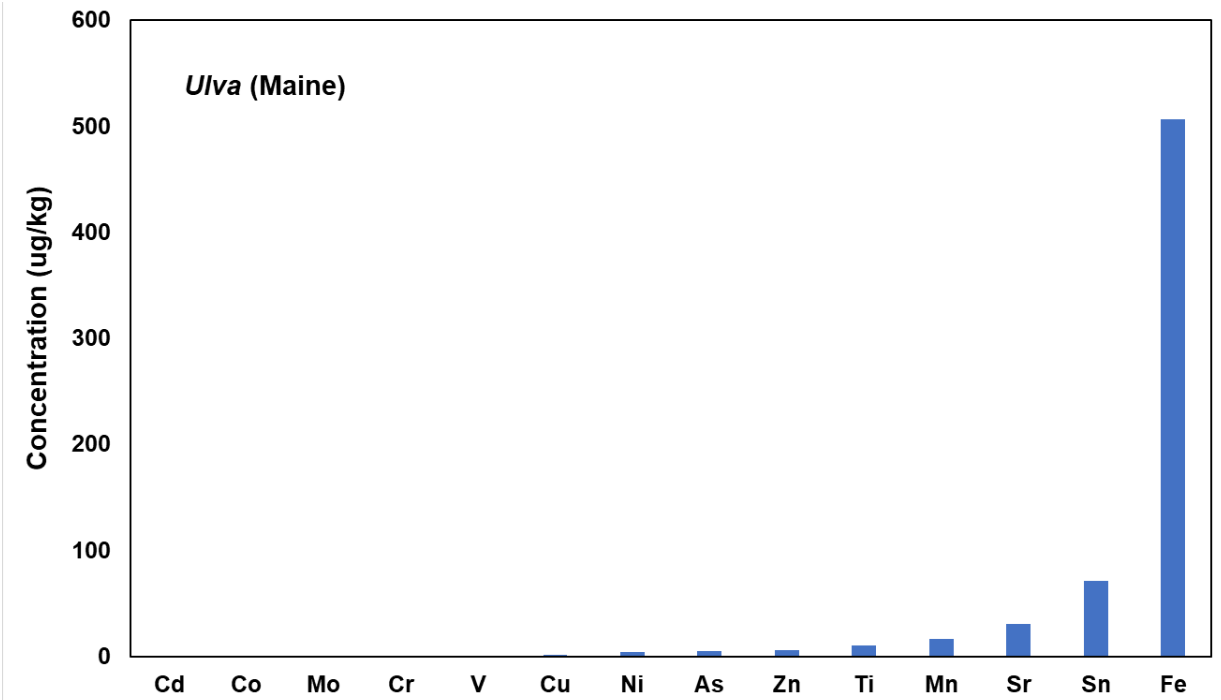

Figure 8.6. Concentrations (ug/kg) of cations in commercial Ulva (from Maine).

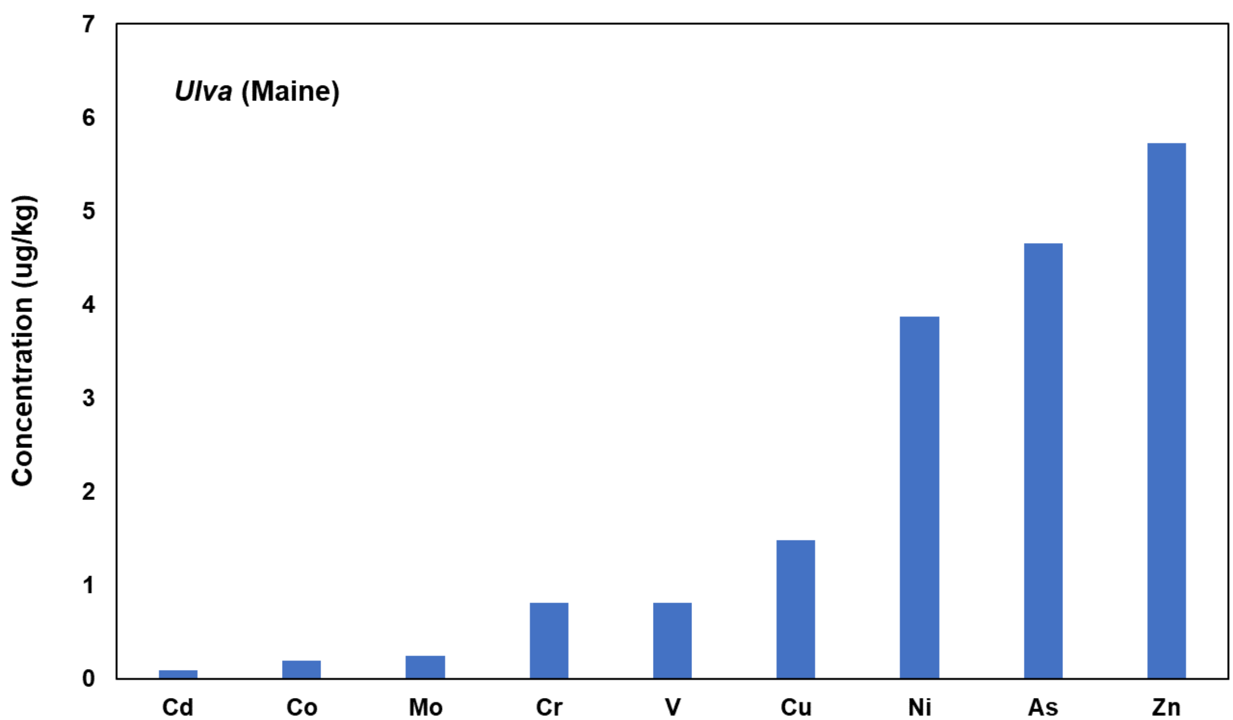

Figure 8.7. Concentrations (ug/kg) of cations in commercial Ulva (from Maine).

8.2.3.2 Alaska Kelp

The concentration of rare-earth and other trace elements for the Blue Evolution *Saccharina* samples, including concentration averages, standard deviations, and minimum/maximum values, are shown in Table 8.6. The sum of concentrations (ug/kg) of rare-earth and other elements in Blue Evolution *Saccharina* samples was higher in the stipes compared to the respective blades of the same plant (Figure 8.8). The concentrations of rare-earth and other trace elements for the Blue Evolution *Alaria* samples, including concentration averages, standard deviations, and minimum/maximum values, are shown in Table 8.7. The sum of concentrations (ug/kg) of rare-earth and other elements in Blue Evolution *Alaria* samples was also higher in the stipes than in the respective blades of the same plant (Figure 8.9). The concentrations of rare-earth and other trace elements for the Seagrove Kelp samples, including concentration averages, standard deviations, and minimum/maximum values, are shown in Table 8.8. The sum of concentrations (ug/kg) of rare-earth and other elements was highest in the bull kelp stipes (NE-SG-S), about 5,800 ug/kg. (Figure 8.10).

Table 8.6. Concentrations (ug/kg) of elements in Blue Evolution *Saccharina* samples. Concentrations below the detection limit are marked as *. Concentration averages, standard deviations, and minimum/maximum values are shown the four right columns.

Element	Analyte		SA-AL	SA-P-4-B	SA-P-4-S	SA-W-4-B	SA-W-4-S	SA-W-5-B	SA-W-5-S	SA-W-6-B	SA-W-6-S	Average	Stdev	Min	Max
			Saccharina BE 2019	*Saccharina* BE 4/2020	*Saccharina* BE 4/2020	*Saccharina* BE 4/2020	*Saccharina* BE 4/2020	*Saccharina* BE 5/2020	*Saccharina* BE 5/2020	*Saccharina* BE 6/2020	*Saccharina* BE 6/2020				
			Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)
Scandium	45Sc	ppb	170.38	363.47	375.20	289.41	475.89	198.10	198.70	106.51	201.80	264.38	119.29	106.51	475.89
Gallium	71Ga	ppb		103.39	315.91	91.73	386.61	54.05	114.79	19.51	112.91	149.86	129.79	19.51	386.61
Rubidium	85Rb	ppb		2853.17	1994.00	1797.41	1637.94	2005.29	1577.12	1602.68	1609.18	1884.60	428.12	1577.12	2853.17
Yttrium	89Y	ppb	41.96									41.96	#DIV/0!	41.96	41.96
Niobium	93Nb	ppb		21.82	84.79	24.38	115.25	9.58	34.27	5.17	35.15	41.30	38.59	5.17	115.25
Ruthenium	101Ru	ppb		3.29	2.46	3.11	2.02	2.83	3.14	4.22	3.28	3.04	0.65	2.02	4.22
Rhodium	103Rh	ppb	8.58	10.09	10.81	14.20	8.14	11.30	13.90	20.57	15.52	12.57	3.93	8.14	20.57
Palladium	108Pd	ppb	16.63	274.30	350.70	401.38	257.96	315.72	402.15	544.23	460.38	335.94	150.00	16.63	544.23
Silver	109Ag	ppb	*	298.07	32.56	33.65	44.77	23.43	33.24	17.56	38.85	65.27	94.44	17.56	298.07
Lanthanum	139 La	ppb	129.87	183.72	536.60	248.42	1805.85	128.31	189.83	102.30	214.85	393.31	545.24	102.30	1805.85
Cerium	140Ce	ppb	89.77	308.54	1074.70	193.43	1346.98	140.16	344.80	258.97	383.01	460.04	441.24	89.77	1346.98
Praseodymium	141Pr	ppb	8.32	37.24	138.31	25.70	159.07	17.73	43.60	11.73	47.43	54.35	55.42	8.32	159.07
Neodymium	146Nd	ppb	34.66	159.61	591.56	110.77	652.69	75.85	186.60	46.40	202.82	229.00	230.98	34.66	652.69
Samarium	147Sm	ppb	7.78	42.11	141.71	30.27	145.00	20.78	45.72	9.17	48.62	54.57	52.47	7.78	145.00
Europium	153Eu	ppb	2.84	9.91	36.71	7.59	36.68	4.85	12.81	3.17	14.03	14.29	13.30	2.84	36.71
Gadolinium	157Gd	ppb	8.32	39.19	149.41	28.79	159.29	18.80	47.90	11.09	52.41	57.24	57.18	8.32	159.29
Terbium	159Tb	ppb	*	6.08	23.49	4.64	24.77	2.96	7.29	1.36	8.14	9.84	9.10	1.36	24.77
Dysprosium	163Dy	ppb	6.44	32.39	123.82	25.20	131.64	15.69	39.95	6.75	43.87	47.31	47.51	6.44	131.64
Holmium	165Ho	ppb	*	5.85	23.00	4.68	24.04	2.91	7.51	1.28	8.28	9.69	8.84	1.28	24.04
Erbium	166Er	ppb	3.54	15.17	59.71	12.38	62.58	7.61	19.14	3.61	21.40	22.79	22.63	3.54	62.58
Thulium	169Tm	ppb	*	1.86	7.17	1.61	7.62	0.96	2.38	0.46	2.72	3.10	2.75	0.46	7.62
Ytterbium	172Yb	ppb	3.00	10.68	42.23	9.02	43.50	5.41	13.99	2.90	15.91	16.30	15.72	2.90	43.50
Lutetium	175Lu	ppb	*	1.47	5.56	1.30	5.74	0.80	1.89	0.46	2.02	2.41	2.07	0.46	5.74
Rhenium	185Re	ppb	4.51	17.62	124.31	19.29	93.34	81.11	121.74	6.53	125.06	65.95	53.40	4.51	125.06
Osmium	189Os	ppb		0.07	0.07	0.05	0.07	0.02	0.02	0.02	0.05	0.05	0.02	0.02	0.07
Iridium	193 Ir	ppb		5.28	0.49	3.66	5.81	2.30	0.51	2.07	0.58	2.59	2.13	0.49	5.81
Uranium	238U	ppb	30.96	64.02	145.97	111.86	148.20	89.52	131.14	112.34	113.33	105.26	38.40	30.96	148.20
Arsenic	As 193.696	ppb	60743.48	61497.38	59152.85	51067.29	46219.19	83364.76	82511.14	62763.39	84792.95	65790.27	14346.00	46219.19	84792.95
Calcium	Ca 317.933 R	ppb	6574157.50	5912213.76	8380832.54	6648703.60	7445436.14	5481905.65	8803161.13	8924946.20	10164893.08	7592916.62	1569520.52	5481905.65	10164893.08
Cadmium	Cd 226.502	ppb	1396.93					738.41	545.13	377.31	671.03	745.76	389.12	377.31	1396.93
Cobalt	Co 228.616	ppb	*	48.35	644.31	216.01	1427.36	45.13	104.33	26.78	468.67	372.62	481.67	26.78	1427.36
Chromium	Cr 267.716	ppb	426.50	788.03	2582.45	667.91	3041.02	338.03	976.38	142.53	965.27	1103.12	1014.49	142.53	3041.02
Copper	Cu 324.752	ppb	506.34	2803.32	4310.78	2581.53	4212.40	12258.00	11814.59	5311.26	4107.36	5322.84	4047.15	506.34	12258.00
Iron	Fe 259.939	ppb	219877.07	586258.81	1817738.70	530538.80	2184109.40	277611.55	661770.47	128971.04	670817.57	786410.38	721430.10	128971.04	2184109.40
Potassium	K 766.490 R	ppb	142346422.37	135070408.72	123649619.10	79318093.45	108929935.78	101921125.75	89997269.34	80804412.79	90032232.93	105785502.25	23345948.57	79318093.45	142346422.37
Lithium	Li 610.362 R	ppb	*									#DIV/0!	#DIV/0!	0.00	0.00
Magnesium	Mg 285.213	ppb	4669842.94	6188625.29	5280621.50	6935385.90	5923492.36	5916169.76	5542201.59	5382784.10	5665727.02	5722761.16	634502.89	4669842.94	6935385.90
Manganese	Mn 257.610	ppb	9140.51	14734.30	33365.20	17057.35	44095.74	10592.51	20259.37	8182.67	23637.24	20118.32	12014.94	8182.67	44095.74
Molybdenum	Mo 202.031	ppb	*	330.15	446.61	574.31	401.91	311.52			461.65	421.02	96.35	311.52	574.31
Sodium	Na 589.592 R	ppb	29282976.28	44013862.49	28424412.84	52970778.21	35784545.94	42213371.14	30989943.44	23848274.60	30751803.09	35364440.89	9287511.00	23848274.60	52970778.21
Nickel	Ni 231.604	ppb	1074.64	2825.63	4874.18	2620.77	5327.50	2535.12	2653.74	2585.00	4891.32	3265.32	1425.78	1074.64	5327.50
Tin	Sn 189.927	ppb	49806.53	139335.79	141730.06	155087.11	155023.21	136008.25	152625.56	129957.33	148674.98	134249.87	32873.79	49806.53	155087.11
Strontium	Sr 421.552 R	ppb	573610.44	426775.86	497379.86	619368.54	389525.93	441373.14	633750.42	875357.87	747409.85	578283.54	160279.88	389525.93	875357.87
Titanium	Ti 334.940	ppb	7882.56	11685.19	47676.00	12543.94	61408.41	4325.81	17949.25	2262.40	19112.27	20538.43	20355.79	2262.40	61408.41
Vanadium	V 290.880	ppb	629.44	462.87	4456.76	-194.64	4218.86	-188.95	2867.08	211.12	3045.29	1723.09	1909.27	-194.64	4456.76
Zinc	Zn 206.200	ppb	15672.69	21028.33	21248.87	20164.79	24912.52	14091.94	21698.85	23284.56	24871.16	20774.86	3748.45	14091.94	24912.52
SUM - REE (ug/kg)			567.56	4868.43	6391.24	3493.91	7781.46	3236.08	3594.16	2901.07	3781.60				
SUM - TE (mg/kg)			183814.17	192453.68	168371.09	147285.25	161007.33	156515.98	136942.10	120199.85	138348.58				

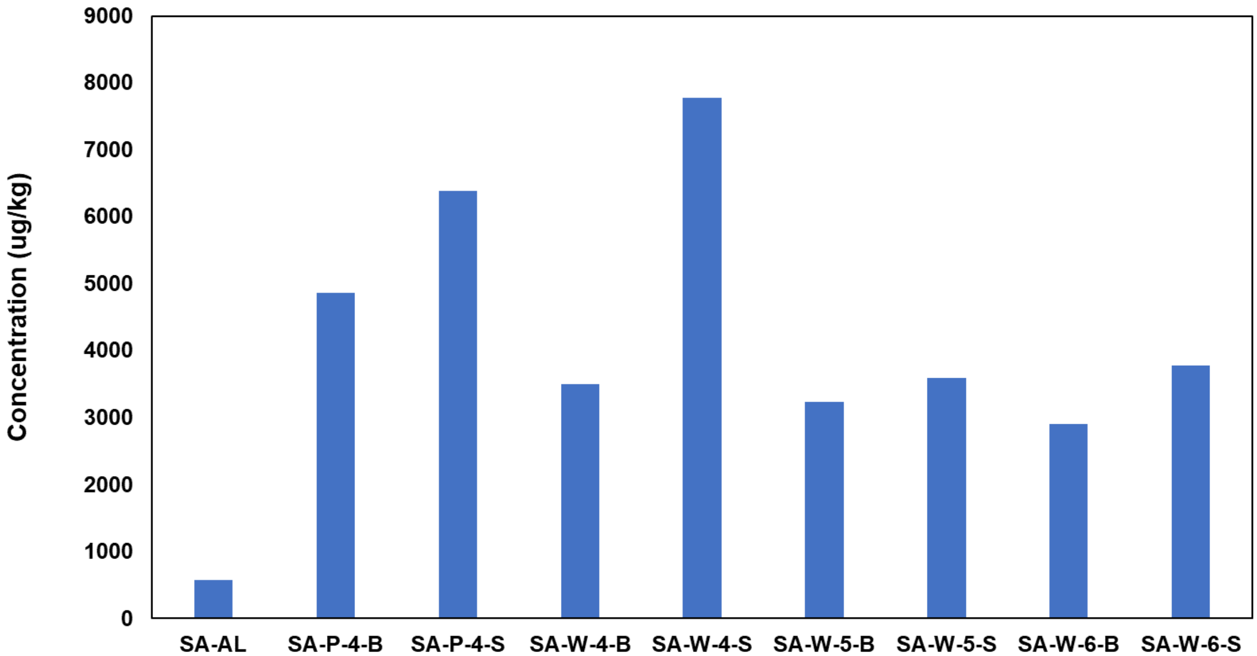

Figure 8.8. Sum of concentrations (ug/kg) of rare-earth and other elements in Blue Evolution *Saccharina* samples. B = blade, S = stipe.

Table 8.7. Concentrations (ug/kg) of elements in Blue Evolution *Alaria* samples. Concentrations below the detection limit are marked as *. Concentration averages, standard deviations, and minimum/maximum values are shown the four right columns.

Element	Analyte		AL-AL	AL-P-4-B	AL-W-4-S	AL-P-5-B	AL-P-5-S	AL-P-6-B	AL-P-6-S	Average	Stdev	Min	Max
			Alaria BE 2019	*Alaria* BE 4/2020	*Alaria* BE 4/2020	*Alaria* BE 5/2020	*Alaria* BE 5/2020	*Alaria* BE 6/2020	*Alaria* BE 6/2020				
			Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)
Scandium	45Sc	ppb	503.47	143.32	47.94	95.37	110.59	115.66	44.37	151.53	159.30	44.37	503.47
Gallium	71Ga	ppb		38.66	10.63	37.43	21.72	21.42	11.48	23.56	12.18	10.63	38.66
Rubidium	85Rb	ppb		1428.02	3014.70	1697.22	2219.01	1977.34	2215.57	2091.98	546.38	1428.02	3014.70
Yttrium	89Y	ppb	70.34							70.34	#DIV/0!	70.34	70.34
Niobium	93Nb	ppb		8.49	1.74	9.86	4.13	4.93	2.75	5.32	3.21	1.74	9.86
Ruthenium	101Ru	ppb		3.04	2.76	3.24	3.63	4.08	3.26	3.34	0.46	2.76	4.08
Rhodium	103Rh	ppb	14.81	13.76	11.37	15.50	17.61	19.62	16.94	15.66	2.70	11.37	19.62
Palladium	108Pd	ppb	8.10	372.43	302.32	429.60	475.13	495.82	440.99	360.63	168.53	8.10	495.82
Silver	109Ag	ppb	17.22	28.87	50.97	40.72	39.71	35.48	39.48	36.06	10.61	17.22	50.97
Lanthanum	139 La	ppb	79.04	213.71	42.54	99.90	114.03	109.52	70.49	104.17	54.33	42.54	213.71
Cerium	140Ce	ppb	66.32	91.49	25.53	99.83	46.07	49.61	21.85	57.24	30.31	21.85	99.83
Praseodymium	141Pr	ppb	7.14	12.06	2.83	14.28	6.53	7.60	3.06	7.64	4.27	2.83	14.28
Neodymium	146Nd	ppb	36.75	50.82	11.17	62.70	27.81	31.89	13.34	33.50	18.72	11.17	62.70
Samarium	147Sm	ppb	10.68	12.86	2.44	15.34	7.37	8.52	3.24	8.64	4.76	2.44	15.34
Europium	153Eu	ppb	4.29	3.69	0.93	4.90	2.43	2.85	1.45	2.93	1.46	0.93	4.90
Gadolinium	157Gd	ppb	3.43	12.70	2.67	17.96	7.70	9.03	3.75	8.18	5.62	2.67	17.96
Terbium	159Tb	ppb	1.61	2.08	0.38	2.79	1.26	1.46	0.60	1.45	0.83	0.38	2.79
Dysprosium	163Dy	ppb	9.66	10.76	2.04	15.91	6.84	8.08	3.33	8.09	4.68	2.04	15.91
Holmium	165Ho	ppb	1.93	2.01	0.41	3.16	1.34	1.69	0.69	1.61	0.91	0.41	3.16
Erbium	166Er	ppb	5.96	5.33	1.04	8.79	3.61	4.72	2.03	4.50	2.59	1.04	8.79
Thulium	169Tm	ppb	*	0.66	0.11	1.22	0.46	0.65	0.27	0.56	0.39	0.11	1.22
Ytterbium	172Yb	ppb	5.69	3.91	0.88	7.55	2.94	4.31	1.65	3.85	2.30	0.88	7.55
Lutetium	175Lu	ppb	*	0.57	0.14	1.20	0.48	0.72	0.29	0.57	0.37	0.14	1.20
Rhenium	185Re	ppb	5.96	12.75	8.43	15.58	13.85	17.55	12.56	12.38	4.00	5.96	17.55
Osmium	189Os	ppb		0.02	0.00	0.04	0.02	0.05	0.02	0.03	0.02	0.00	0.05
Iridium	193 Ir	ppb		1.97	0.47	0.37	1.47	1.53	0.38	1.03	0.71	0.37	1.97
Uranium	238U	ppb	175.40	229.85	59.22	187.61	235.72	160.89	225.59	182.04	61.47	59.22	235.72
Arsenic	As 193.696	ppb	57300.80	48192.84	53044.79	66529.38	69395.30	78530.17	66794.78	62826.87	10484.69	48192.84	78530.17
Calcium	Ca 317.933 R	ppb	8391694.27	6242994.23	5173739.56	7128956.89	10506307.44	8012748.32	10307099.02	7966219.96	1982566.34	5173739.56	10506307.44
Cadmium	Cd 226.502	ppb	279.59							279.59	#DIV/0!	279.59	279.59
Cobalt	Co 228.616	ppb	25.97	28.17	-126.09	66.56	113.08	85.90	30.19	31.97	77.16	-126.09	113.08
Chromium	Cr 267.716	ppb	429.79	543.44	216.32	390.63	147.16	252.17	152.05	304.51	152.05	147.16	543.44
Copper	Cu 324.752	ppb	863.31	2648.88	1351.62	3768.15	2563.33	2164.56	1514.19	2124.87	977.34	863.31	3768.15
Iron	Fe 259.939	ppb	174886.86	245902.83	44856.04	217522.61	103205.19	115566.62	47195.95	135590.87	79500.51	44856.04	245902.83
Potassium	K 766.490 R	ppb	58534461.95	62304441.94	153129414.11	70963203.95	83539759.52	85725373.71	92016108.11	86601823.33	31854055.59	58534461.95	153129414.11
Lithium	Li 610.362 R	ppb	*							#DIV/0!	#DIV/0!	0.00	0.00
Magnesium	Mg 285.213	ppb	5715971.84	7693227.29	5576567.50	6138539.62	5879007.41	7044652.42	6294921.52	6334698.23	769733.20	5576567.50	7693227.29
Manganese	Mn 257.610	ppb	8271.36	8966.83	2406.54	9122.40	5404.77	6483.38	2986.13	6234.49	2766.16	2406.54	9122.40
Molybdenum	Mo 202.031	ppb	*	362.82	233.89	278.39	239.84	118.70	149.24	230.48	88.32	118.70	362.82
Sodium	Na 589.592 R	ppb	32624800.58	61484547.82	33994724.80	31578520.84	34532852.09	37572648.41	32437506.03	37746514.37	10648862.83	31578520.84	61484547.82
Nickel	Ni 231.604	ppb	870.08	2528.40	2141.21	2671.65	2309.96	1648.53	1445.15	1945.00	649.78	870.08	2671.65
Tin	Sn 189.927	ppb	59071.97	170044.52	137433.39	157196.41	132769.05	175619.89	154419.50	140936.39	39321.69	59071.97	175619.89
Strontium	Sr 421.552 R	ppb	795713.67	548665.20	432080.78	663495.18	689553.82	723166.97	612268.63	637849.18	120055.67	432080.78	795713.67
Titanium	Ti 334.940	ppb	6249.77	3921.90	501.44	4797.91	1481.14	1946.67	682.01	2797.26	2213.14	501.44	6249.77
Vanadium	V 290.880	ppb	18.21		1642.23	2067.24		1576.09	1538.61	1368.48	783.98	18.21	2067.24
Zinc	Zn 206.200	ppb	14588.14	24096.53	12398.69	17607.85	14962.81	16429.05	12908.41	16141.64	3953.46	12398.69	24096.53

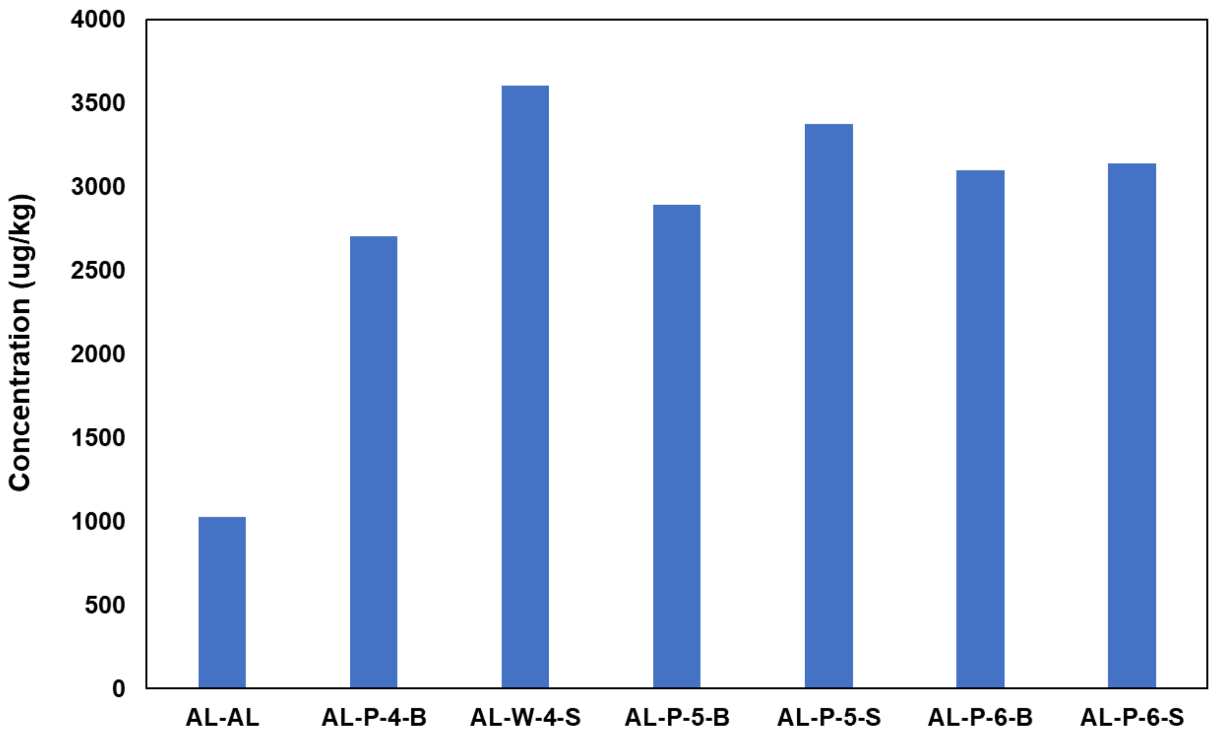

Figure 8.9. Sum of concentrations (ug/kg) of rare-earth and other elements in Blue Evolution *Alaria* samples. B = blade, S = stipe.

Table 8.8. Concentrations (ug/kg) of elements in Seagrove Kelp samples. Concentrations below the detection limit are marked as *. Concentration averages, standard deviations, and minimum/maximum values are shown the four right columns.

Element	Analyte		CO-SG	HE-SG	AL-SG	NE-SG-S	MA-SG	SA-SG	Average	Stdev	Min	Max
			Costaria SG 2020	*Hedophyllum* SG 2020	*Alaria* SG 2020	*Nereocystis* SG 2020	*Macrocystis* SG 2020	*Saccharina* SG 2020				
			Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)	Conc. (ug/Kg)
Scandium	45Sc	ppb	48.59	41.53	67.00	74.67	51.96	35.08	53.14	15.09	35.08	74.67
Gallium	71Ga	ppb	4.965418656	4.44	5.47	4.75	4.81	5.41	4.97	0.40	4.44	5.47
Rubidium	85Rb	ppb	2160.498798	2142.94	1168.09	4577.41	2311.84	2150.73	2418.59	1135.78	1168.09	4577.41
Yttrium	89Y	ppb							#DIV/0!	#DIV/0!	0.00	0.00
Niobium	93Nb	ppb	1.42	2.22	2.28	0.88	7.64	4.43	3.15	2.51	0.88	7.64
Ruthenium	101Ru	ppb	4.36	2.71	4.33	2.94	2.88	2.73	3.32	0.79	2.71	4.36
Rhodium	103Rh	ppb	20.95	11.35	21.65	14.12	14.54	13.13	15.96	4.29	11.35	21.65
Palladium	108Pd	ppb	557.59	300.66	569.27	359.85	371.52	339.00	416.32	116.54	300.66	569.27
Silver	109Ag	ppb	21.55	41.66	41.26	13.08	5.47	46.61	28.27	17.21	5.47	46.61
Lanthanum	139 La	ppb	62.59	70.87	45.97	628.29	101.34	346.63	209.28	233.85	45.97	628.29
Cerium	140Ce	ppb	9.41	36.93	10.91	13.45	120.86	56.97	41.42	43.15	9.41	120.86
Praseodymium	141Pr	ppb	1.33	2.09	3.14	1.25	8.98	5.01	3.63	2.97	1.25	8.98
Neodymium	146Nd	ppb	5.15	8.37	14.68	3.59	28.99	18.98	13.29	9.65	3.59	28.99
Samarium	147Sm	ppb	1.38	1.57	3.77	0.74	3.33	3.24	2.34	1.26	0.74	3.77
Europium	153Eu	ppb	1.60	0.92	2.20	0.53	1.68	1.44	1.39	0.59	0.53	2.20
Gadolinium	157Gd	ppb	1.60	2.13	5.55	0.88	5.74	4.28	3.36	2.10	0.88	5.74
Terbium	159Tb	ppb	0.27	0.29	1.01	0.09	0.73	0.55	0.49	0.34	0.09	1.01
Dysprosium	163Dy	ppb	1.65	1.50	6.84	0.42	3.92	2.79	2.85	2.29	0.42	6.84
Holmium	165Ho	ppb	0.34	0.34	1.68	0.09	0.86	0.60	0.65	0.57	0.09	1.68
Erbium	166Er	ppb	1.04	0.92	5.38	0.25	2.68	1.75	2.00	1.85	0.25	5.38
Thulium	169Tm	ppb	0.16	0.13	0.84	0.05	0.39	0.22	0.30	0.29	0.05	0.84
Ytterbium	172Yb	ppb	1.22	0.90	5.62	0.25	2.63	1.55	2.03	1.93	0.25	5.62
Lutetium	175Lu	ppb	0.23	0.16	0.97	0.07	0.43	0.24	0.35	0.33	0.07	0.97
Rhenium	185Re	ppb	9.01	9.38	10.70	10.09	4.01	17.85	10.17	4.45	4.01	17.85
Osmium	189Os	ppb	0.05	0.02	0.04	0.05	0.07	0.02	0.04	0.02	0.02	0.07
Iridium	193 Ir	ppb	0.86	0.83	0.65	0.95	0.88	0.64	0.80	0.13	0.64	0.95
Uranium	238U	ppb	251.34	144.33	445.22	94.98	384.20	98.16	236.37	150.51	94.98	445.22
Arsenic	As 193.696	ppb	63945.57	94210.85	56932.16	45566.72	93359.16	83944.80	72993.21	20381.01	45566.72	94210.85
Calcium	Ca 317.933 R	ppb	9933295.33	6840522.15	11119976.38	5275352.85	8988510.60	6692218.51	8141645.97	2227421.76	5275352.85	11119976.38
Cadmium	Cd 226.502	ppb				1898.85	2974.55	507.32	1793.57	1236.98	507.32	2974.55
Cobalt	Co 228.616	ppb						200.20	200.20	#DIV/0!	200.20	200.20
Chromium	Cr 267.716	ppb	179.69	261.16	103.18	53.02	423.20	102.35	187.10	136.74	53.02	423.20
Copper	Cu 324.752	ppb	472.79	969.90	633.26	512.05	350.58	638.40	596.16	212.34	350.58	969.90
Iron	Fe 259.939	ppb	26129.94	22252.86	32162.98	8642.96	61018.51	44638.71	32474.33	18305.75	8642.96	61018.51
Potassium	K 766.490 R	ppb	95303458.92	84978146.13	49983536.59	200517785.95	79141833.42	95627779.54	100925423.42	51579504.59	49983536.59	200517785.95
Lithium	Li 610.362 R	ppb							#DIV/0!	#DIV/0!	0.00	0.00
Magnesium	Mg 285.213	ppb	6697828.75	5800007.11	10105462.35	6645881.04	6528613.96	5397844.50	6862606.28	1671911.00	5397844.50	10105462.35
Manganese	Mn 257.610	ppb	4416.62	3271.38	4485.08	1478.81	6344.81	3109.87	3851.10	1640.34	1478.81	6344.81
Molybdenum	Mo 202.031	ppb		101.79		67.61	739.95	124.55	258.48	321.83	67.61	739.95
Sodium	Na 589.592 R	ppb	37473832.19	29256012.33	67995819.00	59578683.58	32599468.21	25787464.47	42115213.30	17428854.24	25787464.47	67995819.00
Nickel	Ni 231.604	ppb	1495.67	1153.83	1703.35	1036.78	1068.78	1134.32	1265.45	270.33	1036.78	1703.35
Tin	Sn 189.927	ppb	171865.26	161884.79	241462.40	165889.64	164257.96	152960.16	176386.70	32470.58	152960.16	241462.40
Strontium	Sr 421.552 R	ppb	793358.54	425455.16	760476.07	431797.05	505991.22	456083.36	562193.57	169039.59	425455.16	793358.54
Titanium	Ti 334.940	ppb		75.47			842.39	319.73	412.53	391.79	75.47	842.39
Vanadium	V 290.880	ppb	1333.96	2281.77	807.47	1556.30	3214.09	2195.28	1898.14	847.58	807.47	3214.09
Zinc	Zn 206.200	ppb	4048.46	5292.53	6485.66	1211.33	1389.92	4332.83	3793.45	2111.66	1211.33	6485.66

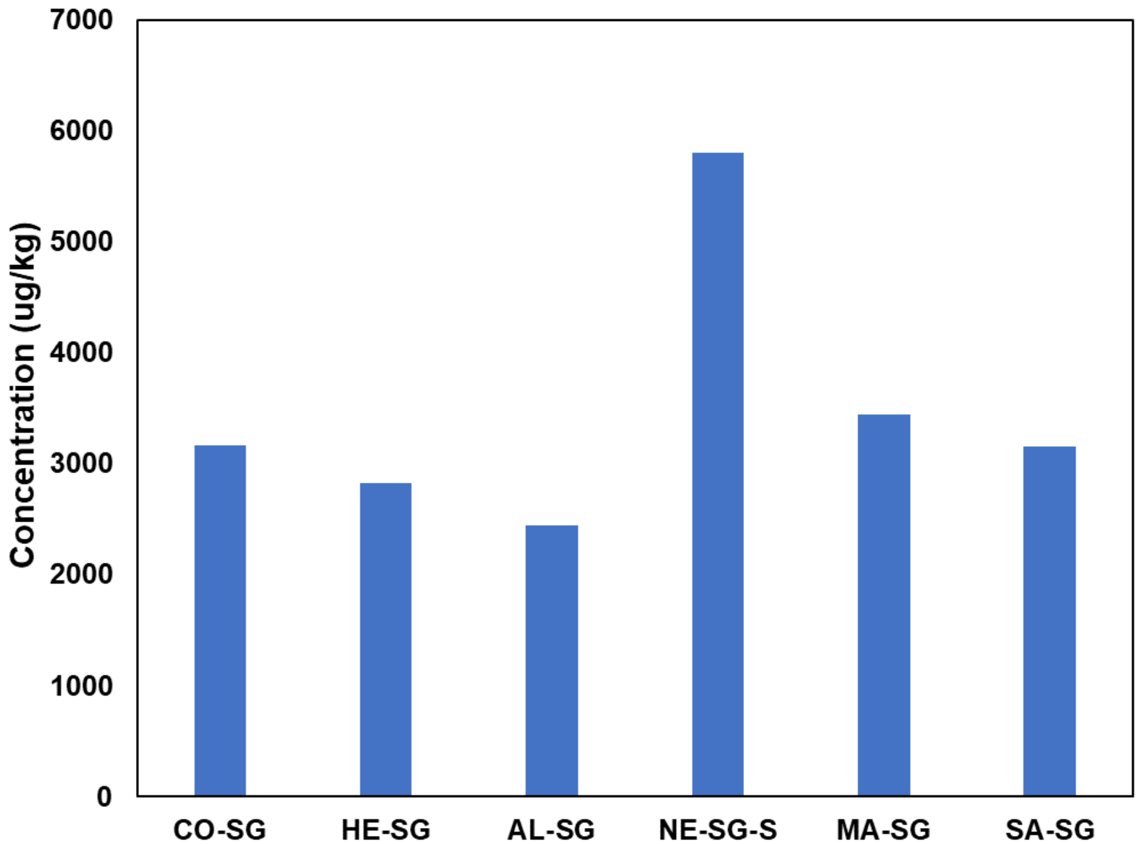

Figure 8.10. Sum of concentrations (ug/kg) of rare-earth and other elements in Seagrove Kelp samples. B = blade, S = stipe.

8.3 References

Chen H, D Zhou, and G Lou, et al. 2015. "Macroalgae for Biofuels Production: Progress and Perspectives." *Renewable and Sustainable Energy Reviews* 47: 427–437. doi:10.1016/j.rser.2015.03.086.

Lorbee AJ, J Lhanstein, and V Bulone, et al. 2015. "Multiple-Response Optimization of the Acidic Treatment of the Brown Alga Ecklonia Radiata for the Sequential Extraction of Fucoidan and Alginate." *Bioresource Technology* 197: 302–309. doi:10.1016/j.biortech.2015.08.103 (2015).

9.0 Co-development of Marine Renewable Energy and Kelp Processing Capabilities

Alaska's coastal waters contain the largest potential to provide energy from the ocean of any state in the United States. With small, remote communities distributed along its coast, each operating with its own microgrid and a nascent MRE industry, there has historically been a low demand for this emerging technology. Still, the high cost of diesel generated electricity in these remote communities has provided a driver for energy innovation and investment, which has been targeted by the marine energy industry, as well as other renewable energy technology developers (Holdmann et al. 2019).

Many coastal Alaska towns are interested in new industries to diversify their economy, because they may be dependent on tourism or resource-based industries, like fishing or logging, which can fluctuate from year to year. One such emerging industry is growing and processing kelp. While other seaweeds are potentially of interest for mariculture, this investigation focuses kelp species as a potential new economic driver in coastal Alaska. In Alaska, kelp is currently harvested for commercial use both by farming and wild collection. Kelp farming and harvest for food production has recently increased in coastal Alaska; the ADFG reports a 600% increase in kelp sold from 2017 to 2019 (Stekoll 2019; ADFG 2021). With the growth cycle of farmed kelp starting in the fall, and the harvest of kelp biomass typically being conducted in the spring to early summer, the industry is potentially complementary to the existing summer fisheries, like salmon.

As the kelp industry is growing, the energy required for processing may put pressure on an already limited and costly electricity supply. The U.S. Energy Information Authority cites Alaska's average commercial electricity cost as 19.83 cents/kWh, which is nearly double the national average of 10.73 cents/kWh. Aside from a connected corridor of transmission between Anchorage and Fairbanks and extending into the Kenai Peninsula, Alaska consists of many microgrids across the state that often rely on diesel generators for electricity generation.

To reduce dependence on diesel fuel that is typically barged into coastal communities, kelp farming and processing has been proposed a potential source of biofuel. Still, the energy requirements of producing kelp for biofuel must be evaluated to decide if the processing needs can be met through the existing microgrid or new renewable energy development. While biofuel production is likely the largest energy consumer of most methods to process seaweed, a similar scenario must be evaluated for all methods of processing kelp, like food processing.

This chapter aims to estimate the electricity needs of the emerging kelp industry and existing kelp industry, then compare those demands to the potential of nearby MRE installations.

9.1 Methods

9.1.1 Locations of Interest

Eleven coastal Alaska towns were chosen to be evaluated based on their geographic distribution, potential wave or tidal energy resource, and existing fish processing facilities.

9.1.2 Energy Requirements of Kelp Processing

A literature review was conducted to understand the energy requirements of the existing and emerging kelp industry. Kelp processing requirements depend extensively on the end use for kelp products, so a range of potential end products were examined.

The energy requirements for processes involved in the transformation of algae for human consumption vary with regard to the specific end product. In this nascent U.S. industry, the energy consumption of these specific processes is largely unpublished at present, so instead we provide estimates of processes likely to be involved in processing kelp for consumption.

To use algae for food the majority of the raw algae is first dried, using diverse techniques such as sun-drying, oven-drying, and freeze-drying. Different companies might use one or more of these techniques according to their specific needs and capabilities to remove most of the water from the algae in order to prepare it for further production, so the energy requirements of each drying method were investigated. Sun-drying can be performed by exposing the raw algae to the sun light for approximately 4 days, which is the technique that requires the least equipment. Oven-drying can be carried out by inserting the raw algae in a 60°C oven for 15 hours, which makes it the fastest technique. Lastly, freeze-drying has the raw algae freeze for 24 hours in a -70°C environment to dry them in a freeze-drier for 5 days, making this technique the one of longer duration and more steps. However, freeze-drying is also considered to be the technique that best conserves the nutritional value of the product (Chan 1997). The energy requirements were estimated by researching for the individual requirements of their components, such as the average consumption for an industrial freezer or oven and compiling approximate process data.

Two methods of biofuel productions were considered in processing kelp: AD (anaerobic digestion) and HT (hydrothermal liquification). An estimate of the energy requirements for these processes was produced by comparing literature information about larger-scale projects as well as using data presented as energy per mass to scale up to the project requirements. The data gathered from literature were compared and averaged to obtain the energy requirement estimates. For this project, we estimated a mature commercial processing kelp biofuel plant would process 4.5 T of harvested kelp per day.

A third potential product in kelp and other algae processing is the production of high-value chemicals, such as alginate. Alginate can be extracted by a variety of techniques and in multiple scenarios, which in some cases can be carried out in correlation with biofuel extraction techniques. The specific technique used to extract alginate will have a significant impact on the yield percentage and on the energy required for the process. In this study, three example cases from the literature of the most efficient technique were reviewed as well as a technique that can be carried out in parallel with AD.

In addition to the differences between techniques, another key element needs to be considered for alginate extraction: the scale of production. To compare each individual process to other processes in this review, 4.5 T of raw kelp per day was used as a scaling factor, but for alginate extraction, this scale will require a large amount of energy to be conducted and it may not reflect the likely processing procedure in the future. A literature review, conducted to survey the methods that were used to convert alginate and thus to estimate the energy requirements, identified a few different methods and approaches. In some of the studies, the energy per ton of algae was provided for each process and in the others specific details were selected to scale the process presented to the desired number of tons processed per day.

9.1.3 Energy Requirements of Fish Processing

Fish processing energy requirements were calculated based on gathered literature data. Similar to the biofuel calculations, the gathered data were scaled to adjust them to the scale of the project.

9.1.4 Evaluation of Marine Renewable Energy Resource

The approximate availability of the MRE resource was extracted based on existing resource data. To characterize the tidal energy resource, seven of the coastal Alaska towns were evaluated. Each town's potential resource was initially inspected using the National Renewable Energy Laboratory's (NREL's) Marine and Hydrokinetic (MHK) Atlas to get an overview of the tidal current resource, then more detailed estimates of the tidal current were gathered from the National Oceanic and Atmospheric Administration's (NOAA's) Tides and Currents locations to incorporate the variability of current speed across the tidal cycle.

Available tidal power (Pa) in the estimated regions was calculated using the total power in the swept area of the turbine (Neary et al, 2014).

$$P_a = \frac{1}{2}\rho A_t U^3$$

where ρ is the density of water at 5.5°C (999.96 kg/m^3), A_t is the swept area of the turbine, and U is the instantaneous velocity of the tidal current. This reflects the available power for a single turbine. In this analysis, the Reference Model 1 (R1) prototype was used to output the generated power, so the output for a single unit is doubled because the assembly contains two turbines. Scaling of expected values can be also done for arrays of units by multiplying the total number of turbines found in the array.

Velocity data from relevant ocean current velocity locations were downloaded from NOAA's Tides and Currents predictions website for the most recent full calendar year. Using the velocity data and the available power equation the power for each registered velocity was calculated for the full year, accounting for opposite direction velocity by including an absolute value to the calculation. The whole data set was analyzed to determine seasonal changes as well as regular oscillations, then values for the average were presented in addition to the high and low values. To represent the likely output from a tidal turbine, the available power data were scaled by multiplying them by a capacity factor of 0.3 based on recommendations from the experimental conditions defined within the R1 prototype report (Neary et al, 2014).

For wave resource, the NREL MHK Atlas annual wave power density data were downloaded and evaluated to determine the wave energy potential near Alaska communities. The best location for MRE harvesting was selected based on a distance and potential energy output criteria, thereby maximizing potential output within a maximum 60 km radius to reduce transmission costs; for some locations, a slightly smaller potential output was selected because of major differences in the locations' distance from town. The expected wave energy power output was based on the minimum environmental conditions required set by the prototype reports and the distance reference was based on minimizing the use of marine transmission lines. While wave power density likely has a higher range in the winter months, annual averages were used to estimate the available power for this first-order examination.

Average significant wave height and period values were gathered from the NREL MHK Atlas, obtaining an average expected output for each of the locations for which wave energy data are available; some more inland towns, such as Dillingham, Wrangell, and Naknek, did not have significant wave resource data and likely would not be suitable for wave energy technology. This average was obtained by using all the data points provided by the NREL website for each of the locations because some locations did not have the same number of data entries. The same procedure was used for both significant wave heigh and period. For the Wavestar prototype, the approximate power output was obtained by comparing wave data with a range output table presented in the report (Kramer et al, 2011).

Reference Model 3 (R3) was used to calculate available electricity generation given the available wave resource (Neary et al, 2014). Performance data presented in the Reference Model reports were compared with the environment data gathered to obtain an estimate output range for a single unit of the different prototypes. Wave energy devices are likely to be installed in arrays with a series of units, but estimates were generated using a single unit for scaling simplification. In addition, a Wavestar wave energy prototype (Kramer 2011) was considered because of its similarities in operation characteristics and higher potential output.

The wave available for the R3 power was calculated using the following formula from the prototype report (Kramer 2011):

$$J_s = \frac{\rho g^2}{64\pi} H_s^2 T_e$$

where

Hs = the wave significant height,
Te = the energy period,
g = the gravity, and
Js = the energy flux per unit of wave-crest length.

This total available wave power was adjusted by a capacity factor of 0.3 and calculated for a single unit for scaling simplicity when dealing with arrays.

The recorded values for significant wave height and energy period were compared with the Wavestar design tables to obtain an electrical output estimate. This was done to obtain an estimate of power to be obtained by the array model presented by Wavestar and compare it with the possible arrays to be formed with the R3 model.

9.2 Results

9.2.1 Energy Landscape across Coastal Alaska

The locations in this study were selected based on a variety of criteria, including their involvement in the fish production industry, their energy need, and MRE output potential. The majority of the cities use diesel fuel as the main source for electricity generation, which can be benefited by the extra energy produced by MRE or other new energy sources (Anchorage, University of Alaska, n.d.). The cities that do not rely on diesel fuel as their main source of electricity can use their high potential for MRE production to benefit from the biofuels and other products produced in the kelp processing facilities.

All of the chosen locations have an active involvement in the fishing and fish processing industries, having from two to eight fish processing companies and an average of four (ADFG 2020). In addition, the fish processing facilities have licenses for 2.5 T or more of fish processed per day (Department of Environmental Health, n.d.), which is likely a r scale similar to what a mature kelp industry might be processing.

Detailed information about electricity cost as well as the primary electricity source for each location is presented in Table 9.1 (Anchorage, University of Alaska, n.d.).

Table 9.1. Regional cost of electricity in coastal Alaska locations.

Location	$/kWh	Primary Source of Electricity
Adak	1.21	Diesel
Dillingham	0.52	Diesel
False Pass	0.42	Diesel
Kodiak	0.18	Hydroelectric and wind
Naknek	0.58	Diesel
Unalaska	0.46	Diesel
Wrangell	0.11	Hydroelectric
Cordova	0.35	Hydroelectric and oil
Sitka	0.11	Hydroelectric
Yakutat	0.54	Diesel
Craig	0.25	Hydroelectric

9.2.2 Energy Requirements for Food Production

To provide a sense of the energy required to produce food from algae, the energy requirements of the base processes where estimated based on data form various sources, and they are presented in Table 9.2 (Jiang et al. 2013; Ferrite Microwave Technologies 2016; Chan 1997; Terehovics 2018).

Table 9.2. Food processes energy requirements.

Process	Process Description	Energy Usage	Source
Oven dry	60°C for 15 h	21.1 kWh/T	Ferrite Microwave Technologies 2016
Freeze dry	Freezer 24 h at -70°C then 5 days of freeze-drying	70-130 kWh/T in addition to 24.8 MWh/T	Terehovics 2018; Jiang, 2013
Sun dry	Sun-drying for 4 days	N/A	Chan 1997

9.2.3 Biofuel Production Energy Requirements

Upgraded versions of AD and HTL produce different types of biofuel, however, it is not expected to produce both in the same facility. Therefore, a scenario of 4.5 T/d for each process was considered in which a day is considered a standard 8 hour working day. Considering the 8-hour processing day scenario, the kilowatt-hours were calculated by scaling the available data, adjusting either mass or energy per hour. For scenarios in which the energy per mass is given the total energy for the 4.5 T is found, then the value is divided by 8 hours to obtain the final kilowatt-hours. Similarly, for scenarios in which a specific time is given for a process the time is accounted for in the final kilowatt-hour calculation.

Different processes will have different output percentages; within the processes presented in Table 9.3, the kilograms of biofuel range form 67.5–315 kg of biofuel for the 4.5 T/ of raw algae. To obtain the output gallon estimate for both fuels their respective densities need to be considered, making a final output of 15–73 gallons and 13–62 gallons for biodiesel and biomethane, respectively.

Table 9.3. Biofuel processes energy requirements.

Process	Energy per Mass	Present Scenario (kWh)	Source Reference
HTL	6.52 MJ/Kg	1,100	Adam McCutchan Hise 2015
HTL	6.51 MJ/kg	1,017.30	Pearce 2016
HTL	3.2 MJ/kg	500	Chen 2018)
AD	0.221 kWh/kg	124.3	Atta Ajayebi 2013)
AD	0.433 kWh/kg	243.3	Langlois 2012)

9.2.4 Alginate Processing Energy Requirements

The variety of existing alginate extraction processes have different energy requirements. The most common of these processes involves using chemicals to extract the alginate. Parts of the chemical extraction process are kept for other processes, but some steps are changed to reduce the energy consumption.

The use of ultrasound to reduce the total energy of the alginate extraction process has been studied. These processes are condensed into ultrasound assisted extraction (UAE), in which different studies present variations of ultrasound configurations as well as complementary steps to reduce the total energy consumption.

Table 9.4. Alginate energy requirements.

Process	Energy per Mass (kWh/kg)	Energy Required (kWh)	Source
Alginate Chemical	23.91	13,482	Langlois 2012
Alginate UAE	7.5	4,219	Youssouf 2016
Alginate UAE	20.83	11,719	Fernández 2018
Alginate UAE	8.33	4,688	Ötles 2009

9.2.5 Fish Processing Energy Requirements

To estimate fish processing energy requirements, a similar literature review was completed. In one study, data from four fish processing facilities in Alaska provide an average yearly energy consumption (Kelleher 2001). The data presented in kilowatts per year were scaled by the number of hours in a year to get a kilowatt processing estimate. Another study presented a table of components within the processing plan, the kilowatt consumption of each component and the number of hours the components are active per day (Alzahrania 2019). These data were compiled to derive an estimate of 301.9 kW of power draw. A third study presented data regarding the energy consumption of a fish processing plant based on the tons of fish to be processed in the facility (Ronde 2010). This value was scaled to an approximate energy consumption based on the 4.5 tons of algae expected to be produced in the algae processing facilities. The final power requirements estimate based on the projected weight was 232.9 kW.

The values from these three fish processing articles where averaged to obtain an estimate of the power requirements for a fish processing facility. The averaged value of 308 kW can be compared with the estimated electricity outputs from the renewable energy technologies that are possible in coastal Alaska.

9.2.6 Marine Energy Resource Availability

Available tidal power varied between regions and location. Detailed NOAA current velocity data were available for more accurate calculations of power output (Figure 9.1), though that was not always available at the ideal current locations based on the MHK Atlas, so we also tabulated the nearest location of modeled tidal resource that was >1 m/s (Table 9.5). Wrangell, False Pass, and Dillingham have particularly promising nearby average tidal resource greater than 1 m/s.

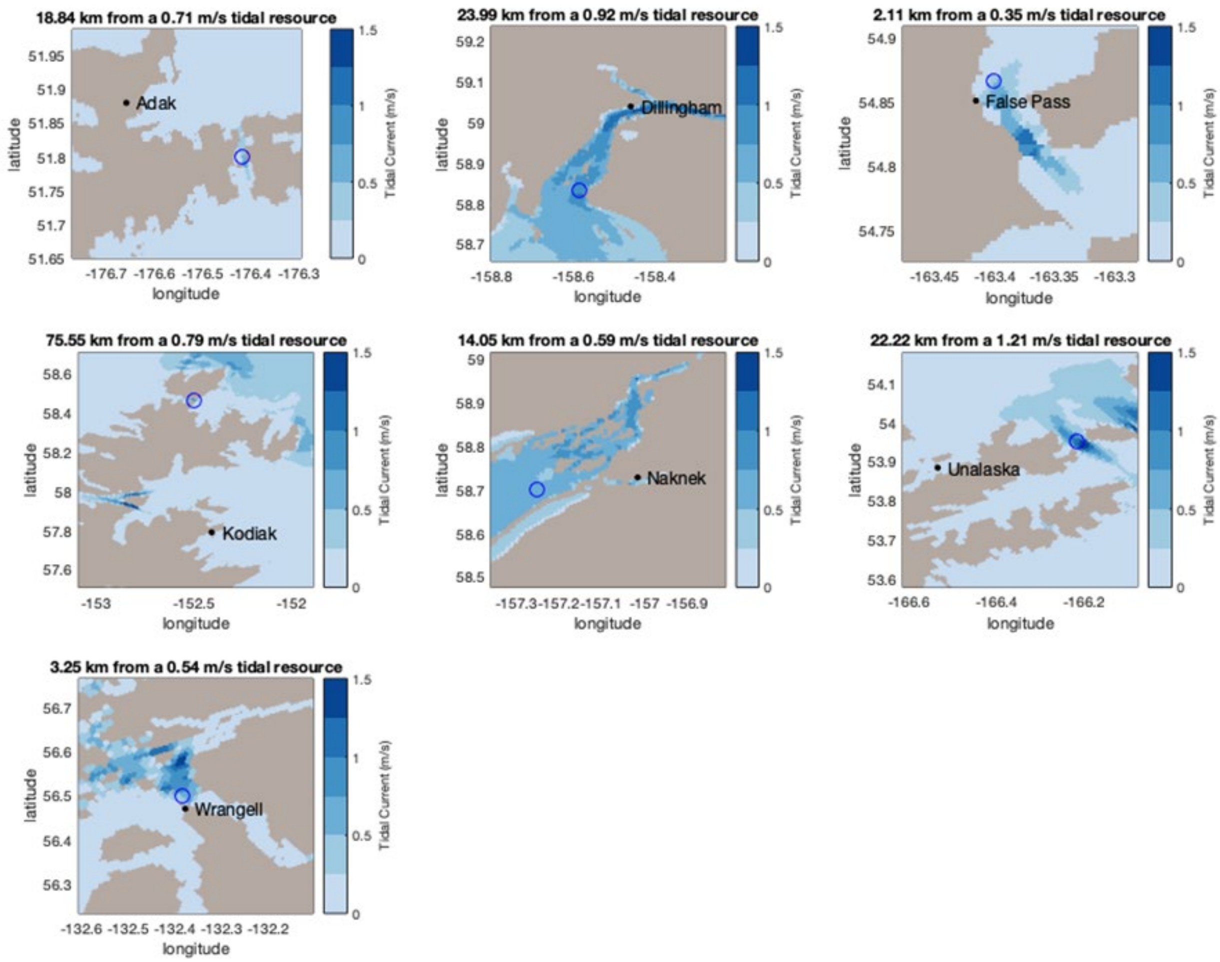

Figure 9.1. Selected Southwest Alaska current rates. Blue circles indicate location of NOAA current data for calculations of approximate tidal power output in various coastal Alaska locations, with average modeled tidal current data shown in shades of blue.

Table 9.5. Tidal energy approximate outputs.

City	Average Power Output (kW)	Standard Deviation	Distance to Resource at Buoy (km)	Average Resource at NOAA Location (m/s)	Distance to Resource Averaging >1 m/s (km)
Adak	36.02	33.13	18.84	0.71	28.03
Dillingham	27.51	16.58	23.99	0.92	0.59
False Pass	29.26	18.26	2.11	0.35	3.48
Kodiak	62.77	41.98	75.55	0.79	26.12
Naknek	11.17	6.95	14.05	0.59	25.41
Unalaska	87.41	72.62	22.22	1.21	21.42
Wrangell[a]	19.66	16.16	3.25	0.54	5.31

(a) Outside of SWAMC communities but included for comparison.

Wave power density modeled from the MHK Atlas is generally more available in outer coast cities (Figure 9.2). The data downloaded from the MHK Atlas was used in the formula obtained from the R3 prototype report (Kramer 2011). Table 9.4 lists the average power output to be obtained in each location where wave energy is available.

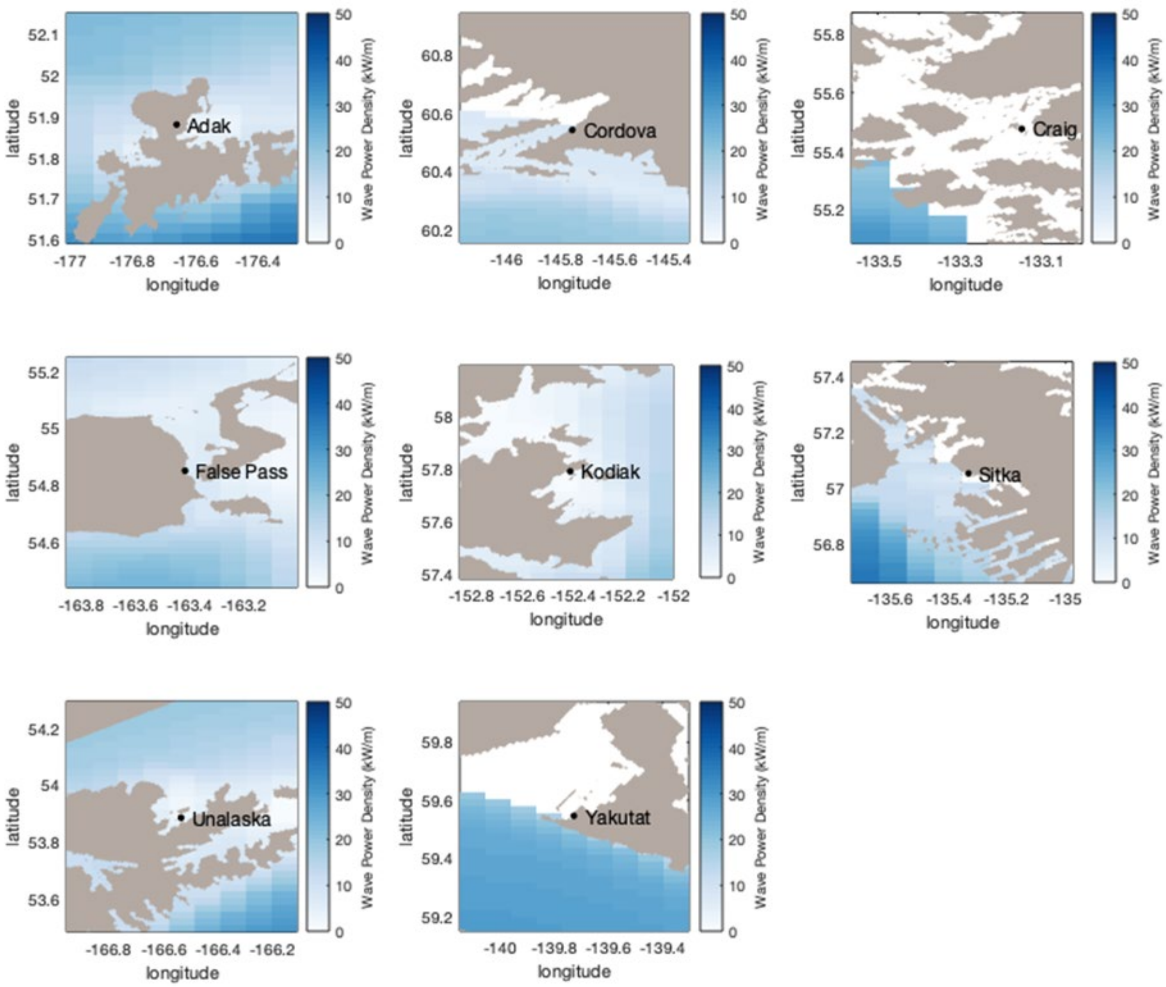

Figure 9.2. Wave power density variation is shown in blue for coastal Alaska towns. White regions indicate lack of data availability in the modeled wave power density estimates.

Table 9.6. R3 prototype expected energy outputs.

Region	Average Power Output (kW)
Adak	59.26
False Pass	28.22
Kodiak	68.60
Unalaska	70.76
Cordova	65.59
Sitka	112.65

Region	Average Power Output (kW)
Yakutat	89.18
Craig	103.72

For the Wavestar prototype, the units are displayed in arrays for different outputs. In the prototype report (Kramer 2011) there were arrays for 600 kW and 6 MW, however, these are presented for different environmental conditions. For the case studied, the 600 kW array is the one used for calculations; this array is smaller in size and produces its maximum power at smaller wave sizes. The 600 kW prototype array or “C5” has 20 floaters, each having a diameter of 5 m that are distributed in two rows of 70 m length, where the whole array can operate in water depths ranging from 1015 m.

Using the available information from the Wavestar report about the C5, the expected power outputs for the C5 array were approximated. These values were obtained by comparing the environmental wave data with a table presented in the report that provides power to the grid estimates based on ranges of wave heights and periods (Table 9.7).

Table 9.7. Wavestar expected energy outputs.

Region	Average Energy Output (kW)
Adak	322
False Pass	182
Kodiak	457
Unalaska	294
Cordova	265
Sitka	337
Yakutat	337
Craig	337

Comparing the R3 and the C5 prototype, an array of 20 floaters of the R3 would produce a larger power output, but the R3 prototype could have an array of multiple devices to achieve the desired power output, though it is possible the R3 prototype would require more space to accomplish the same power output. Based on the R3 report, a single unit of the R3 prototype has a 20 m diameter and the units are recommended to be spaced by 600 m if placed in arrays, and at an approximate of 100 m water depth. The power outputs for the larger-scale prototypes are comparable to the R3, outputting approximately 3 MW for 10 units and the Wavestar 6 MW for 20 larger floaters.

9.2.7 Costs of Transmission Lines

The cost of transmission lines is driven by several variables—length, location (land or water) and power being the factors that impact cost the most. To provide a reasonable estimate for this study the distance from our selected locations must be divided into land and marine distances. The marine and the land distance data from Miranda (2017) can be used to multiply by 250,000/mile or 3,750,000/mile to obtain the total cost of land and marine transmission lines, respectively. These values are the average of the range provided by the source in order to account for other variables that affect the cost.

The distance was approximated using a distance measurement feature (Google 2021) to obtain an approximate land and marine distance for each location. These distances are then multiplied by the above values to obtain an estimate of the total cost for each location as shown in Table 9.8. For the locations in which both wave energy and tidal energy are possible, the estimated cost for both locations are presented while minimizing marine distance to reduce costs.

Table 9.8. Estimated transmission line cost

Location	Land Distance (miles)	Marine Distance (miles)	Estimated Cost ($M)
Adak Tidal	12.9	0.5	$5.1
Adak Wave	10.5	3.5	$15.8
Dillingham Tidal	13.0	2.1	$11.1
False Pass Tidal	0.4	0.9	$3.3
False Pass Wave	15.0	25.0	$97.5
Kodiak Tidal	71.0	5.0	$36.5
Kodiak Wave	43.0	13.0	$59.5
Naknek Tidal	1.2	7.8	$29.6
Unalaska Tidal	10.1	1.5	$8.2
Unalaska Wave	17.0	9.5	$39.9
Wrangell Tidal	1.5	0.8	$3.4
Cordova Wave	5.3	20.0	$76.3
Sitka Wave	12.0	13.0	$51.8
Yakutat Wave	3.4	8.0	$30.9
Craig Wave	44.0	13.0	$59.8

9.3 Discussion

While significant marine energy resource is available at the scale needed for kelp processing, transmission remains a large barrier to production of marine energy in coastal Alaska. To take advantage of marine energy, processing facilities could consider collocation with a renewable energy resource as opposed to being located the existing town center.

9.3.1 Kelp Processing Energy Requirements

To process kelp for biofuels or alginate, municipalities may need to consider additional electricity generation, but existing electricity supply may be sufficient for processing kelp for food. Current kelp farm operations in Alaska are generally targeting the food market, which could be due to the simplicity of processing in these remote locations.

9.3.2 Fish Processing Compared to Kelp Processing

To compare the scale of a fish processing facility to be operated under the same energy requirements and the ton/day production capabilities that this facility would have, we used the 308 kW power draw from the fish processing plant compared to the HTL processes for kelp. Assuming that the kelp processing facility is running 8 hours/day and the usage is approximately 1,000 kWh/d based on our literature estimates, the facility would draw about 125 kW. While this 1,000 kWh/d is less than the fish processing draw, it is a significant power draw; an average U.S. energy usage is on the order of 1,000 kWh/month.

A scaling factor was applied to estimate that 547.6 kWh are required per ton of fish processed. The energy requirements per ton then can be compared to the electricity requirements of the algae processing facilities to obtain the number of tons of fish that can be produced under the energy requirements from a kelp processing facility or vice versa. Based on the energy requirements from other processes, the renewable energy sources are expected to be scaled to produce an approximate of 1.1 MWh, which is around two times the energy required to process a ton of fish based on the previous calculations. Using the fish energy requirements, the expected output and an assumption of 8 hours of production per day, a total of 16 T of fish can be expected to be processed in an algae facility per day.

9.4 References

Ötles S. (2009). Handbook of Food Analysis Instruments. Taylor & Francis Group, LLC.

Alaska Department of Fish and Game. (2020). Commercial Permit and License Holders Listing. Retrieved from https://www.adfg.alaska.gov/index.cfm?adfg=fishlicense.holders

Alaska Department of Fish and Game. (2021). Aquatic farming: Aquatic plants production data. Retrieved from https://www.adfg.alaska.gov/index.cfm?adfg=fishingaquaticfarming.aquaticfarminfo_aquaticplants

Ajayebi A, E Gnansounou, and JK Raman. (2013). Comparative life cycle assessment of biodiesel from algae and jatropha: A case study of India. *Bioresource technology*, *150*, 429-437.

Alzahrani A, L Petri, and Y Rezgui. (2019). Analysis and simulation of smart energy clusters and energy value chain for fish processing industries. 6(1) 534-540. Elsevier.

Anchorage, University of Alaska. (n.d.). Alaska Energy Data Gateway. Retrieved from https://akenergygateway.alaska.edu/

Chan J, P Cheung, and P Ang. (1997). Comparative Studies on the Effect of Three Drying Methods on the Nutritional Composition of Seaweed Sargassum hemiphyllum (Turn.) C. Ag. Advance ACS Abstracts.

Chen W-T, Y Zhang, T Lee, et al. (2018). Renewable diesel blendstocks produced by hydrothermal liquefaction of wet biowaste. Nature Sustainability.

Department of Environmental Health. (n.d.). Retrieved from ACTIVE PERMITS: https://dec.alaska.gov/eh/fss/active-permits/

Ferrite Microwave Technologies. (2016). Drying With Industrial Microwave Ovens A Short Guide For Calculating Energy Requirements.

Flórez-Fernández N, H Domingues, and M Torres. (2018). A green approach for alginate extraction from Sargassummuticum brown seaweed using ultrasound-assisted technique. Elsevier.

Google. (2021). Retrieved from Google Maps.

Hise A. (2015). Interdependence of Financing Parameters and Processing Improvements in the Design of Economically Competitive Algal Biofuel Production Pathways.

Holdmann G, R Wies, and J Vandermeer. (2019). Renewable energy integration in Alaska's remote islanded microgrids: Economic drivers, technical strategies, technological niche development, and policy implications. Proceedings of the IEEE, 107 (9): 1820-1837.

Jiang H, M Zhang, Y Liu, A Mujumdar, and H Liu. (2013). The energy consumption and color analysis of freeze/microwave freeze banana chips analysis of freeze/microwave freeze banana chips. Elsevier.

Kelleher G, E Kolbe, and G Wheeler. (2001). Improving Energy Use and Productivity in West Coast and Alaska Seafood Processing Plants. Oregon State University.

Kramer M, L Marquis, and P Frigaard. (2011). Performance Evaluation of the Wavestar Prototype. European Wave and Tidal Energy Conference.

Langlois J, J-F Sassi, G Jard, et al. (2012). Life cycle assessment of biomethane from offshore-cultivated seaweed. Biofuels.

Miranda L, M Mueller-Stoffels, E Whitney. (2017). An Alaska case study: Electrical transmission. Journal of Renewable and Sustainable Energy 9(6).

Neary V, M Previsic, A Jepsen, et al. (2014). Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies. Albuquerque: Sandia National Laboratories. SAND2014-9040.

NOAA. (n.d.). Retrieved from https://tidesandcurrents.noaa.gov/map/index.html

NREL. (n.d.). Retrieved from https://maps.nrel.gov/mhk-atlas/?aL=0&bL=clight&cE=0&lR=0&mC=40.21244%2C-91.625976&zL=4

Pearce M, M Shemfe, and C Sansom. (2016). Techno-economic analysis of solar integrated hydrothermal liquefaction. Elsevier.

Ronde H, A Ranne, and E Pursiheimo. (2010). Integrated Renewable Energy Solutions for Seafood Processing Stations. Proceedings of the International Conference on Energy and Sustainable Development: Issues and Strategies. Chiang Ma: IEEE.

Stekoll, MS. (2019). The seaweed resources of Alaska. Botanica Marina, 62(3), 227-235.

Stoutenburg E and M Jacobson. (2010). Optimizing Offshore Transmission Links for Marine Renewable Energy Farms. IEEE.

Terehovics E, R Soloha I Veidenbergs, and D Blumberga. (2018). Analysis of fish refrigeration electricity consumption. Elsevier.

Youssouf L, L Lallemand, P Guraud, et al. (2016). Ultrasound-assisted extraction and structural characterization by NMR of alginates and carrageenans from seaweeds. 166 (15) 55-63. Elsevier.

Appendix A – Life Cycle Assessment

Additional information and data used for the greenhouse gas life cycle assessment (GHG-LCA) of kelp-to-energy production in Southwest Alaska, as well as more comprehensive environmental tradeoff results, are presented here. Three feedstock scenarios, two conversion scenarios, and two comparison fossil fuel scenarios were modeled in this report. Additional coproduct offsets were also considered for the region.

A.1 Full System Boundary

The full system boundary diagram of the GHG-LCA (Figure A.1) illustrates the complexity of full scenario LCAs of biomass feedstock, energy/fuel production, and baseline comparisons.

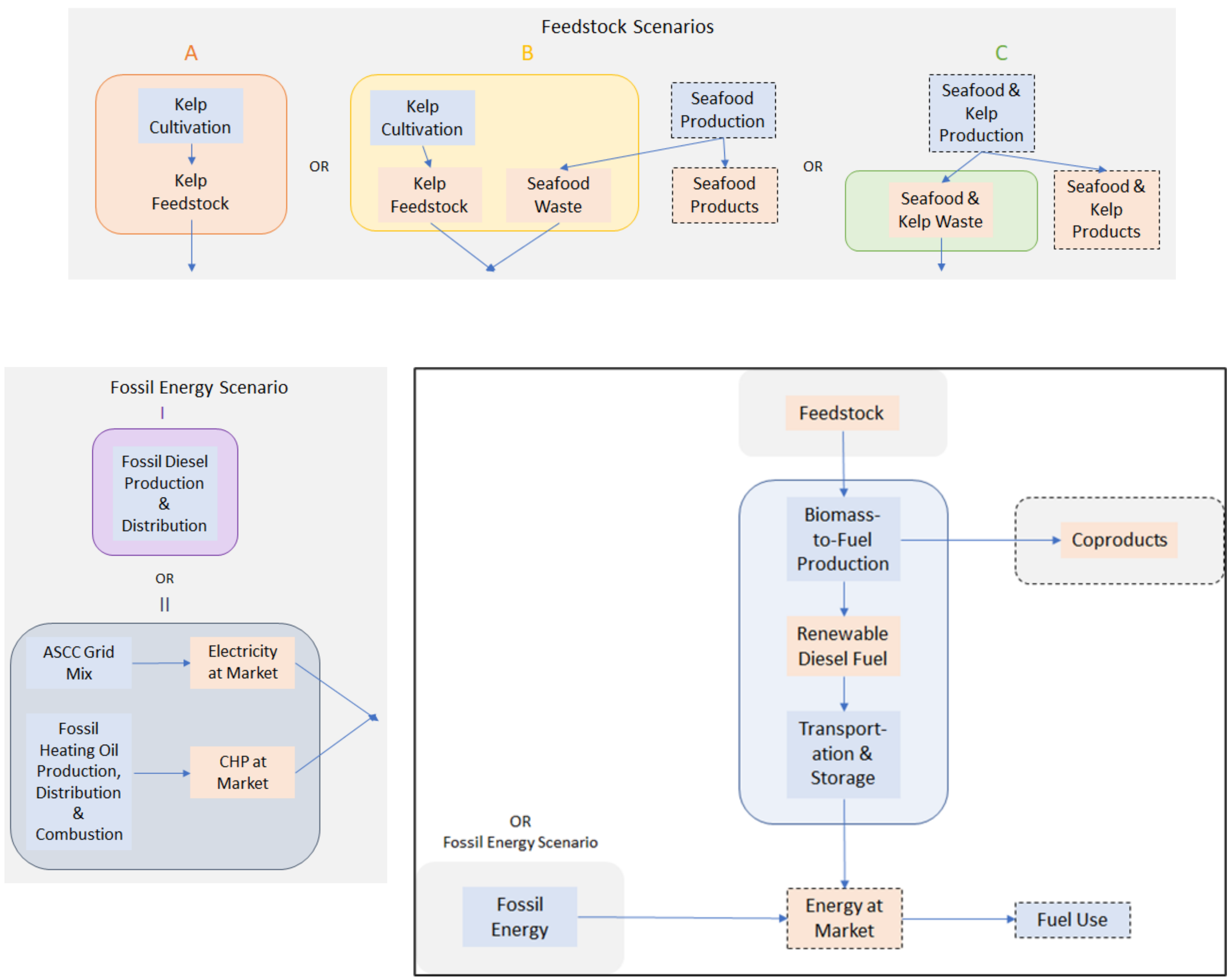

Figure A.1. The full illustration of the GHG-LCA system boundary diagram.

A.2 Expanded Anaerobic Digestion Yield Table with Original Data

LCIA data for kelp and fish species anaerobic digestion (AD) yields are compiled in Table A.1.

Table A.1. Anerobic digestion yields for various kelp and fish species and feedstocks.

Anaerobic Digestion Yields Feedstock	Yield CH_4 m³/ 10,000 lb Wet Feedstock	Source	Method	Given Data (VS: volatile solids)
A. nodosum	146.6	Allen et al. 2015	BMP	32.3 CH_4 m^3 / ton
A. nodosum	67.8	Milledge et al. 2019	BMP	166 L CH_4 / kg VS added
A. esculenta	122.1	Allen et al. 2015	BMP	26.9 CH_4 m^3 / ton
F. vesiculosus	88.1	Allen et al. 2015	BMP	19.4 CH_4 m^3 / ton
F. spiralis	148.5	Allen et al. 2015	BMP	32.7 CH_4 m^3 / ton
F. serratus	61.3	Allen et al. 2015	BMP	13.5 CH_4 m^3 / ton
H. elongate	95.8	Allen et al. 2015	BMP	21.1 CH_4 m^3 / ton
L. digitata	102.2	Allen et al. 2015	BMP	22.5CH4 m3 / ton
Laminaria saccharina	134.3	Gunaseelan 1997	CSTR, highest reported	0.23 m^3 CH_4 / kg VS added
Macrocystis pyrifera	181.0	Gunaseelan 1997	CSTR, highest reported	0.310 m^3 CH_4 / kg VS added
S. latissima	156.6	Allen et al. 2015	BMP	34.5 CH_4 m^3 / ton
Saccharina latissimi	232.9	Milledge et al. 2019	BMP	342 L CH_4 / kg VS added
S. polyschides	156.6	Allen et al. 2015	BMP	34.5 CH_4 m^3 / ton
Sargassum fluitans	96.3	Gunaseelan 1997	BMP, whole plant	0.165 m^3 CH_4 / kg VS added
Sargassum pteropleuron	84.7	Gunaseelan 1997	BMP, whole plant	0.145 m^3 CH_4 / kg VS added
Average yield kelp:	***129.1***			
Cuttle fish waste	885.6	Kafle et al. 2005	BMP	0.54 m^3 CH_4 / kg VS added
Fish waste collected off beach in Tanzania; species not identified	439.7	Mshandete et al. 2004	Batch digester	0.39 m^3 CH_4 / kg VS added
Mackerel fish waste	708.9	Kafle et al. 2005	BMP	0.51 m^3 CH_4 / kg VS added
Mackerel fish waste	729.4	Eiora et al. 2012	BMP	0.59 L CH_4/ gram VS added
Needle fish waste	686.0	Eiora et al. 2012	BMP	0.48 L CH_4/ gram VS added
Pacific saury fish waste	544.4	Kafle et al. 2005	BMP	0.43 m^3 CH_4 / kg VS added
Tuna fish waste	374.4	Eiora et al. 2012	BMP	0.28 L CH_4/ gram VS added
Sardine fish waste	393.2	Eiora et al. 2012	BMP	0.47 L CH_4/ gram VS added
Average yield fish waste:	***595.2***			

A.3 EIO-LCIA Results

The results from the 2007 model of the free online Economic Input-Output Life Cycle Impact Assessment (EIO-LCIA) tool developed by Carnegie Mellon (found at http://www.eiolca.net/) is shown in Table A.2. The 2007 model was used because the funding for updates to the model has not been available while Carnegie Mellon maintains access to the existing 2007 data set and model website. However, 2002 data can be used to produce a full suite of U.S. Environmental Protection Agency TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) impact categories. In addition to global warming potential (GWP) in CO_2equivalents (CO2eq) per million British thermal units (MBTU), Table A.2 provides embodied energy, CO, NH_3, NOX, PM_{10}, $PM_{2.5}$, SO_2, and VOCs.

Table A.2. Economic Input-Output Life Cycle Impact Assessment

	Fish Harvest	Grains	Seafood	Frozen Food	Refining	Diesel	Fertilizers	Pipeline Transport	Waste Management	Wastewater Treatment	Electricity
	Sector #114000: Wild-Caught Fish And Game	**Sector #1111B0: Fresh Wheat, Corn, Rice, and Other Grains**	**Sector #311700: Seafood**	**Sector #311410: Frozen Food**	**Sector #324110: Gasoline, Fuels, and By-Products of Petroleum Refining MOD)**	**Sector #324110: Gasoline, Fuels, and By-Products of Petroleum Refining**	**Sector #325310: Fertilizers**	**Sector #486000: Pipeline Transport**	**Sector #562000: Waste Manage-ment and Remediation**	**Sector #221300: Drinking Water and Wastewater Treatment**	**ASCC Grid Mix GREET 2020**
GWP (T CO2eq/ MBTU)	333	3030	540	1010	410	764	2500	2160	1570	329	169
Embodied Energy (TJ/MBTU)	8.95	21.2	8.63	11.2	5.8	98.9	28.5	28.6	6.41	1.06	
CO (T/MBTU)	0.767	4.06	1.47	2.07	0.75	2.72	2.58	3.69	12.1	0.373	0.00012
NH_3 (T/MBTU)	0.024	11.4	1.84	2.82	0.015	0.015	0.889	0.013	0.316	0.052	
NOx (T/MBTU)	0.502	3.99	1.14	1.87	0.73	2.9	2.73	9.69	1.55	0.346	0.00064
PM10 (T/MBTU)	0.06	21.8	0.239	3.13	0.058	0.062	0.306	0.085	0.325	0.032	0.00002837
PM2.5 (T/MBTU)	0.046	5.76	0.126	0.932	0.073	0.128	0.329	0.26	1.63	0.053	0.00002439
SO2 (T/MBTU)	0.135	0.892	0.296	0.632	0.225	0.395	2.55	0.306	0.403	0.388	0.0001
VOC (T/MBTU)	0.665	3.52	0.613	1.23	0.59	6.91	2.1	6.55	1.68	0.124	0.00004263

A.4 Data for Diesel, Fertilizer, and Waste Offsets from Kelp Coproducts in Alaska

In addition to the diesel fuel primary production, bio-sludge and biomass coproducts from both AD and hydrothermal liquefaction (HTL) can be used for fertilizer and waste disposal reduction offsets (refer to the flow data and calculations in Table A.3 and

Table A.3. Inventory data for fertilizer and diesel use.

	Fertilizer	Value	Source	Waste Management	Value	Source	Biodiesel	Value	Source
Reference Flow	Tons fertilizer per year for Alaska	3000	Baum 2010	Tons fertilizer per year for Alaska	3000	Baum 2010	Total biodiesel produced per year in SWAMC	96,198 gal	PCE Data
Economic Value	$/ton fertilizer	$470	Quinn 2020	$/T waste management	$139	Ross, et al. 2004	avg. $ / gal diesel (for communities of interest)	$ 2.57	PCE Data
LCI Model Parameter	$ fertilizer per year	$1,410,000	Calculation	$/T waste management	$417,000	Calculation	$ biodiesel per year	$ 247,529.86	Calculation

LCI = life cycle inventory; PCE = Power Cost Equalization (Program); SWAMC = Southwest Alaska Municipal Conference.

Table A.4. Annual environmental impact offset results for fertilizer and diesel replacement with kelp coproduction Alaska.

Environmental Impact	Fertilizer Offset (Alaska)	Waste Management Offset (SWAMC Region)	Diesel Offset (SWAMC region)	Unit
Total GWP impact	-3525.00	-654.69	-189.11	T CO2e
Total Energy	-40.19	-2.67	-24.48	TJ
CO	-3.64	-5.05	-0.67	T
NH_3	-1.25	-0.13	0.00	T
NOx	-3.85	-0.65	-0.72	T
PM_{10}	-0.43	-0.14	-0.02	T
$PM_{2.5}$	-0.46	-0.68	-0.03	T
SO_2	-3.60	-0.17	-0.10	T
VOCs	-2.96	-0.70	-1.71	T

A.5 Additional Environmental Impact Indicator Results

A more expansive spectrum of environmental impact indicator results for the comparisons of the kelp and fish waste, fossil fuel, and combined heat and power (CHP) scenarios are presented in Figure A.2 and Figure A.3. These comparisons illustrate the tradeoffs in overall life cycle emission reductions between the seafood and kelp waste scenarios and fossil fuel scenarios in GWP but with increasing ammonia (NH_3) emissions that can contribute to acidification and eutrophication. However, the spectrum of impacts shows the kelp and fish waste scenario have an even greater reduction in particulate matter emissions less than 2.5 microns than that of GWP when compared to fossil diesel.

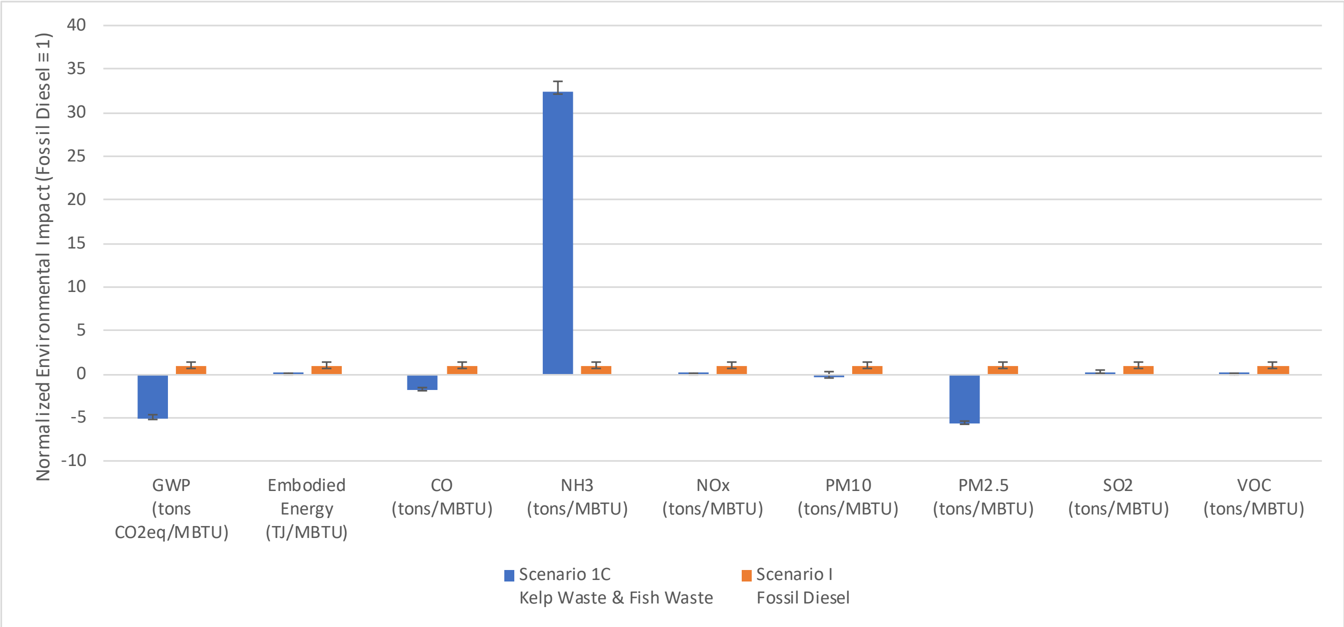

Figure A.2. Environmental impacts of scenario 1C vs. I (renewable diesel vs. fossil diesel).

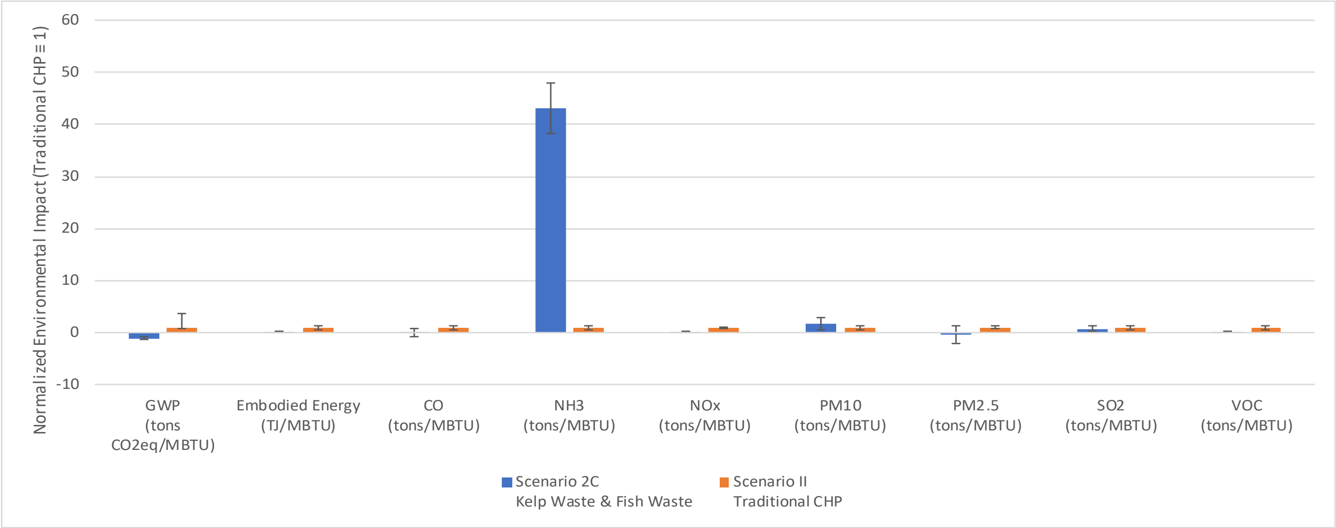

Figure A.3. Environmental impacts of scenario 2C vs. II (CHP vs. Fuel Oil & Electricity Grid Mix).

Appendix B – Needs Assessment

B.1 Steering Committee Goals and Objectives

The Southwest Alaska Municipal Conference (SWAMC) issued the following two questions to each of the Steering Committee (SC) members to get a high-level sense of what each SC member was interested in for this effort:

1. What goals do you want this project to achieve?
2. What outcomes would you like to see?

Each of the SC members responded to the questions and the responses are listed below.

Respondent 1 – Southwest Alaska Municipal Conference: Regional Economic Development

1. Identify processes and products that unlock economic activity for new kelp farming and processing in the SWAMC region.
2. Identify product forms that can be processed in the SWAMC region for the benefit of our communities.

Respondent 2 – Mariculture Consultant

1. Identify demand by volume and value for new kelp supplies.
2. Identify synergies with existing fisheries and community infrastructure.
3. Identify species of kelp, and those characteristics that have the greatest market value to Alaska.

Respondent 3 – State of Alaska, Alaska Energy Authority: Energy Development, Biomass

1. Ensure that outcomes are achievable.
2. Ensure use of waste products, using 100% of the biomass, evaluating waste stream.
3. Identify the viability of kelp as a biofuel (quantities, price).
4. Identify viability of incorporating kelp into existing small-scale waste-to-heat generator, possibility incorporating cardboard.

Respondent 4 – Alaska Manufacturing Extension Partnership Center

1. Identify existing resources (production plants, infrastructure, existing manufacturing facilities) Alaska has that could be retooled or repurposed in their off-season to process kelp (asset map).

Respondent 5 – Kodiak Island Borough Local Economic Development and Planning

1. Create a support system to grow viable new resources.
2. Create an educational system to grow the awareness and skills to expand the industry.
3. Diversify the tax base.

Respondent 6 – Blue Evolution: Kelp Hatchery and Product Development

1. Identify higher value or better utilization of waste streams.
2. Identify products and markets related to alginates, extracts, and dried products.
3. Identify how kelp products fit into cosmetics and chemical markets.
4. Increased mechanization of packaging.

Respondent 7 – Alaska Ocean Cluster: New Business Formation

1. See Beau Perry's comments, agree.

Respondent 8 – Wild Source, Sun'aq Tribe of Kodiak

1. Identify product development and market opportunity.
2. Identify processing parameters for ready-to-eat products.
3. Identifying nutritional and chemical components of kelp.
4. Develop marketing fact sheets for various species/products.
5. Introducing new kelp products to existing seafood buyers.

Respondent 9 – Alaska Marine Conservation Council: Community Development, Fish Processing

1. Identify new products and processes appropriate for small-scale and entry-level kelp farmers to develop and bring to market, emphasizing the need for opportunity for community input for mariculture development.
    a. For example, include the development of a community vision and consideration of input from small rural communities.
2. Identify economically feasible processing, storage, and transportation within existing facilities in the region.
3. Provide support in site development, permits, and logistical challenges for small-scale operators.
4. Identify new market pathways for value-added products.

Respondent 10 – Optimera Inc LLC: Technology Development

1. Identify processing requirements and market dynamics of hydrothermal liquefaction fuel from kelp feedstock.
2. Identify global best practices for equipment, processes, and products.
3. Develop pilot projects to test processes for cost modeling at production scale in remote Alaska.

The following organizations did not provide input, although they are active SC members:

- Aleutians East Borough: Local Economic Development and Planning, Mariculture
- Kodiak Kelp Company, Local Kelp Production
- Ecotrust: Regional Distribution Systems.

The overall needs that were identified by the SC were reviewed and summarized as follows:

- Identify processes and products that unlock economic activity for new kelp farming and processing that benefit the isolated coastal communities in the SWAMC region.
- Identify species of kelp whose characteristics have the greatest market value to Alaska.
- Identify synergies with existing fisheries and community infrastructure, including waste streams (e.g., fish processing waste, solid municipal waste) along with kelp as a potential local viable energy source.
- Identify new products and processes appropriate for small-scale and entry-level kelp farmers to develop and bring to market, emphasizing the need for opportunity for community input for mariculture development.
- Create an educational system to grow the awareness and skills to expand the industry.

B.2 Full Table of SWAMC Community Tabular Data

The following table includes all of the SWAMC community tabular data that was collected for the stakeholder engagement activities.

PNNL Notes for Potential Case Study Evaluation	Borough/Census Area	SWAMC Community	PCE Community Population	PCE Cost per kWh	PCE Total kWh Consumed	ADFG Registered Processor Facilities	Distance (km) to mean tidal current >1	Distance (km) to mean tidal current >0.8	Data Notes
High cost per kWh, 2 processing facilities, and most remote	Aleutians West	Adak	308	$1.25	2,138,300	2	28.03	18.37	
	Kodiak Island	Afognak							Not in PCE Report
	Kodiak Island	Akhiok	88	$0.52	248,476				
	Aleutians East	Akutan	993	$0.64	642,584	1			
	Dillingham	Aleknagik							Included in Dillingham PCE Population
	Aleutians West	Atka	54	$0.25	394,484				
	Lake & Peninsula	Chignik Bay	110	$0.37	711,554	1			
	Lake & Peninsula	Chignik Lagoon	85	$0.30	632,674				
	Lake & Peninsula	Chignik Lake	68	$0.58	297,891				
	Dillingham	Clark's Point	55	$0.45	306,720				
	Aleutians East	Cold Bay	72	$0.43	2,351,412				
High kWh consumption, 2 processing facilities, and high	Dillingham	Dillingham	2572	$0.40	19,143,177	2	0.59	0.93	Includes Aleknagik PCE Population
Proposed community from Lake & Peninsula, 4 processing facilities	Lake & Peninsula	Egegik	76	$0.50	621,249	4	84.97	5.35	
	Dillingham	Ekwok	98	$0.00	0				
Proposed community from Aleutians East, 2 processing	Aleutians East	False Pass	73	$0.41	722,482	2	3.48	3.11	
	Lake & Peninsula	Igiugig	57	$0.82	319,544				
	Lake & Peninsula	Iliamna	474	$0.44	3,666,070				Includes Newhalen and Nondalton PCE Population
	Lake & Peninsula	Ivanof Bay							Not in PCE Report
	Kodiak Island	Karluk	29	$0.54	207,644				
	Aleutians East	King Cove				2			Not in PCE Population
	Bristol Bay	King Salmon				1			Included in Naknek PCE Population
Not in PCE, however, 9 processing facilities and large total population	Kodiak Island	Kodiak				9	26.12	25.64	Not in PCE Report
	Lake & Peninsula	Kokhanok	173	$0.87	481,231				
	Dillingham	Koliganek	208	$0.33	621,643				
	Kodiak Island	Larsen Bay	86	$0.07	901,282	1			
	Lake & Peninsula	Levelock	89	$0.55	390,917				
	Dillingham	Manokotak	487	$0.35	808,681				
Mid population, high PCE kWh consumption, 12 processing	Bristol Bay	Naknek	887	$0.32	26,290,460	12	25.41	1.63	Includes King Salmon and South Naknek PCE Population
	Aleutians East	Nelson Lagoon	30	$0.60	302,477	1			AKA Port Moller
	Dillingham	New Stuyahok	504	$0.59	1,841,893				
	Lake & Peninsula	Newhalen							Included in Iliamna PCE Population
	Aleutians West	Nikolski	17	$0.83	206,057				
	Lake & Peninsula	Nondalton							Included in Iliamna PCE Population
	Kodiak Island	Old Harbor	214	$0.45	790,718	1			
	Kodiak Island	Ouzinkie	146	$0.35	696,200				
	Lake & Peninsula	Pedro Bay	32	$0.69	172,527				
	Lake & Peninsula	Perryville	101	$0.89	1,219,667				
	Lake & Peninsula	Pilot Point	76	$0.63	426,698				
	Lake & Peninsula	Port Alsworth	238	$0.34	906,864				
	Lake & Peninsula	Port Heiden	110	$0.36	529,560				
	Kodiak Island	Port Lions							Not in PCE Report
	Dillingham	Portage Creek							Not in PCE Report
	Aleutians West	Saint George	70	$0.85	596,000				
	Aleutians West	Saint Paul	389	$0.45	3,390,261	3			
	Aleutians East	Sand Point	915	$0.56	4,000,844	1			
	Bristol Bay	South Naknek							Included in Naknek PCE Population
	Dillingham	Togiak	870	$0.48	3,090,087	2			
	Dillingham	Twin Hills	86	$0.48	0				
	Lake & Peninsula	Ugashik				1			Not in PCE Report
Highest community population, highest kWh consumption, 6	Aleutians West	Unalaska	4341	$0.27	53,379,409	6	21.42	20.84	AKA Dutch Harbor

Appendix C – Ohio State University Work

This Appendix provides the summary of the work performed by Ohio State University. Their report on this project is provided as received from the University.

Macroalgae protein analysis and extraction screening for protein yield using enzyme-assisted extraction (EAE) for two species of Brown Kelp

A report to:
Pacific Northwest National Laboratories

Prepared by:

Jeff Caminiti,[1] Dennis Heldman,[1,2] Macdonald Wick[1,3]

[1]Department of Food Science and Technology
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3.10.21

THE OHIO STATE UNIVERSITY
COLLEGE OF FOOD, AGRICULTURAL, AND ENVIRONMENTAL SCIENCES

Executive summary

Protein based co-products provide an opportunity for the increased valorization of macroalgae biomass. The goal of this research was to evaluate the protein extraction for two species of brown kelp: *Saccharina* and *Alaria*. The protein extracted into the liquid phase has potential for co-product development while retention of non-protein materials in the solid phase is critical for fuel conversion efficiency. Objectives included: 1) compare protein and mass yield using water, alkali, and enzymatic treatments, 2) compare soluble protein yields after long and short enzymatic treatments, 3) identify major differences in extraction behavior between *Alaria* and *Saccharina* sources. 4) characterize the amino acids and nitrogen content of commercial macroalgae samples.

Kelp protein extraction was conducted in two stages. First, a 1-hour or 18-hour pretreatment with water, NaOH (2.5 N), or buffer solutions with or without Viscoyme® (mixture of polysaccharide enzymes) was followed by enzyme inactivation. Next, concentrated (5 N) or dilute (0.1 N) NaOH was then added in equal volume for 1 hour to the buffer samples. The mass of the separated liquid and solid fractions were recorded. The liquid fraction was analyzed for protein concentrations using Bicinchoninic acid (BCA) protein assay.

The solid fraction masses (dw.) for the samples incubated in dilute NaOH were larger ($p<0.001$) than those incubated in concentrated NaOH. The addition of 12.5 N NaOH aided in the dissolution of cellular components more than the enzymatic treatment.

The protein content of the liquid fraction was also significantly ($p<0.001$) influenced by the presence of NaOH. Approximately 10 times more protein was extracted by 10% NaOH treatment than by distilled water. The 1-hour enzyme treatment extracted more protein than the control treatments. Among the dilute NaOH samples, enzymatic exposure for 18 hours resulted in the most protein extracted.

Enzymatic treatment was effective in increasing protein extraction while minimizing extraction of non-protein components. However, NaOH alone was 5x more effective at extracting proteins, yet the solids dry mass was reduced. Maximizing protein extraction is important, but it is desirable to avoid strong concentrations of NaOH for environmental and safety reasons and the neutralization results in high salt concentrations. To maximize the valorization of a bio-refinement pathway, it is important to understand the full mass balance of extraction and the associated production costs.

Introduction

Macroalgae have gained interest for applications as both food and fuel. During the biorefinery process, multiple processing steps are needed to convert kelp biomass into biofuel. Biofuel production is not yet carbon neutral, nor cost-effective (Cruce & Quinn, 2019). Co-products from the underutilized protein fraction provide an avenue for the increased valorization of macroalgae biomass. The human food market is a good match, considering market size and the value associated with the plant-based beverage and protein markets. The goal of this research was to evaluate the protein extraction process as it relates to the technical and economic aspects of producing food and fuel from two species of brown kelp, *Saccharina* and *Alaria, and to characterize* a selection of additional macro algae species in terms of amino acid composition.

Nine species of macroalgae, of interest for potential human nutrition consideration, were delivered by PNNL. Thirty-five unique samples were accepted including commercially sourced and those cultivated by Blue Evolution. Blue Evolution provided samples from two species: *Saccharina*, *Alaria. Saccharina* and Alaria samples were separated by component (blade or stipe) with collection dates from April, May, and June. The 26 samples were analyzed for amino acid composition and protein nutritional quality. Amino Acid analysis (AA) provides a definitive measure of the quantity and nutritional quality of protein. By pairing the AA with total nitrogen analysis, an estimation for the protein-nitrogen conversion factor can be made.

Blue Evolution provided multiple different samples of *Alaria and Saccharina* macroalgae, thus these species became the focus of the extraction component of the analysis. Commercially produced *Alaria* and *Saccharina* were used to screen for enzyme assisted extraction efficiency and to evaluate the mass and protein balance associated with the initial extraction and separation procedures. Details of the experimental design are provided in **Figure 1** below.

The separation process is the major determinant in the protein yield from the extraction and the value of each new fraction. It is desirable to solubilize the maximum amount of protein from the biomass and retain it in the supernatant. At the same time, fat and carbohydrate must be retained in the pellet fraction. Carbohydrates and fats contaminate the protein whose price is linked to purity, so the more efficient the initial separation, the lesser the downstream processing costs will be. Poor separation efficiency also reduces the value of the solid material. Lower solids mass with the pellet would suggest the carbohydrates destined for biofuel conversion were solubilized (likely via alkali or enzymatic hydrolysis) and incorporated into the supernatant Further, sub-maximal protein extraction could result in a pellet that does not meet biofuel conversion efficiency targets due to its protein content.

Enzymatic treatment employed a commercially available enzyme mixture which targets carbohydrates: Viscozyme (Novozymes Corp) containing arabinase, cellulase, β-glucanase, hemicellulase, and xylanase. The mixtures were originally developed for the brewing industry and have been used on brown seaweed to liberate phenolics (Habeebullah et al., 2020; Sánchez-Camargo et al., 2016), and Sancez, 2016). Hammed et al. (2013) identified 7 reports of Viscozyme's use on macroalgae for the extraction of antioxidants.

Previous attempts to extract and quantify protein yield in macroalgae have explored the effects of enzymes, various extraction times, substrate:enzyme ratios, and temperature. While studying an enzyme blend (Cellic CTec3: cellulases, ß-glucosidases, and hemicellulose). They measured protein content as part of a response surface model showing the substrate:enzyme ratio has a greater effect on protein yield compared to enzyme exposure time (6-18 hr). Fleurence et al. (1995), studied *Chondrus crispus, Gracilaria verrucose,* and *Palmaria palmata* showed increased yield between 2 and 14 hours with the exception of *Gracilaria verrucose.*

The major carbohydrate in *Alaria* and *Saccharina* is alginate containing 37% and 28% of the carbohydrates, respectively. Cellulose was found to be the second most abundant polysaccharide with approximately 10-15% of the carbohydrates (Schiener et al., 2014). The enzyme mixtures selected were expected to break down the cellulosic materials degrading the structure releasing protein. Specific digestion of alginate has been explored by Nguyen et al., (2020), using alginate lyase treatment to extract fucoidan. Future studies could investigate this process for protein extraction applications from brown kelp.

Specific objectives included: 1) compare protein and mass yield using water, alkali, and enzymatic treatments, 2) compare soluble protein yields after a long and short treatment times with commercial enzyme mixtures, 3) identify major differences in extraction behavior between *Alaria* and *Saccharina* sources, 4) characterize the amino acids and nitrogen of the 26 commercial macroalgae samples.

2. Materials and Methods

2.1 Materials

Macroalgae samples were sourced commercially by PNNL. Viscozyme enzymatic cocktail (arabanase, cellulase, β-glucanase, hemicellulase, and xylanase; Sigmaaldrich) and BCA kits were purchased from Sigma Aldrich.

2.2 Particle size reduction

Aaria (AL-HME) was ball milled and passed easily through a 300 μm sieve. Whole, freeze-dried *Saccharina* (SA-HME) was ground frozen in a food processor for 1 min and sieved, passing through 1.18 mm screen. The dry ground powders were stored in airtight containers at -30 °C until use.

2.3 Proximate analysis of ground samples

The moisture content (MC) was determined gravimetrically comparing the mass change after 17 hr of drying at 105 °C (Belluco et al., 1983). Total fat was determined using hexane in a Soxhlet apparatus, recirculating for 2 hours. Total nitrogen was measured using the Dumas method on a Rapid N Exceed Nitrogen Analyzer (Elementar, Ronkonkoma, NY.)

2.3.1 Calculation

Moisture content (MC) was calculated using:

$$MC = \%MC = \frac{m_i - m_d}{m_i} * 100 \qquad \text{eq. 1}$$

Where, m_i was the initial sample mass, and m_d is the mass after 17 hours at 105 °C.

Fat content (FC) was calculated using:

$$FC = \%FC = \frac{m_d - m_n}{m_i} * 100 \qquad \text{eq. 2}$$

Where, m_d are the same initial and dried masses from equation 1, and m_n is the non-fat dried solids mass. Non-fat dried solids are obtained by recirculating hexane over the dried biomass for 2 hours in a Soxhlet apparatus.

Protein content (PC) via Dumas is determined from the percent nitrogen (%N) according to:

$$PC = \%PC = \%N * F \qquad \text{eq. 3}$$

Where F is the proportionality factor that relates % N to protein content (PC) for specific organisms. The value can be determined from amino acid composition and is reported in literature to be 5.17 for brown macroalgae (Biancarosa et al., 2017). Carbohydrates and ash were not measured directly.

2.4 Extraction screening experiment

All samples were extracted in 250-ml tubes with lateral shaking of 120 rpm at 53 °C. The procedure was to:

I) Combine the samples (10 g ±0.5 g) with the specified solvent solution (100 ml) at a 1:10 ratio (w/v) and begin shaking.

II) Shaking occurred for 1 or 18 hours to provide agitation and test the effect of time on enzyme exposure.

III) Heat treat to deactivate enzymes (submerged in boiling water for 10 min).

IV) Adjust the pH of buffered samples using 0.1N NaOH or 5N NaOH (100ml). Proteins are more soluble at neutral and high pH than under the acidic conditions the enzyme requires.

V) Additional shaking for 1 hr to reach equilibration followed. For samples exposed to a final concentration of 2.5 N NaOH, neutralization with HCl and volume adjustment to 400 ml was conducted prior to separation.

VII) Centrifugation (27,000 x g at 4 °C for 30 min) and separation into the liquid supernatant and solid fraction pellet.

VIII) Filtration of the supernatants to remove excess particulates using a 2 µm filter.

IX) Both fractions were freeze dried for preservation.

Extraction independent variables included: macroalgae species, solvent solution, treatment time, and post treatment adjustment. The species include the ground SA-HME and AL-HME powders, the solvent solution included diH_2O, 0.1 M acetate buffer pH 4.5, and 2.5 N NaOH, the adjustments included a dilute (0.1 N) or concentrated 5 N NaOH solution. Water and 2.5 N NaOH conditions were adjusted with the same solvent. All samples treated with NaOH were neutralized with HCl, and water was added to achieve a 400 ml volume addition.

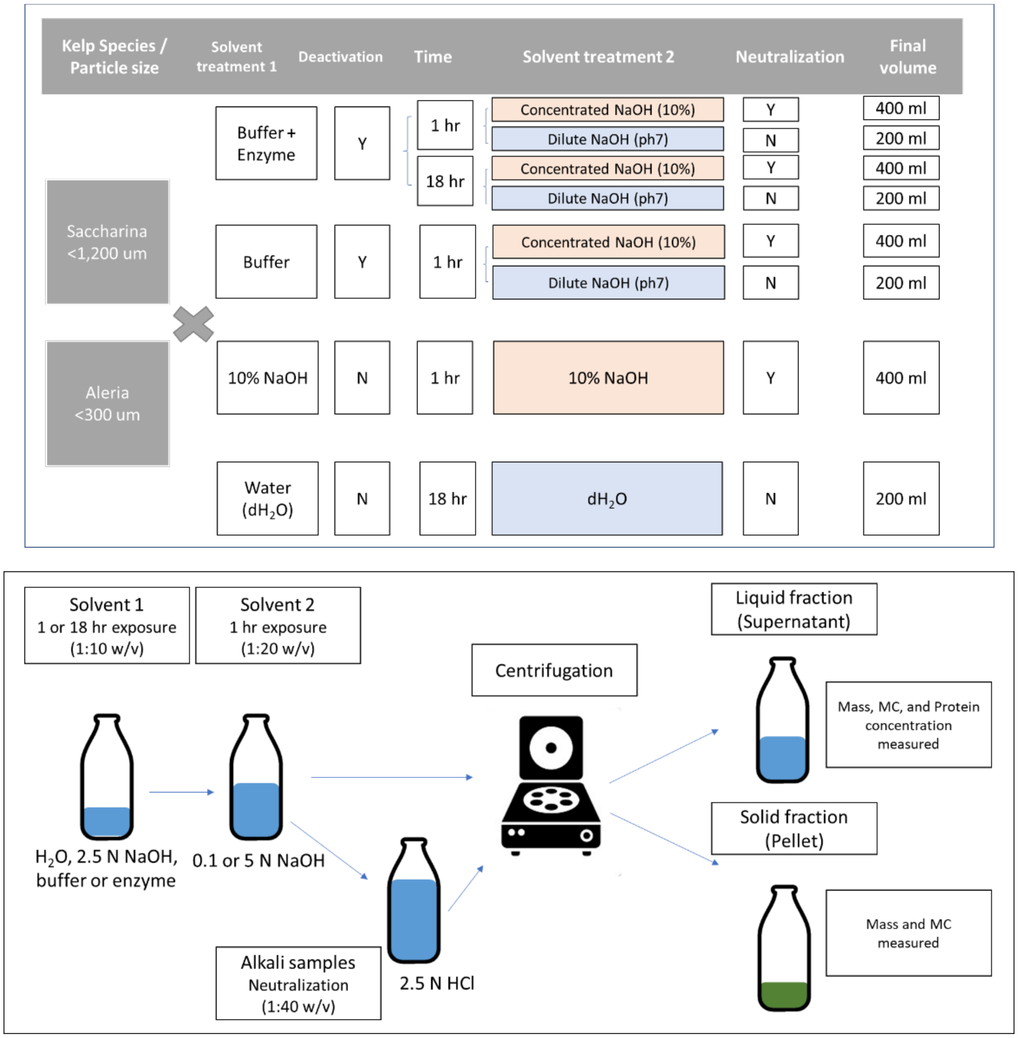

Figure 1: *Top: Experimental design diagram showing the 16 extraction treatment conditions. Bottom: graphical overview of experimental procedure showing initial treatment, adjustment, neutralization, centrifugation, and separation.*

2.5 Post-Extraction analysis

After centrifugation, the mass of the liquid fraction (supernatant) and the solid fraction (pellet) were collected. The MC of each was determined, see section 2.3. Prior to freeze drying, the supernatant was analyzed for protein concentration using Bicinchoninic acid (BCA) method.

2.5.1 Evaluation calculations

Component mass yields were calculated with the following formula:

$$\% \text{ supernatant} = \frac{m_s}{m_t} \qquad \text{eq. 3}$$

$$\% \text{ pellet} = \frac{m_p}{m_t} \qquad \text{eq. 4}$$

Where m_t is the is the total mass added to the extraction jars, m_s is the mass of the supernatant or liquid fraction, and m_p is the mass of the pellet or solid fraction.

Extracted protein was calculated using:

Extracted protein (mg) = $V_s * C_s$

Where V_s equals the volume (ml) of the supernatant collected and C_s is the protein concentration (mg/ml), as determined by BCA.

2.6 Amino Acid analysis by LCMS

Each of the raw whole macroalgae samples was submitted for amino acid analysis along with 6 extract samples from the experiment described in section 2.4. A list of all samples can be found in **Appendix A.**

For amino acid quantification, samples were first hydrolyzed by incubating dried sample with 200 uL H_2O with 10% MSA and 25 uM heavy labeled internal standard (Cambridge Isotope Laboratories), evacuated with N2, and heated at 100 C for 23 hours. Standard solutions of amino acid mixture were also hydrolyzed the same way at concentrations of 0.0, 0.25, 2.5, 25, and 250 uM. After hydrolysis, samples were complately dried down and reconstituted in 50:50 H2O:ACN and placed in LC vials for quantification.

3. Results and Discussion

3.1 Proximate analysis

Table 1: *Proximate analysis for the Alaria and Saccharina samples used in the protein extraction experiments (see Figure 1) compared to Schiener et al., (2014) report on seasonal variation of brown kelp species.*

	Experimental analysis (wet wt.)		Schiener, 2015 (dw.)	
	Alaria	*Saccharina*	*Alaria*	*Saccharina*
% moisture	12.4%	7.2%	NR	NR
% fat	4.4%	4.5%	NR	NR
% protein (Dumas)	8.2%	6.3%	9.4-12%	5.3-9.9%
sum	25.0%	18.1%	-	-
carbohydrates	NR[1]	NR	65-78%	60-80%
Ash	NR	NR	8-12%	2-3%

[1]NR indicates data not reported by the respective source.

The data summarized in **Table 1** shows the biomass proximate composition of the *Alaria and Saccharina* samples studied for protein extraction. The values determined experimentally for MC, FC, and PC are reasonable when compared to the data reported by Schiener et al., (2014). Schiener et al. (2014) report dry weight values while the analysis conducted in our laboratory used freeze-dried kelp with a small amount of residual moisture which may explain variations in protein content. An important conclusion from the work of Schiener et al (2014) is that the reported values are affected by season, thus variability is expected.

3.1 Analysis of recovered solids fraction (pellet):

In the experimental design described in **Figure 1,** two major sample groups from this study are included: neutral (samples adjusted to pH 7, blue boxes) and alkali (Samples adjusted to 10% NaOH, orange boxes). These two groups include controls of water and 10% NaOH, respectively.

During the experiment, visual observation was able to distinguish between the two groups. The pellet characteristics from each group were noticeably different. The neutralized pellets were less-compact, watery, and the cellular matrix was visible and heterogenous. In contrast, the samples from alkali treatment exhibited dense pellet that were sandy, dry, and homogenous. The mass of the pellet (wet weight) was found to be statistically ($P<0.001$) larger for the neutral samples compared to the alkali group. The pellet mass collected from *Saccharina* samples was more variable and slightly greater across all conditions when compared to those from *Alaria*. *Saccharina* samples generally formed a less-compact pellets as well. This is likely attributed to the grinding technique and the difference in final particle size. As an objective comparison of the solids, the dried weights were collected and are shown below in **Figure 2**.

Moisture content analysis of the pellets showed that the neutral (avg. 91%) group had a significantly ($p=0.0044$) higher moisture content (MC) than the alkali group (avg. 85%). The variation in MC is an indication of the solids' ability to hold water. Alkali treatment diminished the solid materials ability to hold water.

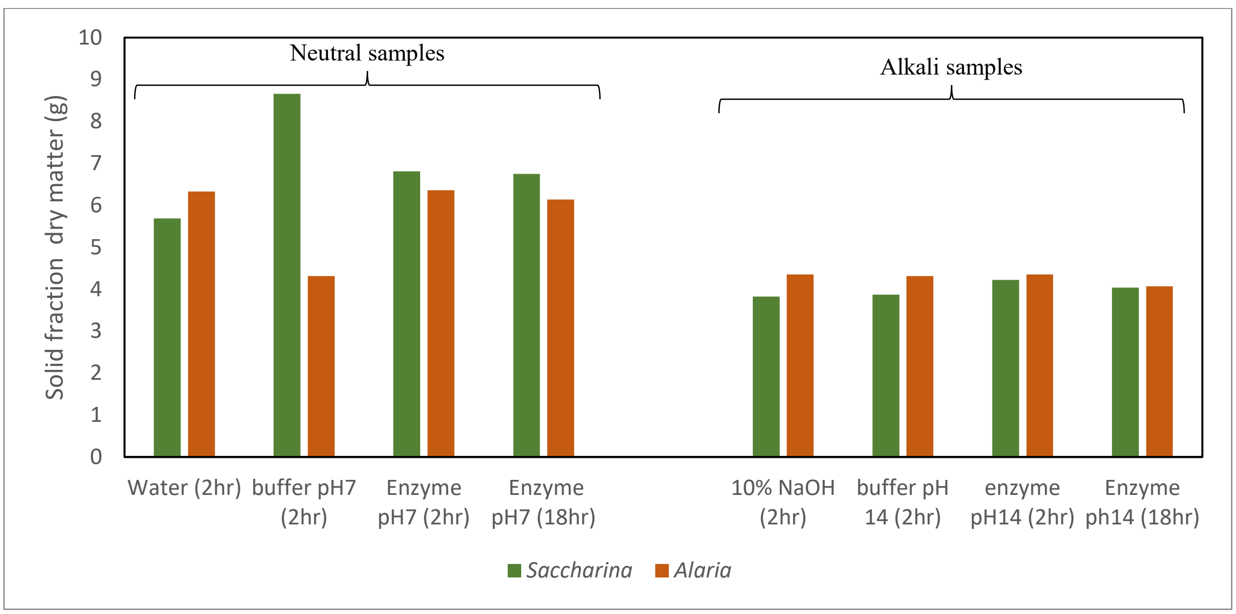

Figure 2: *Pellet dry matter collected for all conditions tested showing pH7 or "neutral" samples on the left and pH 14 or "alkali" samples on the right for Saccharina and Alaria initial mass is approximately 10 grams for all samples.*

Figure 2 shows the dry solid weights collected from the pellets with the neutral samples leaving a significantly ($p<0.0001$) larger pellet solids mass than the alkali samples across all conditions. Differences among species are minimal for most conditions. The initial dry mass solids were approximately 10 grams, thus the alkali samples, on average, lost about 60% of their mass to the solvent while the neutral samples lost about 34% of their mass, on average. Furthermore, due to the neutralization, the alkali samples also contain higher salt content. In situations where pellet mass retention is critical, this is an important observation.

3.2.1 Analysis of recovered supernatant and soluble protein

The analysis of supernatant is focused on the materials extracted; thus, total solids (**Figure 3**) and extracted protein (**Figure 4**) are reported of the supernatant are reported.

The results show significantly ($p<0.0001$) greater solids extracted from the alkali group than the neutral group across all conditions. It is important to recall the final volume of the alkali group was doubled during neutralization. The data presented do not reflect any normalization, but the data as it was collected.

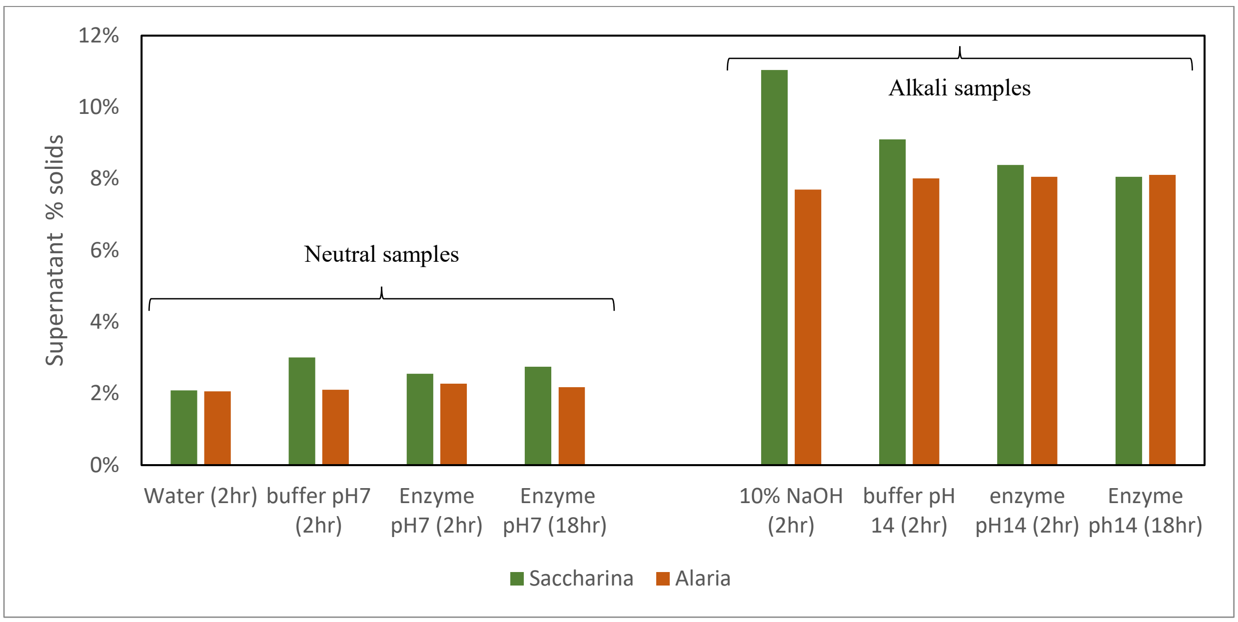

***Figure 3:** Supernatant % solids for all conditions determined via drying at 105 °C for 17 hours. (no adjustments made).*

Analysis of protein concentration in the supernatant showed significantly ($p=0.005$) more protein extracted from the alkali group than the neutral group across all conditions. Also, the *Alaria* samples were significantly more concentrated in the neutral ($p=0.027$) and alkali ($p=0.0317$) groups than the *Saccharina* samples. An unexpected outcome was observed in that diminishing protein concentrations were observed with enzyme addition and extended treatment in the *Alaria* alkali group.

The protein concentrations were multiplied with the supernatant volumes collected to determine a protein yield from the initial 10 g of kelp; **Figure 4** displays these values. Please note BCA protein determination is not an absolute measure of protein content as it is based on a standard protein's affinity to the BCA dye, which may be different than the kelp protein's affinity. Furthermore, these values do not account for processing loss that may be associated with downstream operations such as drying and packaging.

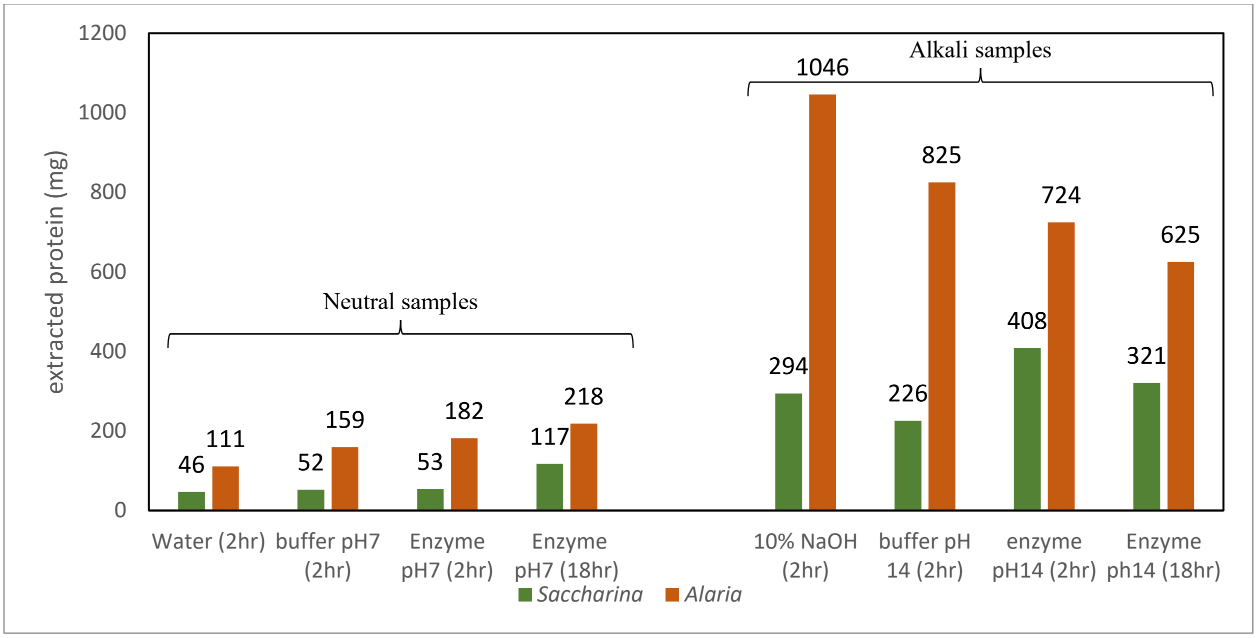

Figure 4: *Extracted protein for the different protein extraction methods evaluated in this study; initial mass is approximately 10 grams for all samples. Values are the product of the BCA protein content times the supernatant volume.*

3.3 Protein conversion factor for 35 commercial kelp samples

3.3.1 Nitrogen analysis of 35 commercial kelp samples

Nitrogen content data is presented in Appendix A for the samples provided. %N ranged from just under 1% in a sample of *Laminaria* from China (LA-CH) to 7.32% in a sample of *Pophyra* from China (PO-CH). Notable trends among the Blue Evolution samples suggest that as harvest date becomes later in the year, less nitrogen is present in the samples. Furthermore, among the *Alaria* and *Saccharina* samples tested, blade samples have greater nitrogen contents compared to the stipe samples.

3.3.2 Amino Acid Analysis and Nitrogen conversion estimation

Preliminary data is presented in Appendix A & B for the nitrogen conversion estimation, based on amino acid analysis, and the full amino acid profiles, respectively. The total protein content determined from the amino acid profile was lower than expected for all samples. This sparked additional investigation into the amino acid analysis methodology. This investigation will continue until reliable results can be confirmed. Data will be prepared for publication at this time.

Conclusions

- For both kelps (*Saccharina*, SA-HME and *Alaria, AL-HME*) evaluated, protein yield is considerably higher after alkali treatment (10% NaOH) compared to enzymatic treatment.
- 10% NaOH treatment decreases the biomass water holding capacity and increases the protein and non-protein material solubility.
- Solids dry matter is affected by solvent selection.
- Differences among the species were likely confounded by grinding method which may be a critical step to maximize protein recovery and to reduce material usage.
- Amino acid analysis is on going and will be published in a peer-reviewed journal when satisfactory results are obtained.

References:

Belluco, S., Losasso, C., Maggioletti, M., Alonzi, C. C., Paoletti, M. G., Ricci, A., Barragán, Á., Dangles, O., Cárdenas, R., Onore, G., Idolo, I., Jacob, a a, Emenike, a F., Kayode, A., Olusegun, O., Uzoma, A., Rukayat, K. Q., Memis, E., Türkez, H., … Anderson, E. N. (1983). Meat and meat products: Preparation of sample. In *Journal of AOAC International* (Vol. 66, Issue 759). https://doi.org/10.1016/j.ifset.2012.11.005

Biancarosa, I., Espe, M., Bruckner, C. G., Heesch, S., Liland, N., Waagbø, R., Torstensen, B., & Lock, E. J. (2017). Amino acid composition, protein content, and nitrogen-to-protein conversion factors of 21 seaweed species from Norwegian waters. *Journal of Applied Phycology*, *29*(2), 1001–1009. https://doi.org/10.1007/s10811-016-0984-3

Cruce, J. R., & Quinn, J. C. (2019). Economic viability of multiple algal biorefining pathways and the impact of public policies. *Applied Energy*, *233–234*(July 2018), 735–746. https://doi.org/10.1016/j.apenergy.2018.10.046

Fleurence, J., Massiani, L., Guyader, O., & Mabeau, S. (1995). Use of enzymatic cell wall degradation for improvement of protein extraction from Chondrus crispus, Gracilaria verrucosa and Palmaria palmata. *Journal of Applied Phycology*, *7*(4), 393–397. https://doi.org/10.1007/BF00003796

Habeebullah, S. F., Surendraraj, A., Zainab, S., Sakinah, A.-H., Saja, F., Aws, A.-G., & Faiza, A.-Y. (2020). Enzyme-assisted extraction of bioactive compounds from brown seaweeds and characterization. *Journal of Applied Phycology*, *32*(1), 615–629. https://doi.org/10.1007/s10811-019-01906-6

Hammed, A. M., Jaswir, I., Amid, A., Alam, Z., Asiyanbi-H, T. T., & Ramli, N. (2013). Enzymatic Hydrolysis of Plants and Algae for Extraction of Bioactive Compounds. *Food Reviews International*, *29*(4), 352–370. https://doi.org/10.1080/87559129.2013.818012

Nguyen, T. T., Mikkelsen, M. D., Nguyen Tran, V. H., Trang, V. T. D., Rhein-Knudsen, N., Holck, J., Rasin, A. B., Cao, H. T. T., Van, T. T. T., & Meyer, A. S. (2020). Enzyme-

Assisted Fucoidan Extraction from Brown. *Marine Drugs*, *18*(296).

Sánchez-Camargo, A. D. P., Montero, L., Stiger-Pouvreau, V., Tanniou, A., Cifuentes, A., Herrero, M., & Ibáñez, E. (2016). Considerations on the use of enzyme-assisted extraction in combination with pressurized liquids to recover bioactive compounds from algae. *Food Chemistry*, *192*, 67–74. https://doi.org/10.1016/j.foodchem.2015.06.098

Schiener, P., Black, K. D., Stanley, M. S., & Green, D. H. (2014). The seasonal variation in the chemical composition of the kelp species Laminaria digitata, Laminaria hyperborea, *Saccharina latissima* and Alaria esculenta. *Journal of Applied Phycology*, *27*(1), 363–373. https://doi.org/10.1007/s10811-014-0327-1

Appendix 1: Nitrogen content of the 35 kelp samples

	Genus	location code	component	month	%N		std.dev.	Protein content (AAA)*	Nitrogen conversion factor
1	*Alaria* (AL)	p	b	apr	3.19	±	0.17	8.4%	2.6
2		p	b	may	1.96	±	0.23	4.0%	2.1
3		p	b	jun	2.01	±	0.33	2.4%	1.2
4		w	s	apr	1.53	±	0.2	1.4%	0.9
5		p	s	may	1.31	±	0.34	2.5%	1.9
6		p	s	jun	1.06	±	0.04	2.4%	2.3
7		al	b		2.68	±	0.16	1.5%	0.6
8		hme	b		1.59	±	0.1	3.6%	2.2
9		sg	w		1.76	±	0.05	1.7%	1.0
10	*Laminaria* (LA)	bc	b		1.28	±	0.23	5.0%	3.9
11		ch	b		0.98	±	0.03	1.2%	1.2
12	*Saccharina* (SA)	p	b	apr	3.76	±	0.07	5.6%	1.5
13		w	b	apr	3.05	±	0.31	1.5%	0.5
14		w	b	may	2.27	±	0.24	4.1%	1.8
15		w	b	jun	3.47	±	0.18	3.0%	0.9
16		w	s	apr	2.62	±	0.15	2.9%	1.1
17		w	s	may	2.34	±	0.23	2.4%	1.0
18		w	s	jun	2.67	±	0.35	5.0%	1.9
19		al	b		3.6	±	0.12	1.7%	0.5
20		bc	b		2.2	±	0.2	1.4%	0.6
21		hme	b		1.21	±	0.14	2.1%	1.7
22		sg	w		1.57	±	0.04	1.5%	0.9
23	*Eualaria* (DK)	ak	b	jul	2.18	±	0.47	1.5%	0.7
24	*Ulva* (UL)	ha	b		2.31	±	0.15	2.5%	1.1
25		hme	b		3.46	±	0.02	2.0%	0.6
26	*Macrocystis* (Ma)	bc	b		1.5	±	0.13	0.6%	0.4
27		sg	w		1.03	±	0.02	1.4%	1.4
28	*Nereocystis* (NE)	bc	b		1.06	±	0.06	1.9%	1.8
29		sg	s		1.14	±	0.02	2.0%	1.7
30	*Palmaria* (PA)	hme	w		2.95	±	0.37	2.1%	0.7
31		os	w		4.09	±	0.28	8.6%	2.1
32	*Porphyra* (PO)	ch	p		7.32	±	0.25	2.8%	0.4
33		me	w		4.24	±	0.61	6.5%	1.5
34	*Costaria custata* (CO)	sg	w		2.03	±	0.09	1.3%	0.6
35	*Hedophyllum* (HE)	sg	w		1.37	±	0.02	0.5%	0.4

Appendix A, continued: Location codes description and details for Appendix A

Location code[1]	Location
P	Popov Island, Alaska
W	Woody Island, Alaska
AL	Alaska
HME	Hancock, Maine
SG	Seagrove
BC	Bamfield BC, Canada
CH	China
HA	Honolulu, Hawaii
OS	Oregon State University

[2]Component code: B stands for Blade and S stands for Stipe.

[3]Sample from Blue Evolution with specified harvesting months. Except[*] is a commercially acquired

*Amino Acid profiles represent most recent data. Analysis is ongoing to validate data for future publications. Ala, Asp, Gln, Glu, and Cys are under further investigation. Trp, as expected was destroyed during hydrolysis.

Appendix B: Amino acid profiles* for 35 kelp samples (table across 3 pages)

	Alaria (AL)									*Laminaria* (LA)	
	P_B_4	P_B_5	P_B_6	W_S_4	P_S_5	P_S_6	AL_B	HME_B	SG_W	BC_B	CH_B
	1	2	3	4	5	6	7	8	9	10	11
Ala	36.07%	28.67%	27.59%	121.15%	39.40%	39.26%	47.71%	27.17%	18.56%	24.34%	51.68%
Arg	2.89%	3.22%	2.95%	4.47%	3.11%	3.95%	3.71%	2.85%	4.02%	2.68%	1.73%
Asn	0.98%	0.29%	0.60%	-0.28%	0.39%	0.30%	0.57%	0.45%	1.42%	0.49%	-0.26%
Asp	65.10%	61.88%	52.94%	36.80%	64.65%	68.72%	65.21%	74.71%	64.97%	63.33%	75.27%
Cys	0.02%	NF	0.02%	NF	0.37%	0.10%	0.06%	0.18%	NF	0.02%	0.09%
Gln	28.22%	33.22%	45.94%	46.19%	44.77%	39.65%	32.53%	30.89%	30.00%	31.47%	43.08%
Glu	35.37%	26.69%	24.19%	17.69%	26.88%	32.92%	20.90%	34.33%	28.02%	35.67%	33.02%
Gly	9.69%	10.83%	8.27%	8.16%	7.99%	5.46%	13.16%	9.77%	10.12%	12.84%	3.12%
His	0.76%	0.99%	0.84%	0.95%	0.83%	0.98%	0.82%	0.64%	1.03%	0.51%	0.40%
Ile_Leu	2.65%	3.20%	2.10%	3.14%	1.46%	1.70%	4.17%	2.67%	3.01%	2.27%	2.15%
Lys	3.04%	3.07%	2.14%	3.71%	1.83%	2.50%	3.74%	2.65%	3.97%	2.44%	1.29%
Met	1.10%	0.97%	0.97%	0.59%	0.52%	0.67%	1.33%	0.54%	1.40%	0.72%	0.66%
Phe	2.72%	3.05%	2.26%	3.60%	1.64%	2.03%	3.77%	2.51%	3.52%	1.66%	2.53%
Pro	3.23%	3.53%	2.76%	2.18%	2.79%	2.91%	4.58%	2.95%	4.12%	2.05%	3.80%
Ser	7.84%	6.33%	4.71%	5.20%	6.93%	5.32%	6.00%	6.54%	7.62%	5.63%	5.16%
Thr	2.66%	3.51%	2.07%	2.25%	1.13%	1.58%	3.05%	2.23%	2.41%	1.53%	1.88%
Trp	0.04%	0.01%	0.00%	0.03%	0.01%	0.00%	0.14%	0.01%	0.00%	0.02%	0.15%
Tyr	1.21%	2.52%	1.96%	3.19%	1.33%	2.21%	3.47%	2.33%	2.87%	1.84%	1.17%
Val	1.48%	2.09%	1.80%	3.12%	1.87%	2.08%	2.34%	1.94%	1.91%	1.34%	1.60%

*Amino Acid profiles represent most recent data. Analysis is ongoing to validate data for future publications. Ala, Asp, Gln, Glu, and Cys are under further investigation. Trp, as expected was destroyed during hydrolysis.

Appendix B: part 2*

	Saccharina (SA)											*Eualaria* (DK)
	P_B_4		W_B_4	W_B_5	W_B_6	W_S_4	W_S_5	W_S_6	AL_B	BC_B	HME_B	SG_W
	12	AK_B_7	13	14	15	16	17	18	19	20	21	22
Ala	44.7%	23	65.3%	17.2%	11.9%	89.3%	38.5%	28.7%	36.3%	26.3%	28.7%	18.7%
Arg	3.4%	NF	1.9%	3.5%	4.0%	2.3%	2.0%	1.9%	3.6%	2.1%	1.8%	1.8%
Asn	0.5%	0.34%	-0.2%	1.2%	0.3%	0.8%	0.3%	0.7%	1.0%	0.6%	0.4%	0.7%
Asp	58.5%	-0.37%	21.0%	65.7%	64.0%	113.3%	126.2%	144.4%	55.6%	34.7%	46.0%	40.0%
Cys	NF	2.89%	0.0%	0.0%	NF	0.1%	0.3%	NF	NF	0.1%	0.1%	NF
Gln	27.7%	0.06%	56.0%	34.7%	27.5%	38.0%	37.5%	34.2%	29.8%	38.7%	40.7%	48.4%
Glu	26.1%	53.75%	21.6%	24.1%	28.5%	20.6%	30.8%	35.6%	19.8%	32.5%	29.4%	27.6%
Gly	10.1%	41.21%	5.3%	13.1%	15.3%	9.7%	5.6%	10.5%	18.1%	10.0%	8.5%	7.0%
His	1.0%	0.17%	0.4%	0.9%	0.3%	0.9%	0.8%	0.7%	1.2%	0.6%	0.5%	0.5%
Ile_Leu	4.1%	0.03%	1.6%	3.6%	3.6%	3.6%	2.4%	1.6%	3.7%	2.2%	2.0%	1.8%
Lys	4.0%	0.69%	1.4%	3.4%	1.7%	2.6%	2.7%	1.9%	3.9%	1.7%	1.7%	1.5%
Met	1.6%	0.26%	0.3%	1.4%	0.5%	1.3%	0.8%	0.9%	1.8%	0.8%	0.7%	0.8%
Phe	3.6%	0.11%	1.5%	3.4%	3.7%	3.4%	3.2%	2.4%	4.0%	2.0%	2.2%	1.8%
Pro	4.6%	0.56%	2.4%	3.4%	4.9%	4.0%	4.1%	3.2%	3.6%	2.4%	4.0%	2.2%
Ser	5.1%	2.14%	4.9%	5.5%	6.5%	8.0%	6.7%	5.2%	5.2%	4.9%	5.0%	4.5%
Thr	7.8%	0.84%	1.0%	3.4%	2.7%	3.2%	2.2%	2.2%	4.6%	1.5%	1.8%	1.7%
Trp	0.2%	0.23%	0.0%	0.0%	0.0%	0.2%	0.1%	0.0%	0.4%	0.1%	0.0%	0.0%
Tyr	1.8%	0.00%	2.0%	1.3%	2.7%	1.4%	1.3%	0.3%	1.4%	1.0%	2.0%	0.9%
Val	2.2%	NF	1.6%	1.7%	2.3%	3.2%	1.7%	1.3%	2.4%	1.7%	1.5%	1.4%

*Amino Acid profiles represent most recent data. Analysis is ongoing to validate data for future publications. Ala, Asp, Gln, Glu, and Cys are under further investigation. Trp, as expected was destroyed during hydrolysis.

Appendix B part 3

	Ulva (UL)		*Macrocystis* (Ma)		*Nereocystis* (NE)		*Palmaria* (PA)		*Costaria custata* (CO)		*Costaria custata* (CO)	*Hedophyllum* (HE)
	HA_B	HME_B	BC_B	SG_W	BC_B	SG_S	HME_W	OS_W	CH_P	ME_W	SG_W	SG_W
	24	25	26	27	28	29	30	31	32	33	34	35
Ala	25.28%	18.53%	42.12%	NF	35.24%	56.35%	9.44%	12.14%	12.51%	39.45%	28.34%	NF
Arg	3.20%	3.73%	3.11%	2.44%	2.96%	2.39%	4.55%	3.57%	3.34%	3.24%	4.18%	2.66%
Asn	1.04%	0.68%	0.40%	0.56%	1.11%	0.74%	0.88%	0.63%	-0.09%	0.29%	0.89%	-0.79%
Asp	73.49%	71.38%	34.21%	68.31%	44.16%	37.25%	10.18%	147.19%	77.61%	77.35%	67.70%	9.26%
Cys	0.03%	0.02%	0.17%	0.10%	0.06%	0.02%	NF	0.03%	0.02%	0.04%	0.12%	NF
Gln	33.72%	30.17%	52.81%	42.06%	28.34%	38.81%	27.08%	25.89%	26.72%	32.38%	37.11%	64.95%
Glu	30.68%	30.78%	11.10%	10.78%	32.18%	35.66%	27.73%	28.58%	29.37%	33.45%	15.56%	-3.59%
Gly	8.90%	11.95%	6.82%	10.08%	9.68%	6.31%	9.16%	15.55%	15.79%	10.95%	11.67%	7.06%
His	0.80%	0.80%	0.67%	0.90%	0.86%	0.48%	0.91%	0.83%	0.32%	0.55%	0.98%	0.86%
Ile_Leu	2.88%	3.12%	3.66%	3.16%	2.42%	1.48%	4.14%	2.77%	3.26%	2.58%	3.83%	4.13%
Lys	3.12%	3.33%	2.94%	3.67%	3.32%	1.58%	3.86%	3.93%	2.38%	2.84%	4.53%	2.32%
Met	1.41%	0.97%	1.00%	1.51%	1.12%	0.81%	1.35%	0.65%	0.27%	0.87%	1.16%	1.01%
Phe	3.20%	3.56%	3.51%	5.30%	3.33%	1.46%	3.79%	2.60%	3.34%	1.99%	3.84%	5.00%
Pro	3.68%	3.54%	2.60%	2.54%	4.70%	4.47%	4.44%	3.92%	4.67%	3.07%	5.06%	3.05%
Ser	4.60%	4.61%	6.81%	11.55%	6.61%	6.63%	7.75%	8.93%	5.04%	4.97%	6.64%	9.49%
Thr	3.13%	2.58%	1.73%	3.50%	2.14%	0.98%	4.10%	2.39%	3.78%	2.74%	3.89%	2.67%
Trp	0.02%	0.02%	0.05%	0.02%	0.01%	0.01%	0.00%	0.01%	0.01%	0.01%	0.04%	0.11%
Tyr	2.24%	2.67%	3.65%	3.39%	2.90%	NF	2.94%	2.43%	2.92%	1.76%	3.73%	NF
Val	1.62%	1.88%	2.65%	1.55%	2.39%	1.32%	2.74%	1.53%	2.13%	1.83%	1.97%	2.94%

*Amino Acid profiles represent most recent data. Analysis is ongoing to validate data for future publications. Ala, Asp, Gln, Glu, and Cys are under further investigation. Trp, as expected was destroyed during hydrolysis.

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