Greenhouse Gas Emissions

KELP PRODUCTS

A Study of ATLANTIC SEA FARMS

COMMISSIONED BY: Island Institute

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FOREWORD FROM ISLAND INSTITUTE

INTRODUCTION

Purpose

Maine's seafood sector is a cornerstone of the state's economy and identity—and increasingly, a vital player in climate solutions. Between 2022 and 2024, Island Institute commissioned greenhouse gas (GHG) assessments—analyses that measure the amount and sources of GHG associated with specific activities—to better understand the emissions footprint of Maine's lobster, mussel, kelp, and oyster supply chains.

Island Institute's GHG assessment reports provide a foundational benchmark for understanding how seafood producers can cut emissions, lower operating costs, and adapt to changing climate and market conditions. Using illustrative case studies and quantified results, these analyses identify practical solutions and highlight clear opportunities to implement state-level policies and programs that encourage energy-efficient, climate-smart practices. These efforts also strengthen the sector's resilience to other climate change impacts, helping to position Maine as a leader in sustainable seafood production.

This report supports many of the recommendations in the 2024 update to *Maine Won't Wait: A Four-Year Climate Action Plan* and the *2025 Plan for Infrastructure Resilience*, produced by the Infrastructure Rebuilding and Resilience Commission. Island Institute highlights specific opportunities closely aligned with these plans and offers meaningful benefits to the sector.

Methodology

To understand the GHG emissions associated with Maine's seafood sectors, third-party analyses of businesses were conducted using standardized lifecycle accounting protocols to quantify carbon emissions across every major stage of production—from bait sourcing and vessel fuel use to processing, storage, and distribution.

While the businesses studied—Luke's Lobster, Bangs Island Mussels, Atlantic Sea Farms, Mook Sea Farm, Deer Isle Oyster Company, Bombazine Oyster Company (formerly Ferda Farms), and Pemaquid Oyster Company—are leaders in their respective fields, the goal was not to produce industry-wide averages. Instead, these businesses served as illustrative case studies, offering a real-world snapshot of emissions sources and reduction opportunities.

Data was collected directly from the companies and supplemented with interviews, site visits, and operational records. Upstream and downstream impacts, such as aquaculture seed production, fuel sourcing, and product distribution, were also modeled where possible. All GHG analyses in these reports follow the steps and guidelines as defined by the International Organization for Standardization (ISO) standards. Results are presented in accordance with ISO standards and categorized based on the GHG Protocol Corporate Accounting and Reporting Standards. Each case study reflects the best available data from a specific point in time and is intended to inform—not define—sector-wide practices.[i] Importantly, all of the findings, connections, and recommendations in these reports are based on analyses of seafood businesses and are meant to be illustrative examples. They are not assumed to be representative of their entire respective seafood industry.

i Three separate consultants were used across the reports. While all followed standard GHG protocols, some differences in approach were inevitable.

WHAT'S AT STAKE

Natural resource-dependent businesses like fishing, aquaculture, and other marine-based industries are particularly vulnerable to climate and environmental changes that could significantly impact Maine's economy. Maine's seafood sector alone contributed over $3.2 billion dollars in total economic input to the Maine economy in 2019 and employed more than 34,000 people, but this sector and the jobs it supports is currently facing many harmful impacts from ocean climate change.[ii]

The seafood sector is at the onset of a once-in-a-century energy transition as it looks for ways to decarbonize through electrification, low-carbon fuels, optimization tools, and efficiency technologies.[iii] If Maine is to meet its climate goals, and we are to avoid the worst impacts of change in all sectors, including the marine sector, we must drastically reduce emissions.[iv] By drastically reducing emissions, we will be less vulnerable to environmental and economic risks.

EXECUTIVE SUMMARY

Maine's coastal communities are facing rising seas, stronger storms, aging infrastructure, and increasing energy costs. These challenges threaten not only individual businesses, but the viability of Maine's iconic working waterfronts and the greater marine economy.

At the heart of this effort is a systems-level challenge: How can we sustain and grow Maine's marine economy while modernizing infrastructure, reducing emissions, and increasing resilience—especially when time, funding, and capacity are in short supply?

Drawing on a long history of working directly with community leaders and business owners, Island Institute commissioned a series of GHG analyses to measure the carbon footprint of key seafood supply chains. The goal of these studies is two-fold: first, to assess options that enable seafood businesses to reduce emissions, lower operating costs, and adapt to changing climate and market conditions; and second, to identify practical solutions—supported by illustrative case studies and quantified results—and highlight clear opportunities to implement state-level policies and programs that promote energy-efficient, climate-smart practices.

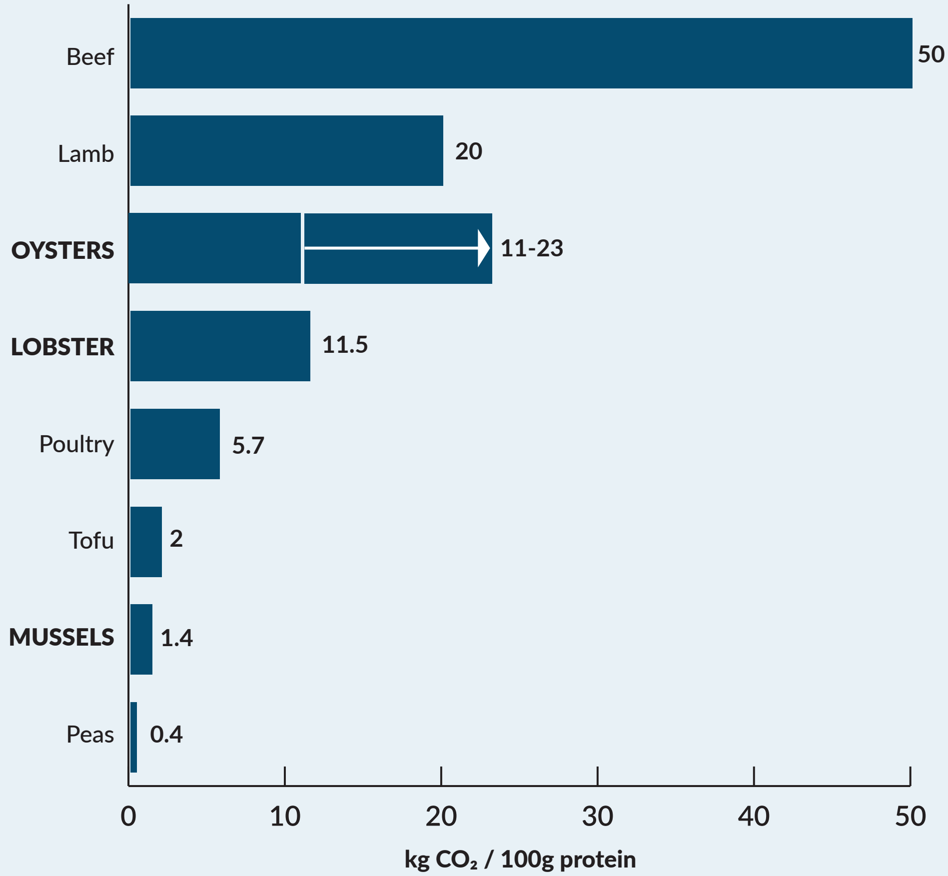
The findings are clear: Maine seafood is already among the lowest-carbon protein sources available (Figure A). At the same time, meaningful opportunities exist to reduce emissions for businesses operating on the front lines of climate change.

Clean energy and decarbonization efforts bring co-benefits to the seafood sector. Through GHG emissions reductions, marine businesses can reduce their contribution to global climate change, a key driver in business uncertainty. Reducing emissions also stabilizes or lowers operating costs, allowing businesses to reinvest in resilient business operations.

Strategic investments—especially in the electrification of work boats and associated shoreside charging and clean energy infrastructure—can significantly cut emissions, lower long-term operating costs for businesses, and strengthen Maine's leadership in sustainable food production. For example, replacing a single 100-horsepower, four-stroke internal combustion outboard engine with an equivalent power electric outboard motor would reduce operations emissions by 11–16 metric tons per year.[v]

ii SEA Maine Roadmap
iii https://www.energy.gov/eere/maritime-decarbonization
iv *Maine Won't Wait Climate Action Plan*
v Estimation based on calculations of real-world electrification projects implemented by Island Institute with partner businesses.

Figure A. Results from GHG assessments of Maine seafood businesses compared to common land-based protein sources.[vi]



Each report underscores the opportunity for targeted investments in this sector to help businesses take advantage of existing State and Federal programs that can reduce emissions in the building envelope and in the transportation sector. These reports also highlight the importance of continued data collection and piloting ways to reduce on-the-water emissions. Cutting emissions through efficiency measures that reduce the need for energy, in any form, results in lower operational costs. For example, phase change materials can help reduce demand from the electrical grid during peak demand hours, reducing costs for the business, and helping to reduce emissions and stress on the grid. In Maine, the mix of electricity on the grid is relatively clean, making the shift from fossil fuels to electricity a cost-effective, climate friendly strategy.

This report offers a path forward. With deeper collaboration, targeted investment, and shared innovation, we can turn these findings into real-world projects that secure Maine's working waterfronts and shape a resilient, sustainable marine economy—one that can serve as a national model.

vi These findings reflect only the results from Island Institute's commissioned studies of individual seafood businesses. They have not undergone third-party verification and should not be used for marketing purposes.

Shared Findings

These in-depth analyses, covering seven Maine seafood businesses, indicate highest emissions in the following three areas:

- Fossil fuel use on fishing and aquaculture vessels.
- On-shore energy consumption for the built environment, including heating, drying, refrigeration, freezing, and hatchery operations.
- Land-based transportation and distribution impacts emissions directly or indirectly for all aspects of business operations. Emissions from distribution activities are highly variable depending on distance covered and distribution method.

Recommendations for Business

- Transition on-land medium-and heavy-duty vehicles, as well as on-the-water vessels, to non-fossil fuel-based energy sources (i.e., electric and hybrid vehicles and vessels).
- Increase charging infrastructure located at or near the water's edge to accommodate vehicle and vessel electrification.
- Improve operational efficiency through process optimization and smart technologies to reduce run time in daily farming operations.
- Improve operational efficiencies on the shore-side processing and handling facilities to lower energy use, GHG emissions, and operational costs.
- Improve crop yields and minimize waste by upgrading farming gear and on-the-water processing equipment.

RECOMMENDATIONS FOR POLICY AND STATE PROGRAMS

Proven solutions exist to tackle some of these high emission areas, while also delivering long-term financial benefits to Maine's seafood businesses. As with many energy efficiency-related improvements, these solutions may require upfront capital costs to see a longer-term shift in operating costs. While existing statewide incentive programs for energy efficiency upgrades and clean energy transition can support this work, there is an opportunity to expand these programs to meet and improve the efficiency of building and shoreside transportation needs for the seafood sector. Tailoring communication and outreach about these opportunities to individuals who work in the working waterfront and on the water could accelerate energy efficient and clean energy adoption and reduce emissions in the sector.

At the same time, emerging technologies—particularly related to transitioning marine work boats from fossil fuels to electric propulsion—hold significant promise and merit further exploration. Electric outboards are currently being piloted by members of the aquaculture industry, and this technology continues to show promise for reducing operational cost and carbon emissions. Using the existing statewide incentive programs as models could help incentivize and de-risk the adoption of newer technologies critical to the transition away from fossil fuels.

These recommendations align with statewide priorities outlined in both the updated *2024 Maine Won't Wait: A Four-year Climate Action Plan*, as well as the *2025 Plan for Infrastructure Resilience*. In many cases, these recommendations reinforce or expand goals already established by the State.

The Infrastructure Rebuilding and Resilience Commission 2025 report outlines recommendations to protect infrastructure, including working waterfronts, from elevated storm impacts related to climate change. The *Maine Won't Wait* plan underscores the importance of helping businesses with clean energy solutions. As noted in the plan: "[making businesses more climate friendly can save on both operating costs and emissions" and we need to "[h] elp Maine businesses and other entities take advantage of electrification, efficiency, electric vehicle, and clean-manufacturing business incentives and recognize exceptional efforts."[vii]

Many seafood businesses, however, lack the time, resources, and technical expertise to implement these solutions on their own. Successfully implementing these recommendations will require substantial capacity-building and technical support from organizations within the sector. With the right assistance at a state-wide scale, Maine's seafood businesses can modernize their infrastructure, lower emissions, enhance resilience, and ultimately strengthen and grow the state's marine economy.

Specific recommendations include:

- Increase awareness and uptake of existing programs, particularly Efficiency Maine Trust's Custom Program, to support efficiency upgrades in the built environment by the seafood sector.[viii]
- Assess whether the seafood sector represents a good use case for medium- and heavy-duty vehicle electrification and prioritize this sector for implementation support because of the co-benefits to adaptation for these businesses.[ix]
- Support the collection of data on the performance and long-term cost and emissions reductions of electric and hybrid work vessels through demonstration projects. Use data to expand existing electric vehicle incentives to cover marine vessels and shoreside infrastructure.[x]
- Maintain and increase access to capital—including low-interest loans with flexible terms and other incentives such as tax credits or grants—to help defray the costs of energy efficiency and beneficial electrification upgrades.[xi]
- Support and incentivize businesses to take advantage of behind-the-meter clean energy generation and storage—such as on-site solar panels that power a business directly without relying on the grid.[xii]
- Support research to better understand the use of kelp aquaculture might help capture and store carbon.[xiii]

"Some sectors of Maine's marine economy have electrification and emission reduction opportunities, while others require more innovation and clean-fuel options... Maine and key stakeholders should continue to support innovation and efforts to help commercial marine and small harbor craft adopt electrified propulsion and other low- and zero-emission vessel technologies."

— Maine Won't Wait, A Four-Year Climate Action Plan for Maine, 2024 Update

vii *Maine Won't Wait 2.0* (2024) Strategy D2, pages 93 and 98 (2024)

viii *Maine Won't Wait 2.0* (2024) Strategy B1 - Boost efficiency in commercial and institutional buildings through high-efficiency electric heating and water heating systems, building control technologies, and improvements to building envelopes.

ix *Maine Won't Wait 2.0* (2024) Strategy A2 - By 2028, pilot projects for zero-emission trucks, municipal and school buses, ferries, and boats to demonstrate and evaluate performance, reliability, and cost savings. Develop an incentive program for zero-emission medium- and heavy-duty vehicles.

x *Maine Won't Wait 2.0* (2024) Strategy A2 - By 2028, pilot projects for zero-emission trucks, municipal and school buses, ferries, and boats to demonstrate and evaluate performance, reliability, and cost savings. Develop an incentive program for zero-emission medium- and heavy-duty vehicles.

xi *Maine Won't Wait 2.0* (2024) Strategy C-1 Decrease energy burdens while transitioning to clean energy - Expand financing and ownership models for Maine people and businesses to access clean energy and energy efficiency opportunities.

xii *Maine Won't Wait 2.0* (2024) Strategy C-1 Decrease energy burdens while transitioning to clean energy - Expand financing and ownership models for Maine people and businesses to access clean energy and energy efficiency opportunities.

xiii *Maine Won't Wait 2.0* (2024) Increase the total acreage of conserved natural and working lands in the state to 30 percent by 2030.

A NOTE ON GRID INFRASTRUCTURE

A significant barrier to implementing energy efficiency, clean energy, and future electrification technologies is the current grid condition, including aging infrastructure and energy capacity capabilities. Recommendations in both *Maine Won't Wait* plan and the *Plan for Infrastructure Resilience* highlight the importance of strengthening the resilience of the State's electrical grid. This is especially critical for seafood businesses who operate on the edges of the grid, including working waterfronts and islands. Investing in island and coastal grid infrastructure will contribute to improving reliability and capacity, enabling more businesses to tap into clean, grid-powered energy, and support future community and economic development and resiliency. Expanding power capacity in these remote areas will enable the electrification of equipment and charging infrastructure that requires 3-phase power, a type of electrical power commonly used for large commercial or industrial operations. Only approximately 25% of Maine's coast currently has access to 3-phase power[xiv] Upgrading the infrastructure to accommodate these high-power uses is critical to expand electrification and decarbonization strategies in the seafood sector.

xiv This data comes from a forthcoming shoreside charging infrastructure report comissioned by Island Institute.

ACKNOWLEDGEMENTS

This work would not have been possible without the following funders, seafood businesses, and consultants, whose collaboration was critical for this body of work:

Atlantic Sea Farms	Participating Seafood Business
Bangs Island Mussels	Participating Seafood Business
Bombazine Oyster Company (formerly Ferda Farms)	Participating Seafood Business
Council Fire	Consultant, Luke's Lobster Report
Dana Morse	Darling Marine Center
Deer Isle Oyster Company	Participating Seafood Business
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Luke's Lobster	Participating Seafood Business
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Mook Sea Farm	Participating Seafood Business
Nichole Price	Bigelow Laboratory for Ocean Sciences
Pemaquid Oyster Company	Participating Seafood Business
Pure Strategies	Consultant, Bangs Island Mussels and Atlantic Sea Farms Reports
RISE Research Institutes of Sweden	Consultant, Mook Sea Farm, Bombazine Oyster Company (formerly Ferda Farms), Deer Isle Oyster Company, and Pemaquid Oyster Company Reports
Shane Rogers	Clarkson University
Susan Powers	Clarkson University

EXECUTIVE SUMMARY OF KELP STUDY

Atlantic Sea Farms (ASF) is a women led company located in Biddeford, Maine that grows and processes kelp. In partnership with Island Institute, ASF is interested in better understanding the environmental impact of their farmed kelp, Ready Cut Kelp, and Maine Kelp Powder and how it compares to other kelp. The goal of the study is to calculate the product carbon footprint (PCF) of ASF's farmed kelp, Ready Cut Kelp, and Maine Kelp Powder, and identify hot spots within their production.

Product Carbon Footprint (PCF) is a tool used to quantify environmental impact of a product throughout the entire life cycle, from material extraction, processing, transportation, and end of life. This report contains the full PCF background, methodology, and results documentation for ASF farmed kelp and kelp products as required by ISO 14067:2018(E) Greenhouse Gases - Carbon Footprint of Products - Requirements and Guidelines for Quantification. Results are also presented in alignment with the GHG Protocol Corporate Accounting and Reporting Standards.

Pure Strategies calculated the annual carbon emissions of 571,161 pounds of ASF farmed kelp, 235,034 pounds processed Ready Cut Kelp, 5,760 pounds Ready Cut Kelp distributed, 49,247 pounds processed Maine Kelp Powder, and 5,520 pounds Maine Kelp Powder distributed from cradle to distribution hub for the time period of July 1, 2022 to June 30, 2023. The PCF results are also normalized to 1 pound of ASF farmed kelp, Ready Cut Kelp, and Maine Kelp Powder. This normalized impact is important as not all Ready Cut Kelp and Maine Kelp Powder produced during the study period is shipped out.

The environmental impact is represented by global warming potential (GWP), expressed as kilograms carbon dioxide equivalent (kg CO2e). Greenhouse gas emissions have been calculated for three categories: direct emissions (Scope 1), indirect emissions (Scope 2), and indirect emissions upstream and downstream in the value chain (Scope 3).

RESULTS AND RECOMMENDATIONS

The total study period product carbon footprint is 457,169 kg CO2 for the farming, processing, and storage and distribution of farmed kelp, Ready Cut Kelp, and Maine Kelp Powder. This is equal to 0.14kg

CO2 per pound of farmed kelp, 1.1kg CO2 per pound of Ready Cut Kelp shipped to customers, and 5.7kg CO2 per pound of Maine Kelp Powder shipped to customers. It is important to note that not all Ready Cut Kelp and Maine Kelp Powder are sold during the study period. Study period emissions include those for all processes that occur during the study period; the distribution of unsold Ready Cut Kelp and Maine Kelp Powder will occur in the future and are therefore excluded from the study. The PCF results in Table 1 on the following page are organized by scope and the results in Figure 1 are organized by ASF process, to better understand the drivers of carbon emissions.

Carbon capture within the kelp itself and sequestration in the ocean resulting from kelp growth are excluded from the analysis. All carbon contained in the kelp will be released once the kelp is eaten or disposed, therefore negating any captured carbon. Carbon sequestration in the ocean due to growing kelp is a novel concept with insufficient peer reviewed science to support such a claim. Published studies are of permanent kelp farms rather than those growing kelp for consumption and are not applicable.

Table 1: ASF carbon footprint by GHG Protocol Scope

Scope	Description	Annual Emissions (kg CO2e)	Percent of total
Scope 1 - fugitive	Fugitive emissions from refrigerants during blast freezing and on-site cold storage	37,352	8%
Scope 1 - mobile combustion	Fuel use from ASF owned and rented trucks during kelp farming	5,764	1%
Scope 1 - mobile combustion	Diesel use during 24 hour post harvest refrigeration	359	0%
Scope 1 - mobile combustion	Fuel use from rented trucks for kelp transport to ASF facility	2,914	1%
Scope 1 - stationary combustion	Natural gas used at ASF processing facility	25,557	6%
Scope 2	Electricity use at ASF processing facility	21,166	5%
Scope 3 - Category 1	Consumables used during kelp farming	49,681	11%
Scope 3 - Category 1	Packaging for kelp powder	4,127	1%
Scope 3 - Category 1	Processing for kelp powder	149,943	33%
Scope 3 - Category 1	Packaging for ready cut kelp	2,175	0%
Scope 3 - Category 1	Tap water used for kelp processing	648	0%
Scope 3 - Category 3	Upstream emissions of scope 1 fuel used in kelp farming	858	0%
Scope 3 - Category 3	Upstream emissions of scope 1 and 2 fuel and electricity in kelp processing	14,997	3%
Scope 3 - Category 4	Fuel use by ASF partner farms during kelp farming	21,400	5%
Scope 3 - Category 4	Warehousing for 24 hour cold storage post harvest	25	0%
Scope 3 - Category 4	Upstream transport to and from dehydrators	59,412	13%
Scope 3 - Category 4	Warehousing for off-site storage of kelp powder	194	0%
Scope 3 - Category 4	Upstream transport for rental blast freezer, off-site frozen kelp storage, and distribution of ready cut kelp	12,975	3%
Scope 3 - Category 4	Cold storage of blast frozen kelp processed during study period	26,680	6%
Scope 3 - Category 5	Waste generated during kelp farming	51	0%
Scope 3 - Category 5	Waste generated during kelp processing	18,892	4%

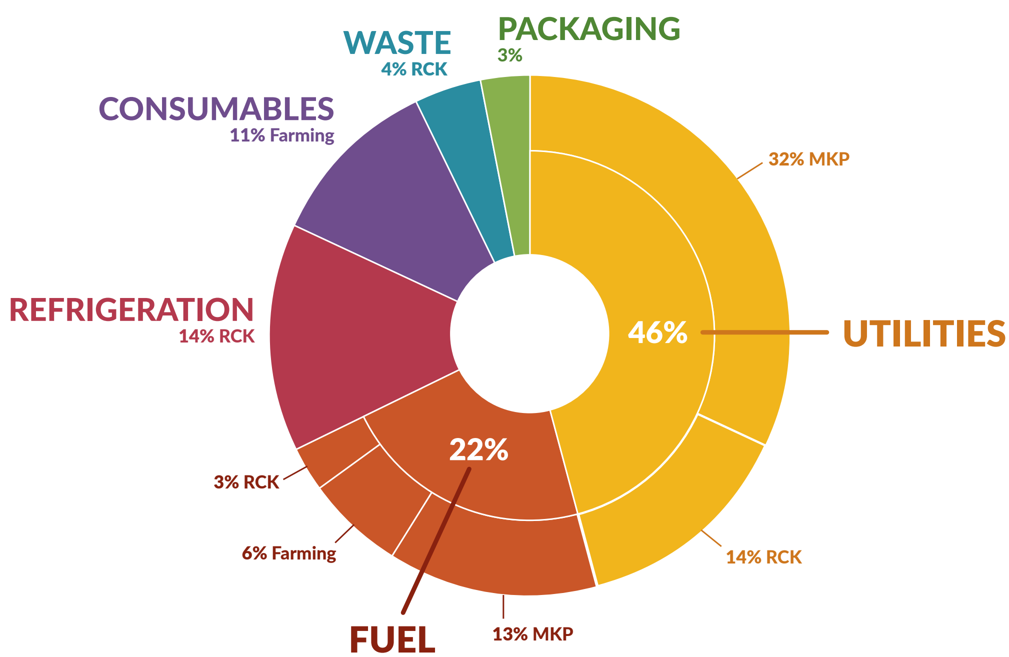

Figure 1.
Process contribution to ASF study period carbon footprint

Fuel use for boat and truck transport throughout the value chain contributes 22% of the PCF. Reducing fuel use across the board by 10% by minimizing idling or increasing efficiency has the potential to save about 10,000kg CO2 annually.

ASF utilities contribute 6% and purchased electricity within the value chain contributes an additional 6% of the carbon footprint. Sourcing renewable energy via renewable energy credits (RECs) has the potential to reduce emissions by about 13,000kg CO2 annually. Increasing to 100% renewable energy has the potential to reduce emissions by about 26,000kg CO2 annually.1 Adopting renewables at ASF partners has a similar impact: adopting 50% renewable energy has the potential to reduce emissions by 14,000kg CO2 and adopting 100% renewable energy has the potential to reduce emissions by over 28,000kg CO2 each year.

Farmed kelp yield has a significant impact on the product carbon footprint. Assuming all farming inputs remain the same, a 20% increase in yield has the potential to save about 13,000kg of CO2 annually, and a 20% decrease in yield has the potential to increase annual CO2 emissions by about 19,000kg. ASF was expecting their yield to be about 56% higher than it was. A 56% increase in yield has the potential to save about 28,000kg CO2 annually. Yielding more kelp with the same amount of resources means the impact per pound will decrease.

Farming consumables contribute 11% of the carbon footprint. Galvanized mooring chains account for half of farming consumable emissions. They have an estimated lifespan of 2.5 – 3.5 years. Increasing the lifespan to 5 and 10 years can save 6,000kg and 10,000kg CO2e, respectively. Investigating other materials that may be more durable and less impactful could reduce emissions further.

The impact of storing more than 295,000 pounds of farmed kelp not processed, unsold Ready Cut Kelp and unsold Maine Kelp Powder produced during the study period is significant, adding 25-45% to the baseline impact. The storage durations are between 19 and 34 months for cold storage of farmed and Ready Cut Kelp and 12 and 34 months for dry storage of Maine Kelp Powder. The short storage durations have an impact of 113,000kg CO2e, or a 25% increase. The long storage durations have an impact of 204,000kg CO2e, or a 45% increase. Prioritize reducing refrigerated storage as it has 19.5 times more carbon emissions than unrefrigerated storage for the same duration and mass and there is 6.6x more inventory in refrigerated storage than unrefrigerated storage.

Storing harvest kelp prior to processing offsite for 19 months rather than 30 reduces the Ready Cut Kelp product footprint by 7%. Reducing storage time from 30 months to 19 months saves over 12,500kg CO2e per year. Each additional month of off-site cold storage of harvested kelp processed during the study period results in ~1,000 kg CO2e. Each additional month of off-site dry storage of sold MKP results in 11 kg CO2e.

Prioritize reducing refrigerated storage times at ASF and partners over unrefrigerated storage. Refrigerated storage of farmed kelp and Ready Cut Kelp has 19.5 times more carbon emissions than unrefrigerated storage of Maine Kelp Powder for the same duration.

Adoption of key interventions can reduce ASF's carbon footprint by 37%. The biggest reduction opportunity is processing all Maine Kelp Powder using electricity instead of directly using fossil fuels. This intervention alone can reduce the annual impact by 18%. Furthermore, adopting 100% renewable energy at ASF facilities and within their value chain has the potential to decrease annual emissions 11%. A best-case scenario assumes 100% adoption of all interventions outlined in Figure 2.

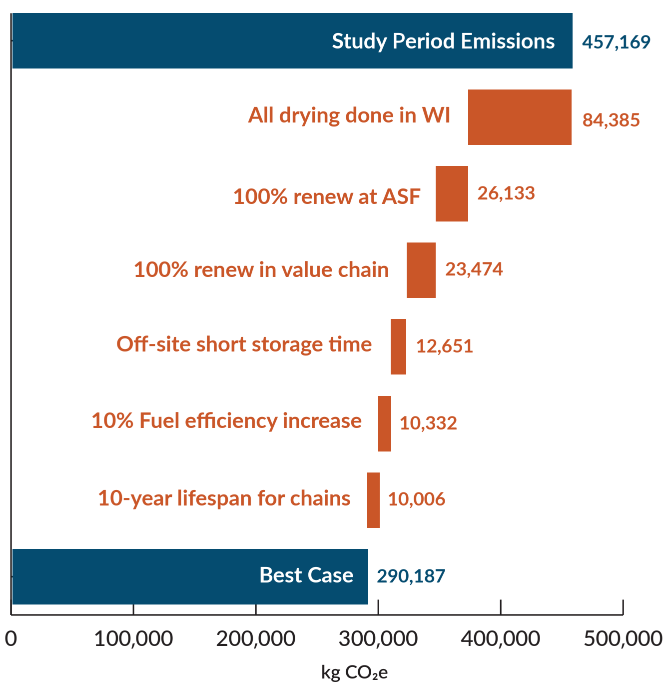

Figure 2.
Sensitivity analysis results of key interventions

BACKGROUND

In 2009, Atlantic Sea Farms (ASF) created the first commercially viable seaweed farm in the US, with the goal of diversifying how our coastal waters are used and provide a domestic, fresh, healthy alternative to imported seaweed products. Climate change is affecting coastal communities in the US and ASF provides a new way for fishing families to work on the water while improving the health of our oceans. ASF's partner farmers are all lobstermen, facing direct and current impacts of climate change daily, so it is in their interest to reduce greenhouse gas emissions as much as possible. Sustainability is a cornerstone of ASF's business model and central avenue toward growing their customer base.

ASF in partnership with Island Institute is interested in better understanding the environmental impact of their farmed kelp and kelp products. It is well known that agriculture is estimated to contribute 30% of total greenhouse gas (GHG) emissions.[2]

Pure Strategies worked with ASF to calculate the product carbon footprint of their blanched kelp. Kelp is farmed in Maine and Rhode Island by lobstermen; processed by ASF in Biddeford, Maine; stored; and transported to a distribution hub in Boston. A portion of the farmed kelp is also shipped offsite to be dried and stored. Product carbon footprint is calculated for farmed kelp, processed kelp, and dried kelp, expressed as mass carbon dioxide equivalent (CO2e). ASF's fermentation process and products are excluded from the analysis.

Pure Strategies calculated the life cycle carbon emissions of all kelp harvested in 2023 and all Ready Cut Kelp and Maine Kelp Powder sold in 2023 from cradle to distribution hubs and normalized those results to one pound. The environmental impact is represented by global warming potential (GWP), expressed as kilograms carbon dioxide equivalent (kg CO2e).

Product carbon footprint is a tool used to quantify the carbon impacts of a product, holistically, throughout the entire life cycle; from material extraction, manufacturing and assembly, packaging, transportation, use, and end of life. The impacts associated with the product are assessed by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to help make a more informed decision. This product carbon footprint was conducted using product specific primary data provided by Atlantic Sea Farms (ASF), secondary material and process inputs and outputs from the ecoinvent database, and carbon dioxide emissions using IPCC GWP 100yr methodology, literature, and the EPA Emission Factors Hub.

Product carbon footprint (PCF) is a tool used to quantify the carbon impacts of a product, holistically, throughout the entire life cycle, from material extraction, manufacturing and assembly, packaging, transportation, use, and end of life. The impacts associated with the product are assessed by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to help make a more informed decision. This PCF was conducted using product specific primary data provided by ASF (e.g. consumables, energy and fuel use, waste streams, etc.), secondary material and process inputs and outputs from the life cycle assessment databases, literature, EPA Emissions Hub, and Intergovernmental Panel on Climate Change (IPCC) 2021 GWP100 impact assessment method, using SimaPro LCA software.

The most widely recognized standardized guidelines for PCF have been developed by the International Organization of Standardization (ISO). This report contains the full PCF background, methodology, and results documentation for ASF kelp as required by ISO 14067:2018(E) Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification, and also aligns with ISO 14040:2006(E) Environmental management – life cycle assessment – principles and framework and ISO 14044:2006(E) Environmental management – life cycle assessment – requirements and guidelines.

GOAL

This study was prepared for Island Institute and ASF. The overall goal of the PCF is to calculate the potential contribution of ASF's kelp to global warming, expressed as carbon dioxide equivalents (or CO2e) by quantifying all significant greenhouse gas emissions throughout the kelp farming, processing, and storage and distribution processes.

The study aims to (1) calculate the PCF of ASF farmed kelp and (2) identify hot spots within their product supply chain.

This report is compliant with ISO standards 14040, 14044, and 14067, the standards for life cycle assessment and product carbon footprint and aims to objectively present results and conclusions of the PCF with transparency, outlining the methodology, assumptions, and limitations accordingly. The PCF of ASF kelp is intended to be used by Island Institute and ASF for business purposes and customer communication, in alignment with ISO 14026 Environmental Labels and Declarations.

SCOPE

This section defines the products included in the study, the system boundaries, and modeling methodology.

FUNCTIONS AND FUNCTIONAL UNIT

The study period is July 1, 2022 through June 30, 2023, with data provided by ASF for all operations during this time period. The functional unit is 571,161 pounds of farmed fresh kelp, 5,760 pounds of Ready Cut Kelp sold, and 5,520 pounds of Maine Kelp Powder sold during the study period. Scope includes farming off the coast of Maine, processing at an ASF and contract facilities, storage at ASF and contract facilities, and transport to distribution hubs. Impacts at retail and transport to the end customer are excluded from the scope. ASF produces fermented kelp products, kelp cubes, and kelp burgers, which are outside the scope of the study.

Annual carbon emissions are normalized to one pound of farmed kelp, one pound of Ready Cut Kelp, and one pound of Maine Kelp Powder.

LIMITATIONS

As with any PCF, there are limitations on how the results should be used. Results should not be considered the only source of environmental information relating to a product or process. There are limits to data quality, especially for production of upstream materials, where information may vary widely.

The life cycle impact assessment results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. This product carbon footprint is only representative of kelp grown off the coast of New England, processed by Atlantic Sea Farms, and transported to distribution hubs. This study is not intended to be representative of all kelp farmed globally or in the US as data may vary significantly with the farming process and yield. It is not intended to be representative of the entire kelp industry.

BOUNDARY AND DATA SOURCES

This section gives an overview of the operations included in the study, details of the processes included and excluded from the scope of the study, and the data sources.

SYSTEM BOUNDARY

The study is cradle to gate and the system boundary includes kelp farming, pre-processing and processing at ASF of fresh kelp, offsite and onsite cold and non-cold storage, and offsite drying of kelp.

The flow of kelp from farming through the production and distribution of Ready Cut Kelp and Maine Kelp Powder is complex. The sections below give an overview and system boundaries, along with transport and cold storage duration values. The Data summary and sources section includes locations, kelp calculations, and data and emission factor sources.

Kelp farming process overview

Kelp is grown off the coast of Maine by ASF partner farmers. ASF collects sorus, the spores needed to grow kelp, via boat. ASF partner farmers cultivate and harvest kelp using lobster boats. About 50% of the harvest is transported directly from the wharf to ASF or a dehydrator for further processing. Another 25% of the harvest is stored in cold storage for 24 hours prior to transport to ASF and dehydrators and another 20% of the harvest is kept in a cold storage trailer for 24 hours prior to transport to ASF and dehydrators. The remaining 2% of harvest is sent offsite to a drying trial; the transport and impact of the trial is excluded from the analysis.

Ready Cut Kelp process overview

Figure 4 on the following page shows the Ready Cut Kelp process and storage and distribution boundaries. About 17% of fresh kelp is transported from the wharves to ASF. While more than 50% of all fresh kelp goes through Mussel Farm Road, data on the amount of fresh kelp from MFD and PFE is unknown, so it is assumed that half of the total kelp transported to ASF is from each landing location.

At a pre-processing step at ASF, a portion of fresh kelp is blast frozen at ASF and trucked offsite for cold storage. This transport and storage duration is outside the scope of the study as that kelp is processed in the future.

During the processing step, frozen kelp that has been in cold storage for an average of 30 months is trucked to ASF and combined with the remaining fresh kelp. Kelp is washed, shredded, blanched, packed into 55 gallon drums, and blast

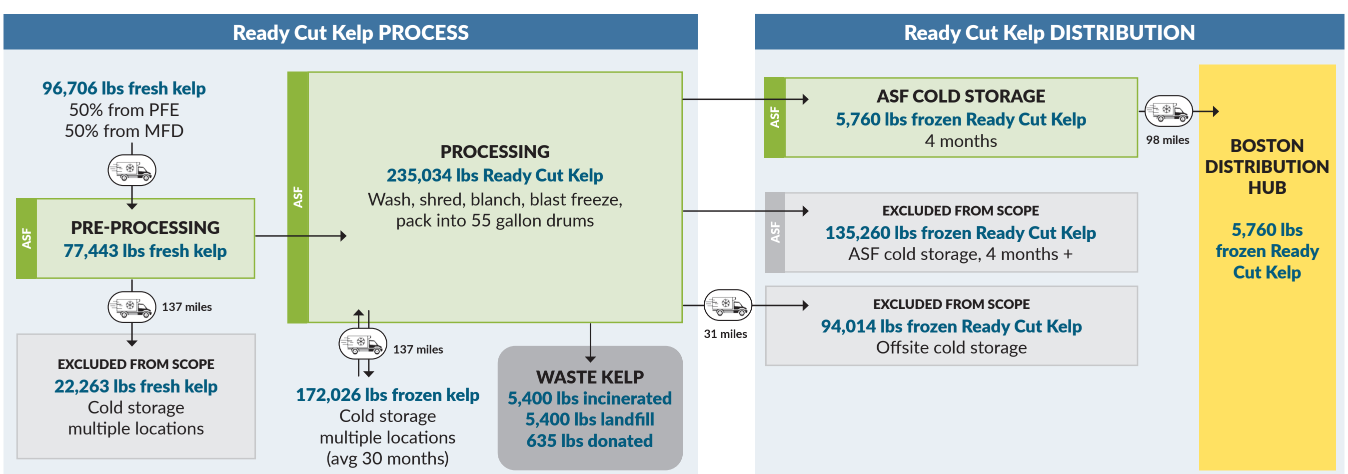

Figure 4.
Ready Cut Kelp system boundaries

frozen. Waste kelp resulting from the processing step is trucked offsite to be landfilled, incinerated, and donated. Once processed, kelp is now Ready Cut Kelp.

A portion of Ready Cut Kelp is shipped offsite for long term cold storage and transport and storage impacts are outside the scope of the study as that frozen kelp will be sold in the future. The remaining frozen Ready Cut Kelp is stored at ASF. Ninety five percent of the frozen Ready Cut Kelp stored at ASF is not sold during the study period, and while this should be excluded from the scope, ASF does not have insight into how much energy is used for storage specifically. Therefore, energy to store all Ready Cut Kelp at ASF is included in the scope. The remaining 5% of frozen Ready Cut Kelp stored at ASF is trucked to Boston for further distribution.

Maine Kelp Powder process overview

Figure 5 on the following page shows the Maine Kelp Powder process and storage and distribution boundaries. About 83% of fresh kelp is transported from the wharves to two dehydrators for processing. At the dehydrators, fresh kelp is dried, milled, and packaged, becoming Maine Kelp Powder.

The majority of Powder is shipped to an offsite warehouse and a small portion is shipped to ASF for storage. At the offsite warehouse, a large portion of the Powder is not sold during the study period, and the storage impacts are excluded from the analysis. Sold powder is stored at the offsite warehouse for an average of 18 months, then is shipped to ASF for storage. At ASF, about half of the Powder is not sold during the study period, and while storage impacts should be excluded from the scope, ASF's energy bill covers their entire facility, so energy needs for Powder storage at ASF cannot be parsed out, and is therefore included in the analysis. The sold portion of Powder is stored at ASF for 24 months prior to sale. Powder is then shipped to Atlanta and Chicago for distribution.

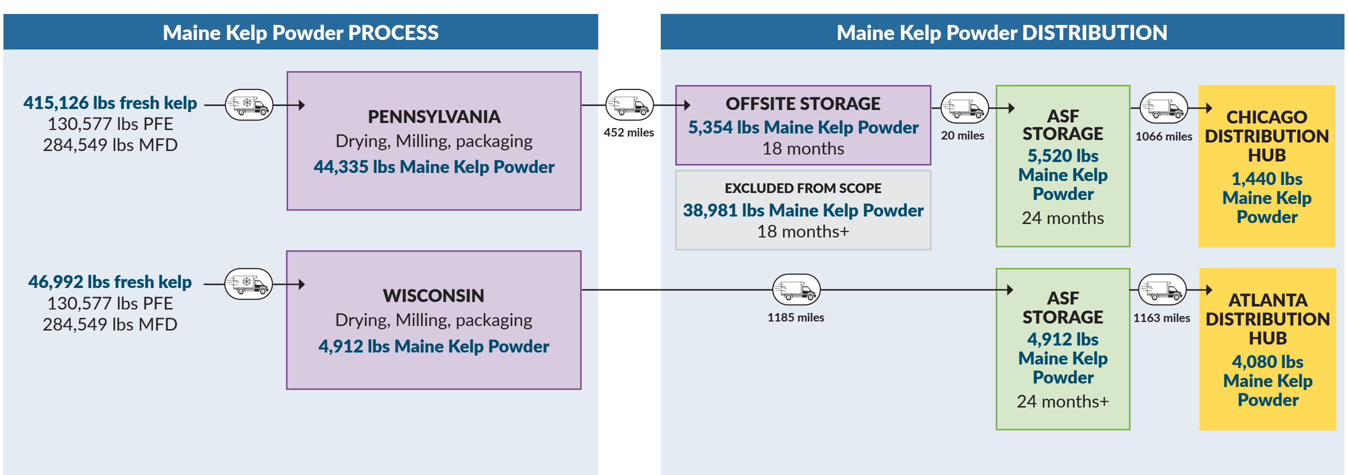

Figure 5.
Maine Kelp Powder system boundaries

DATA SUMMARY AND SOURCES

The amount of kelp processed throughout the supply chain is determined by a combination of ASF records and calculations, as shown in Table 2.

Table 2: Kelp mass and source throughout the supply chain

Step	Amount (lbs)	Data Source	Abbreviation	Equation
Farmed kelp yield	571,161	ASF provided	FY	none
Farmed kelp transported directly to ASF & dehydrator	307,353	ASF provided 55% of total harvest	FT	FT = FY * 55%
Farmed kelp in cold storage building for 24 hrs	139,706	ASF provided 25% of total harvest	FCB	FCB = FY * 25%
Farmed kelp in cold storage trailer for 24 hrs	111,765	ASF provided 20% of total harvest	FCT	FCT = FY * 20%
Fresh kelp transported to ASF	96,706	ASF provided	FTASF	none
Fresh kelp transported to dehydrators	130,577 ME to PA 26,680 ME to WI 284,549 ASF to PA 20,312 ASF to WI	ASF provided	FTD	none
Frozen kelp at ASF trucked to offsite cold storage	22,263	ASF provided; transport & cold storage impacts outside of the scope & excluded from the analysis	FOE	none
Fresh kelp processed at ASF	77,443	Calculated	FPA	FPA = FTASF – FOE
Frozen kelp at offsite cold storage from prior year's harvest trucked to ASF for processing	172,026	Calculated	ZOP	ZOP = RCK – FPA – WPA
Waste kelp from ASF processing	11,435	ASF provided monthly estimates of 900 lbs each to incineration & landfill ASF provided 635lbs donated	WPA	WPA = (12 mo/yr*(600lbs incinerated + 600lbs landfilled)) + 635lbs donated
Ready Cut Kelp produced at ASF	235,034	ASF provided	RCK	none
Ready Cut Kelp stored at ASF	141,020	ASF estimates 60% of Ready Cut Kelp produced	RCA	RCA = RCK * 60%
Ready Cut Kelp stored offsite	94,014	ASF estimates 40% of Ready Cut Kelp produced	RCO	RCO = RCK * 40%
Maine Kelp Powder yield from PA Dehydrator & WI Dehydrator	49,247	ASF provided	MKP	none
Maine Kelp Powder stored at ASF	1,477	ASF estimates 3% of Maine Kelp Powder produced	MKPA	MKPA = MKP * 3%
Maine Kelp Powder stored at NEPW	47,770	ASF estimates 97% of Maine Kelp Powder produced	MKPO	MKPO = MKP * 97%
Maine Kelp Powder distributed from ASF to Chicago	1,440	ASF provided number of trips per month and mass of MKP per trip from ASF to Chicago and these are used to calculate mass	PAC	PAC = 40lbs per month * 3 trips per month * 12 months per year
Maine Kelp Powder distributed from ASF to Atlanta	4,080	ASF provided number of trips per year and mass of MKP per trip from ASF to Atlanta and these are used to calculate mass	PAA	PAA = 1020lbs per trip * 4 trips per year
Maine Kelp Powder distributed in the study period	5,520	Calculated	MKD	MKD = PAC + PAA

Input and emission factor sources vary, based on the availability of data and best fit sources. Table 3 is a summary of all data included in the analysis.

Table 3: Data and emission factor sources summary

Process	Sub-process	Input data source	Emission factor source(s)
Kelp farming	Consumables	Mass & material type from ASF purchasing records Manufacturing processes assumed by Pure Strategies based on material and function	Material & manufacturing process- DataSmart, Ecoinvent, USLCI, World Food LCA Databas
Kelp farming	Fuel use	Boat fuel use from ASF purchasing records Facility addresses provided by ASF Ferry transport from Casco Bay Island Transit Lobster gallons fuel use from partner farms Tanker truck emissions data from literature Travel distances from google maps Truck fuel use from ASF purchasing records	Material – DataSmart, ecoinvent, literature Combustion – EPA Emission Factors Hub
Kelp farming	Refrigeration	Mass of kelp & duration provided by ASF records	Energy – Ecoinvent, US EPA eGRID2021 subregion specific emission factor
Kelp farming	Waste	Amount & disposition provided by ASF records	Waste treatment & disposal – ecoinvent
Ready Cut Kelp production	Fuel use	Facility addresses provided by ASF Estimated percent of Ready Cut Kelp stored offsite (40%) & at ASF (60%) provided by ASF Kelp inventory levels provided by ASF & used to calculate weighted average transport distance for frozen kelp to and from offsite cold storage to ASF Travel distances from Google Maps	Material & combustion – DataSmart & ecoinvent
Ready Cut Kelp production	Packaging	Manufacturing processes assumed by Pure Strategies based on material and function Mass & type of material from ASF purchasing records	Material & manufacturing process - DataSmart, ecoinvent, USLCI
Ready Cut Kelp production	Refrigeration	Energy and refrigerant for offsite cold storage calculated by Pure Strategies using literature data, calculated amount of kelp processed from offsite cold storage, and capacity of one offsite cold storage facility Refrigerant recharge at ASF provided by purchasing records	Refrigerant – ecoinvent, EPA Emission Factors Hub Energy – US EPA eGRID2021 subregion specific emission factor
Ready Cut Kelp production	Utilities	ASF diesel used in the onsite cooler trailer for 6 weeks from diesel delivery bills ASF electricity usage during the study period from ASF energy bills and ASF electrician estimated allocation to fermentation, cooler, freezer, and processing ASF natural gas usage during the study period from ASF energy bills Facility addresses provided by ASF	Combustion – EPA Emission Factors Hub Energy – DataSmart, US EPA eGRID2021 subregion specific emission factor
Ready Cut Kelp production	Waste	ASF monthly kelp waste generation from employee estimate ASF total of all waste sent to treatment from waste hauler bills ASF total of all recycling sent offsite from waste hauler bills 80% non-kelp & non-recyclable waste sent to landfill & 20% incineration based on US EPA Municipal Waste Statistics Amount of wastewater sent to offsite treatment assumed equal to process water	Waste treatment & disposal – DataSmart, ecoinvent
Maine Kelp Powder production	Fuel use	Number of trips and mass of kelp per trip to/from ASF and dehydrators provided by ASF Mass of kelp from wharves to dehydrators, dehydrators to ASF, and ASF to distribution provided by ASF Facility addresses provided by ASF Travel distances from Google Maps	Combustion – ecoinvent, USLCI

Process	Sub-process	Input data source	Emission factor source(s)
Maine Kelp Powder production	Packaging	Mass & material type from ASF and dehydrator purchasing records Manufacturing processes assumed by Pure Strategies based on material and function	Material & manufacturing process- DataSmart, ecoinvent
Maine Kelp Powder production	Utilities	Dehydrator processing electricity and diesel provided by WI & PA Dehydrators Warehouse storage allocated to ASF provided by NEPW & literature used to calculate propane used for heating Facility addresses provided by ASF	Energy – ecoinvent, US EPA eGRID2021 subregion specific emission factor, USLCI

Data uncertainty

Data for ASF farming represents the 2023 farming and harvest season only. Kelp farming yield fluctuates year over year and this dataset only considers one growing season. Past and future seasons are expected to differ from the data presented in this study. It is difficult to understand how inputs will change with yield, though the relationship is not expected to be linear for all farming inputs, as the same amount of many consumables and boat trips will be needed regardless of yield. It is recommended that additional years of data are collected to increase the precision and representativeness of ASF's operations.

Kelp cold storage durations can vary dramatically. Average cold storage durations have been used in the baseline analysis, and the low and high duration times have been tested via sensitivity analysis.

ASSUMPTIONS

Not all data was available to complete the analysis; therefore, some assumptions and surrogate data were required. Details of assumptions are found in section Inventory data and footprint and their impact on the results are discussed in section Sensitivity analyses & recommendations.

It's important to note that a portion of kelp grown during the study period is blast frozen and trucked offsite for long term cold storage and not processed during the study period. This storage duration is outside the scope of the study. At the same time, kelp that was farmed 30 months ago and stored offsite in cold storage for that duration is trucked to ASF for processing. The cold storage for this portion of kelp is included in the scope. As data for farming and cold storage of kelp 30 months ago is not available, it is assumed that farming and cold storage data for the study period is representative of past farming and cold storage data. The farming process itself has not changed in the last 30 months, though yield has fluctuated.

SENSITIVITY ANALYSIS

Sensitivity analyses were performed for the results in order to determine if data assumptions significantly impact the results. Detailed results of the sensitivity analyses are included in Sensitivity analyses & recommendations.

CUT-OFF CRITERIA

The system boundary includes all life cycle stages and materials included in the scope.

ALLOCATION PROCEDURES

Allocation is required when a product system produces multiple products or where inputs are used across product lines and processes. At ASF, allocation is needed to assign impact for utilities, as electricity and natural gas are used for multiple product lines and processes at ASF.

Utilities at ASF include electricity and natural gas for washing, shredding, and blanching kelp (processing kelp for the Ready Cut Kelp product); fermentation for products outside the scope of the study; cold storage; as well as energy needed for typical office tasks including computers, lighting, restrooms, etc. ASF is located in a shared facility without separate metering and is charged a consistent percentage of the electricity usage, for a total of 260,000 kwh during the study period. ASF's electricity estimates the breakdown to be 11,000kWh for fermentation, 20,000kWh for the cooler, 200,000 kWh for the freezer, and the remaining 29,000 kWh for washing, blanching, and office needs. As fermentation is outside the scope of the analysis, those 11,000kWh electricity are excluded from the analysis.

DATA QUALITY

This section outlines the data quality requirements, as specified by ISO 14044 section 4.2.3.6.2 and ISO 14067 section 6.3.5.

Time related coverage

Time related coverage describes the age of data and the minimum length of time which data was collected. All data was collected during the study period, July 1, 2022 through June 30, 2023, and represents the impact of 2023 farming, processing, and drying. All data provided by ASF and its partners, including cold storage facilities and dehydrators, is for the study period. Cold storage durations (low, average, and high) are based on ASF historical data. The average durations are used in the baseline inventory, and the impact of the high and low durations are included as a sensitivity analysis.

Geographical coverage

Geographical coverage describes the geographic area from which unit process data is collected for the study. All data is provided directly by ASF and its partners and represents the locations where processes are occurring. US EPA eGRID2021 regional specific emissions factors for electricity generation were used to calculate emissions for ASF, cold storage locations, and dehydrators. Most of the ecoinvent and DataSmart datasets are US data; European datasets are used when US data is not available.

Technology coverage

Technology coverage describes how well the data set used to develop the LCA model represents the true technological characteristics of the system. Materials and processes were identified through ASF specifications and discussions with ASF. Materials were mapped to ecoinvent and DataSmart processes and surrogate materials were used where material specific data was not available, transport emissions were mapped to the EPA Emissions Factors Hub, and electricity usage was mapped to eGRID2021 data.

Precision

Precision is the measure of the variability of the data values for each data category. Precision cannot be measured as only one data set was provided. Kelp farming yield fluctuates year over year and this dataset only considers one growing season. Past and future seasons are expected to differ from the data presented in this study.

Completeness

Completeness measures the percent of primary data collected and used for each category in a unit process. Consumables for kelp farming and processing, fuel usage on lobster boats, and kelp yield was collected from farmers and provided by ASF. ASF electricity, natural gas, and water use was collected via provider bills and allocated based on expert judgement at ASF. Cold storage and warehouse energy use at offsite facilities was calculated based on literature values as facility data was not available. Transport distances to and from ASF, processors, and cold storage are based on facility locations. Transport trips and mass per trip were provided by ASF. Energy for dehydrating kelp was provided directly by WI and PA dehydrators. In most cases, ecoinvent or DataSmart data was used to represent impacts from material production, assembly processes, use energy, distribution, and end of life. EPA Emission Factors Hub emission data was used for calculating the impact of transportation. Literature data was used to calculate the electricity and refrigerant recharge for cold storage.

Representativeness

Representativeness is the assessment of how the data set used in the LCA model reflects the true system. Data reflects ASF and partner operations during the study period and is considered representative of the study period and 2023 farming, harvest, and processing year.

Consistency

Consistency considers how uniformly the study methodology is applied to the various components of the analysis. The methodology was applied to all components of kelp farming and processing consistently, in terms of modeling and assumptions.

Reproducibility

The LCA modeling has been performed and described such that this LCA could be reproduced by another LCA practitioner. This report contains all life cycle inventory data and all assumptions used to calculate the environmental impact of the kelp farming, processing, and drying operations during the study period.

METHODS AND RESOURCES

This section describes the emissions included in the PCF, methodologies used to calculate emissions, and emission factor data sources.

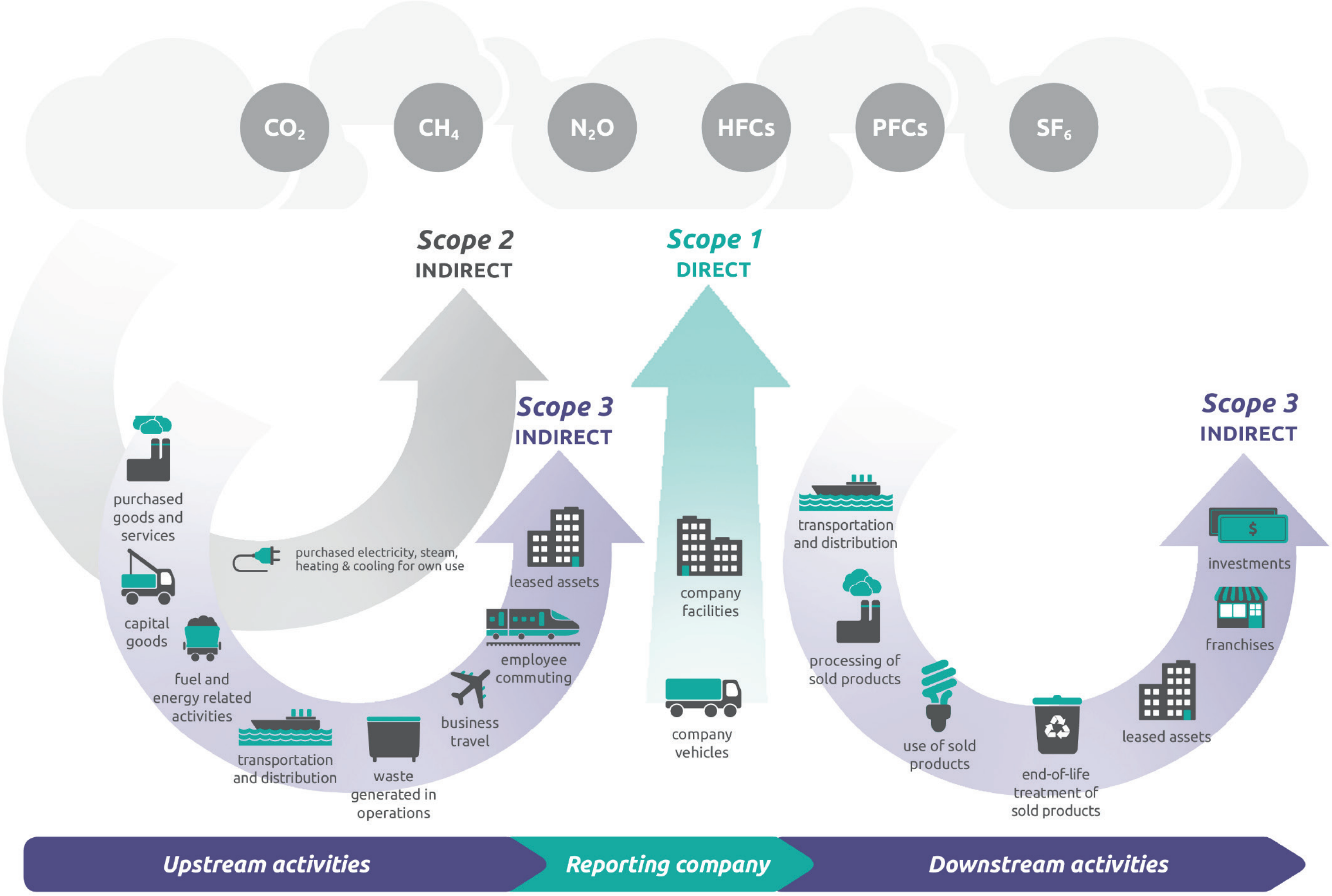

Figure 6.
Overview of GHG Protocol scopes and emissions across the value chain
(WRI, wbcsd. Corporate Value Chain (Scope 3) Accounting and Reporting Standard. Figure 1.1)

EMISSIONS BY SCOPE

The GHG Corporate Standard categorizes a company's direct and indirect emissions into three scopes, as outlined in Figure 6. Scope 1 emissions relate to a company's direct emissions from facilities or equipment owned or controlled by the reporting company. Scope 2 emissions include the indirect emissions from the generation of purchased energy used by the reporting company, most commonly electricity. Scope 3 emissions encompass all other indirect emissions that occur within a company's value chain and are categorized into 15 distinct categories for reporting purposes.

Table 4 provides an overview of the scopes included in this study. The scope of the study is cradle to gate. This includes fuel use from ASF and partner farm boats, refrigeration and energy at ASF and contract facilities, consumables, packaging materials, truck transport by vehicle, and waste generated in operations. For PCFs, capital equipment (e.g., trucks, boats, processing equipment), business travel, and employee commuting are generally excluded and are also excluded in this study. Furthermore, given the scope is cradle to gate, downstream emissions such as processing of sold products, use of sold products, and end of life are excluded.

Category 3 covers the fuel and energy related activities that are not included in scope 1 and 2. This includes extraction, production, and transportation of fuels and electricity consumed by the reporting company and the transmission and distribution losses of electricity. For ASF, this includes the upstream emissions from electricity, natural gas, gasoline used in trucks, and diesel used in onsite refrigeration trailers. For refrigerated box trucks operated by ASF, both upstream and mobile combustion emissions are included in scope 1 as emissions cannot be broken out for this data source.

Table 4: Emission scope and study data included in the scope

Emission Scope	Study data included in the scope
Scope 1 - Direct emissions from sources owned or controlled by ASF	
Fugitive refrigeration	Annual refrigerant recharge of all refrigeration units via maintenance records
Stationary Combustion	Amount of fuel burned onsite via utility bills or ASF records for refrigerated trailer
Mobile Combustion	Miles driven or gallons of fuel used for all ASF owned or operated boats or vehicles
Scope 2 - Indirect emissions from purchased energy	
Purchased Electricity	Electricity purchased via utility bills
Scope 3 - Indirect emissions within ASF's value chain	
Category 1 – purchased goods and services	Mass and material of all purchased goods and services via purchasing records or partner records
Category 3 – Upstream emissions from fuel & electricity	Amount of fuel and electricity used to calculate upstream energy emissions
Category 4 - Upstream transportation and distribution	Miles driven or gallons of fuel used for transportation of products in vehicles or boats not owned or operated by ASF; storage volume and duration for off-site storage
Category 5 – Waste generated in ASF operations	Mass, type, and end of life disposition for all wastes as available

The GHG Protocol separates upstream and downstream transportation and distribution emissions into categories 4 and 9 respectively. These include transportation and distribution that occur in vehicles not owned or operated by the reporting company. Category 4 includes transportation of purchased products and transportation services purchased by the reporting company, including inbound and outbound logistics and transportation within a company's own facilities. Category 9 includes the downstream transportation of sold products that are not paid for by the reporting company. Since ASF pays for the transportation of finished goods to distribution hubs, this is technically categorized as category 4 and are categorized this way in the report. These emissions are however "downstream" of ASF operations. Furthermore, the transportation of purchased goods to ASF facilities was excluded from this study as its impact on overall footprint is negligible.

Carbon capture within the kelp itself and sequestration in the ocean resulting from kelp growth are excluded from the analysis. All carbon contained in the kelp will be released once the kelp is eaten or disposed, therefore negating any captured carbon. Carbon sequestration in the ocean due to growing kelp is a novel concept with insufficient peer reviewed science to support such a claim. Published studies are of permanent kelp farms rather than those growing kelp for consumption and are not applicable.

GREENHOUSE GASES

The greenhouse gases included in this study are carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and fluorinated gases (refrigerants). All gases are converted into CO2 equivalents (CO2e) using the characterization factors outlined in the IPCC Sixth Assessment Report (AR6)[3]. These factors represent GWP which is a measure the amount of energy that 1 ton of each gas will absorb over 100 years relative to the amount that CO2 absorbs. The GWP of each gas used in this study is in Table 5.

Table 5: GWP of greenhouse gases in the study

Gas	GWP (kg CO2e/kg)
CO2	1
CH4	28
NO2	273
R-404A	3,922

EMISSION FACTOR DATA SOURCES

Emission factors, or kilograms of carbon dioxide equivalents (kgCO2e) per process or material were sourced from multiple resources as outlined in Table 6.

Table 6: Emission factor data sources

Source and version	Description	Application to this study
Databases		
DataSmart v2.2	DataSmart data is a combination of USLCI and ecoinvent data, modified specifically to be representative of US operations. Impact assessment method must be used to calculate emission factors. More information at https://longtrailsustainability.com/services/softwa re/datasmart-life-cycle-inventory.	Material, processing, and some transport background datasets are used to calculate emission factors. For example, inventory datasets for polypropylene are used, as the practitioners did not collect primary data on polypropylene production for this study.
Ecoinvent, cut-off by classification, v3.8	Database providing peer reviewed life cycle assessment and data sets, providing background data for materials and processes. Impact assessment method must be used to calculate emission factors. Most ecoinvent data is based on European operations. More information at https://ecoinvent.org/.	Material, processing, and some transport background datasets are used to calculate emission factors. For example, inventory datasets for polypropylene are used, as the practitioners did not collect primary data on polypropylene production for this study.
EPA eGRID2021 NEWE emission factor	The Emissions & Generation Resource Integrated Database (eGRID) is a comprehensive inventory of environmental attributes of electric power systems. The preeminent source of air emission data for the electric power sector, eGRID is based on available plant-specific data for all U.S. electricity generating plants that provide power to the electric grid and report data to the U.S. government. eGRID uses data from the Energy Information Administration (EIA) Forms EIA-860 and EIA-923 and EPA's Clean Air Markets Program Data. Emission data from EPA are carefully integrated with generation data from EIA to produce useful values like pounds of emissions per megawatt-hour of electricity generation (lb/MWh), which allows direct comparison of the environmental attributes of electricity generation. More information and access the data at https://www.epa.gov/egrid/download-data	eGRID utility grid emission factors are from "eGRID subregion annual CO2 equivalent total output emission rate (lb/MWh)"
EPA Emission Factors for Greenhouse Gas Inventories, 18 April 2023	Provides carbon dioxide equivalent emission factors for purchased electricity, mobile combustion, and other transportation. More information and access to the data at https://www.epa.gov/climateleadership/ghgemission-factors-hub.	Emission factors used for burning diesel in boats, gas in truck, and GWP for R-404A refrigerant used at ASF
International Agency Energy (IEA) Life Cycle Upstream Emission Factors 2023 – pilot edition	The pilot database assesses and compiles reliable data to provide a global, harmonized database. More information and access to the data at https://www.iea.org/data-and-statistics/dataproduct/life-cycle-upstream-emission-factorspilot-edition.	Source of upstream emissions from electricity generation
US Department of Energy Fuel Economy	Provides average fuel economy of vehicle makes and models. Accessible at https://www.fueleconomy.gov/feg	Source of average city fuel economy of a 2005 F150 is 13mpg
USLCI	Database developed by the National Renewable Energy Laboratory (NREL) to analyze the environmental impacts of a material, component, or assembly made in the US. More information at https://www.nrel.gov/lci/.	Some material datasets are used to calculate emission factors. For example, inventory datasets for polypropylene are used, as the practitioners did not collect primary data on polypropylene production for this study.
Energy Information Administration (EIA) Commercial buildings energy consumption survey (CBECS)	The CBECS provides basic statistical information about energy consumption, expenditures, and the energy-related characteristics of U.S. commercial buildings. Table C22 provides electricity consumption and conditional energy intensities by building activity subcategories. Accessible at: https://www.eia.gov/consumption/commercial/da ta/2018/index.php?view=consumption#electricity	Average energy use per square foot for commercial warehousing.

Source and version	Description	Application to this study
Literature		
Tailpipe greenhouse gas emissions from tank trucks transporting raw milk from farms to processing plants	Analysis of GHG emissions from tanker trucks delivering raw milk. Accessible at https://www.sciencedirect.com/science/article/pii/S095869461200204X	Source of tanker truck emissions to be used as a proxy for sea water delivery.
Comparison of Ferry Boat and Highway Bridge Energy Use	Analysis of ferry boat energy use. Accessible at: https://mdpires.com/d_attachment/energies/energies-0400239/article_deploy/energies-04-00239.pdf	Source of average fuel economy of ferry boats.
Preliminary study on specific energy consumption of cold storage room in Thailand's cold chain	Provides a model for energy requirements of frozen and refrigerated storage warehouses based on freezer/refrigerator capacity. Accessible at: https://www.sciencedirect.com/science/article/pii/S2352484722010204	Source for estimating electricity needs for offsite cold storage.
US EPA Stationary Refrigeration Leak Repair Requirements, June 2023	Provides refrigerant trigger leak rates for a 12 month period based on the appliance type. Accessible at https://www.epa.gov/section608/stationaryrefrigeration-leak-repair-requirements.	Source for 20% trigger rate for commercial refrigeration.
Software and impact assessment method		
IPCC 2021 GWP 100yr	This method is based on IPCC report "AR6 Climate Change 2021: The Physical Science Basis" and includes the Global Warming Potential (GWP) climate change factors of IPCC with a timeframe of 100 years, where carbon dioxide uptake is implicitly included.	DataSmart, ecoinvent, and USLCI datasets are analyzed with this impact assessment method in SimaPro to calculate material and process specific emission factors.
SimaPro v9.4.0.2	Software program that facilitates the calculation of emission factors using IPCC 2021 GWP 100yr for datasets in SimaPro databases.	SimaPro facilitates the calculation of emission factors for DataSmart, ecoinvent, and USLCI datasets using IPCC 2021 GWP 100yr impact assessment method.

STUDY PERIOD CARBON FOOTPRINT METHODOLOGY

The carbon footprint of a material or process is a function of the amount and emission factor, as shown in Equation 1. Material and process carbon footprints are found in the "study period emissions" column of the process inventory tables in section Inventory data and footprint of this report.

Study period emissions include those related to all kelp processed during the study period. For example, while 141,020 pounds of Ready Cut Kelp were produced, 5,760 pounds were sold. "Study period emissions" includes the production of 141,020 pounds of Ready Cut Kelp and the sales of 5,760 pounds. Storage and distribution impacts of the remaining unsold portion of Ready Cut Kelp (135,260 pounds) is excluded, as it is allocated to the future year in which the Ready Cut Kelp is sold. The carbon footprint of unsold kelp in storage is included in a sensitivity analysis.

Equation 1.
Material or process carbon footprint, kgCO2e = A*EF

Where:
A = annual inventory amount of material or process, typically kg, lb, kWh, number of units
EF = kg CO2e per 1 unit of measure, typically kg CO2e/kg, kg CO2e/lb, kg CO2e/kWh, kg CO2e/1 unit

The annual carbon footprint is a sum of all material and process carbon footprints during the study period.

Equation 2.
Annual carbon footprint = Σ material and process carbon footprints

PER POUND CARBON FOOTPRINT METHODOLOGY

The carbon footprint per pound of kelp is a function of the farming, processing, and storage and distribution annual footprints and mass of kelp at each life cycle stage. The carbon footprint of each life cycle stage is calculated and then normalized to the amount of kelp processed at that stage. Ready Cut Kelp and Maine Kelp Powder require more than one pound of farmed kelp for production due to scrap and dehydration. Variables are defined in Table 2. Kelp mass and source throughout the supply chain.

Equation 3.
kg CO2e 1lb farmed kelp (FK) =
annual carbon footprint kelp farming/FY

Equation 4.
kg CO2e 1lb Ready Cut Kelp (RP) =
annual carbon footprint Ready Cut Kelp processing/RCK

Equation 5.
kg CO2e 1lb RCK storage and distribution (RSD) =
annual carbon footprink RCK storage and distribution/RCD

Equation 6.
kg CO2e 1lb RCK = (((FPA+ZOP+WPA)/RCK)*FK)+RP+RSD

Equation 7.
kg CO2e 1lb Maine Kelp Powder processing (PP) =
annual carbon footprint MKP processing/MKP

Equation 8.
kg CO2e 1lb Maine Kelp Powder storage and distribution (PSD) =
annual carbon footprint MKP storage and distribution/MKD

Equation 9.
kg CO2e 1lb Maine Kelp Powder = ((FTD/MKP)*FK)+PP+PSD

INVENTORY DATA AND FOOTPRINT

The PCF is divided into stages in order to isolate the stages and processes that contribute the most to the carbon footprint. Isolating the stages will in turn enable ASF to continue to improve the environmental performance of their products by concentrating their efforts on the highest impact stages.

For each life cycle stage, Pure Strategies developed a data needs table defining the data used to calculate the inventory inputs. Pure Strategies then worked directly with ASF employees to populate the needs table. Collected data was converted into life cycle inventory model inputs. Details of the life cycle stages and all inputs are below.

KELP FARMING

Kelp farming includes the fuel, consumables, refrigeration, and waste from Sorus collection, seed deployment, and kelp cultivation. Kelp is farmed along the coast of Maine, from Portland to Eastport by partner farmers and much of the data was provided by them.

Overall, farming makes up 15% of total annual emissions. During the study period, 571,161 lbs. of wet kelp was harvested. 81% of the total harvest was sent to the dehydrators for drying, and 17% was sent to ASF for either blast freezing or processing. The remaining 2% was used for a dried kelp trial which is excluded from this study.

Kelp Farming | Consumables

Farm gear data was provided by ASF for two types of farms: 16 farmers each with a 4 acre experimental plot with and 25 farmers each with a 400ft2 plot. The average type and amount of gear per farm was provided and then multiplied by the number of farmers to determine the total gear amount.

Table 7: Summary of farming emissions

Total kelp harvested during study period	571,161 pounds
Farming emissions during study period	78,138 kg CO2e
Farming emissions per pound kelp harvested	0.14 kg CO2e

Table 8: Kelp farming consumables

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Kelp cultivation							
Scope 3 - Category 1	Cultivation - #9 Nylon Twine	275,000	ft	Tank logs 4,200' spools (2lbs each)	131	lb	703
Scope 3 - Category 1	F/2 Nutrients	22	l	Tank logs	22	l	4
Scope 3- Category 1	Organic Nutrients	3	kg	Tank logs Includes Nitrogen, Phosphorus and Iron inputs	3	kg	1
Kelp harvest							
Scope 3 -Category 1	Bulk Bag- polypropylene - polypropylene	583	units	Item weight & harvest records weight = 2.47 lbs, quantity= 583 Lifespan: single us	1,440	lbs	1,711
Scope 3 - Category 1	Bag Tag - tag	583	units	Item weight & harvest records weight = .01 lbs, quantity = 583 Lifespan: single us	6	lbs	11
Scope 3 - Category 1	Pallet - chep pallet	583	units	Item weight & harvest records weight = 40 lbs, quantity = 583 Lifespan: TBD - Not bought new. ~60% are re-used	16,324	lbs	-

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 3 - Category 1	Scale - industrial scale	5	units	Purchasing records weight = 13.5 lbs, quantity =5 Lifespan: 3 years	23	lbs	67
Scope 3 - Category 1	Paperwork - BOLs & Landing Sheets	16	lbs	Harvest Records Usage BOLs & Landing Sheets	16	lbs	10
Scope 3 - Category 1	Rope - 5 ft. rope and metal hooks	8	units	weight = 2.24lbs, quantity = 8 Lifespan: 3 years	6	lbs	32
Scope 3 - Category 1	Flagging Tape	2	units	weight = .5 lbs, quantity = 2	1	lbs	1
Scope 3 - Category 1	Knife victorinox - plastic portion	150	units	weight = .06 lbs, quantity = 150 Lifespan: depends on farmer use, assume 1 yr. Density PP = 0.91g/cm3	1	lbs2	
Scope 3 - Category 1	Knife victorinox - steel portion	150	units	weight = .06 lbs, quantity=150 Lifespan: depends on farmer use, assume 1 year. Density PP=.091g/cm3 Density stainless steel=7.89/cm3	8	lbs	16
Scope 3 - Category 1	DEF	20	gal	Total for the season 32.5 g urea per 100ml water OR (32.5g/100ml * 2785 ml/gal) = 1.230 kg urea/gal	25	kg	32
Seed deployment and farmer monitoring							
Scope 3 - Category 1	Marine Algae Culture Lines - Poly line ⅜", 1,000' long	10,000	ft	3/8 inch = 4.2 lb/100ft 10 lines at 1000 ft long per farm, 16 farms Lifespan: 2-3 seasons	2,688	lbs	6,783
Scope 3 - Category 1	Crosslines - Poly line	492	ft	3/8 inch = 4.2 lb/100ft 3 lines at 164 ft long per farm, 16 farms Lifespan: 2-3 seasons	132	lbs	334
Scope 3 - Category 1	Depth Control Buoys - Traditional lobster buoys, Spongex foam	90	units	7"x14" buoy = 1.35lbs (average of 6x14 and 7x15) Up to 90 buoys per farm, 16 farms Lifespan: 10+ seasons	194	lbs	397
Scope 3 - Category 1	PVC Pipe (encasing ⅜" poly line) - Structure for depth control device	630	ft	1/2x7'long sch 40 pvc pipe, .17lbs/ft Up to 90 pvc pipes per farm, 16 farms Lifespan: 10+ seasons	685	lbs	730
Scope 3 - Category 1	Counterweight - Weight for depth control device, concrete or bricks	90	units	8-10 lbs per counterweight (average of 9 lbs) Up to 90 counterweights per farm, 16 farms Lifespan: 4+ seasons	3,240	lbs	191
Scope 3 - Category 1	Mooring Buoys - A3 or A4 polyballs	20	units	A3 Polyball - 23" x 17" OR A4 Polyball - 27" x 20.5" A3=6.8lbs/ A4=9.5lbs Up to 20 buoys per farm, 16 farms Lifespan: 10+ seasons	261	lbs	387
Scope 3 - Category 1	Galvanized Mooring Chains	650	ft	1/2"; 25' long at 2.54 lbs/ft Up to 26 chains per farm, 16 farms Lifespan: 2-3 seasons	10,566	lbs	23,385

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 3 - Category 1	Mooring Lines - 3strand nylon rope	676	ft	3/4-1"x26' long at 13.3lbs/100ft Up to 26 lines, 16 farms Lifespan: 2-3 seasons	1,008	lbs	5,410
Scope 3 - Category 1	Moorings - Concrete blocks	26	lbs	~1200lbs each block Up to 26 concrete blocks per farm, 16 farms Lifespan: 5+ seasons	99,840	lbs	5,887
Scope 3 - Category 1	State-required Lease Markers - Low-drag buoys	6	units	24" long, 11.5"wide at 4.7lbs each Up to 6 markers per farm, 16 farms Lifespan: 2-3 seasons	180	lbs	259
Scope 3 - Category 1	Mooring Buoys	2	units	18" diameter at 6.8 lbs/buoy 2 buoys per farm, 25 farms Lifespan: 10+ seasons	34	lbs	49
Scope 3 - Category 1	Mooring Ropes	3	units	3/4"x10' at 1.3lbs/ 10'rope 3 ropes per farm, 25 farms Lifespan: 2-3 seasons	39	lbs	98
Scope 3 - Category 1	Mooring Chains	60	ft	3/8"x20' at 1.36lb/ft 3 chains per farm, 25 farms Lifespan: 3-4 seasons	583	lbs	1,290
Scope 3 - Category 1	Concrete Moorings	3	units	1200lbs each 3 concrete moorings per farm, 25 farms Lifespan: 5+ seasons	18,000	lbs	1,061
Scope 3 - Category 1	Culture Line	400	ft	3/8"x400' at 4.2lbs/100ft 1 line per farm, 25 farms Lifespan: 2-3 seasons	168	lbs	424
Scope 3 - Category 1	Buoys for Depth Control Device	4	units	7"x12"at 6x14 = 1.3lbs and 7x15 = 1.4lbs 4 buoys per farm, 25 farms Lifespan: 10+ seasons	13	lbs	19
Scope 3 - Category 1	Counterweights for Depth Control Device	4	units	10lbs each 4 per farm, 25 farms Lifespan: 4+ seasons	250	lbs	200
Scope 3 - Category 1	PVC for Depth Control Device	28	ft	1/2"x7' at .17lb/ft 4 per farm, 25 farms Lifespan: 2-3 seasons	30	lbs	32
Scope 3 - Category 1	Required Lease Marker Buoy	1	units	16" in diameter at 11lbs each 1 per farm, 25 farms Lifespan: 2-3 seasons	110	lbs	158

To calculate material production emissions, Ecoinvent datasets and IPCC 2021 GWP 100yr were used. Where available, processing emissions (i.e.. extrusion, blow molding, weaving) are included. Datasets were unavailable for some materials, and the following proxies were used:

- Urea (32.5%) as a proxy for diesel exhaust fluid
- Mineral water as a proxy for F/2 nutrient medium
- Iron sulfate as a proxy for organic nutrients

Chep pallets are purchased used and therefore have zero material impact.

To calculate the emissions of *Knives–Victorinox*, equal volumes of poly propylene and steel were assumed for the knife composition. Weights of each material were calculated using density.

Due to the changing nature of weather and outdoor conditions, most gear has a lifespan range. Generally, carbon emissions are divided by the lifespan to determine impact per the one year study period. Lifespans have been modeled in the following ways:

- Items with range lifespan (i.e. 2-3 seasons): median lifespan is used (i.e. 2.5 years)
- Items with "plus" lifespan (i.e. 4+ years): minimum lifespan is used (i.e. 4 years)
- Items with "up to" number of units: "up to" value is used

Kelp Farming | Fuel Use

Farming fuel use includes truck emissions from trailering boats and picking up supplies, boat transport for seed deployment and harvest, refrigerated truck transport to transport kelp to MFD and PFE, and 24 hour cold storage post-harvest.

Table 9: Farming fuel use

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Sorus collection							
Scope 1- mobile combustion	Truck + Trailer - gasoline	456	mi	Truck + Trailer gets ~12 mpg ASF owned	38	gal	334
Scope 3- Category 3	Truck + trailer - upstream fuel emissions	456	mi	Truck + Trailer gets ~12 mpg ASF owned	38	gal	86
Scope 1- mobile combustion	Personal Car, in-state - gasoline	754	mi	Not ASF owned	754	mi	239
Scope 1- mobile combustion	Boat - 16' Zodiac - gasoline	30	gal	ASF owned seed lot records	30	gal	268
Scope 3- Category 3	Boat - upstream fuel emissions	30	gal	ASF owned seed lot records	30	gal	68
Scope 1- mobile combustion	Personal car, Rhode Island - gasoline	1,100	mi	Not ASF owned	1,100	mi	348
Scope 3- Category 3	Personal car - upstream fuel emissions (both instate and RI)	1,854	mi	Average fuel economy of 25 MPG	74	gal	168
Kelp cultivation							
Scope 3- Category 4	Seawater	47,600	gal	47,600 gallons total/yr - tank logs	180,404	kg	403

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Seed deployment & farmer monitoring							
Scope 3-Category 4	Lobster Boat (3040ft) - diesel	346	mi	Partner Farmer Seeding efforts Not ASF Owned; Total of 432 hours of use	432	gal	5,391
Scope 3-Category 4	Ferry Boat - diesel	96	mi	Rockland to North Haven Ferry distance = 24 miles (one way) 2 round trip journeys - One for the farmer to come to the mainland to pickup seed and return. The second for the farmer to drop off the harvested kelp and return Passenger miles per gallon = 0.28MPG*5 vehicles = 1.4 MPG	69	gal	856
Scope 1-mobile combustion	Truck - regular gas	2,939	mi	Distributing Seed to Partner Farmers - google maps ASF owned, 15 mi/gal	184	gal	1,616
Scope 3-Category 4	Lobster Boat (3040ft) - diesel	939	mi	Bi- monthly Farmer Checkups from Jan-April, round trip from dock to farm sites per each event Not ASF owned	198	gal	2,471
Scope 1-mobile combustion	25' Center Console Outboard - regular gas	48	mi	round trip distance from Yarmouth town landing boat launch to farm sites ASF Owned	11	gal	133
Scope 1-mobile combustion	Truck - regular gas	383	mi	Trailering boat from ASF HQ to Yarmouth Town landing ASF owned, 12 mi/gal	32	gal	281
Scope 1-mobile combustion	Truck - regular gas	321	mi	round trip distance from ASF HQ to Newport RI for farm audit ASF owned, 15 mi/gal	20	gal	177
Scope 3-Category 3	Truck - upstream fuel emissions from seed deployment & Farmer monitoring	2,939	mi	16 mi/gal	236	gal	535
Kelp harvest							
Scope 3-Category 4	Lobster boat (30-40ft) - diesel	1,359	mi	Based on round trip distance from dock to farm for all landings at each site April - June landings for the full network Not ASF owned Total of 984 hours of boat use	984	gal	12,279
Scope 1 - mobile combustion	Refrigerated rental box truck for kelp harvest	4,030	Tonmi	Total miles per trip and mass of kelp per trip for each harvest. Calculation details below.	4,030	Tonmi	2,369

Fuel use emissions include fuel production and combustion emissions. Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate fuel production emissions, unless otherwise noted. EPA Emissions Factors Hub is used to calculate fuel combustion emissions, unless otherwise noted.

For *refrigerated transport*, Ecoinvent datasets combine fuel production and combustion emissions. Thus, emissions were not able to be broken out into scope 1 and 3, and all emission for refrigerated transport are categorized under scope 1 emissions.

Seawater data for tanker truck emissions is not available and has been calculated using a combination of ASF & literature data.

Equation 10.
Seawater transport emission factor, kgCO2/kg = G*C*(MEF/MD)*D

Where:
G = gallons water transported by ASF = 47,600
C = converting gallons to kg = 3.79kg/gallon
MEF = emission factor for liquid milk from literature; 0.05kgCO2/ kg milk[4]
MD = distance liquid milk is transported from literature; 850km roundtrip
D = roundtrip distance seawater is transported to ASF = 38km

ASF partner farms estimate fuel use to be 1 gallon fuel per hour of lobster boat use. Number of lobster boat hours for seed deployment and harvest at each of 21 farms was provided. Total gallons of diesel used in the lobster boats was calculated by multiplying the total hours by 1 gallon diesel per hour.

Ferry boat diesel data is not available and is calculated using ferry data.

Equation 11.
Ferry gallons of fuel consumed = D/(MPG*V)

Where:
D = total miles traveled via ferry = 96 miles; 24mi one way from Rockland to North Haven[5], 2 roundtrip journeys
MPG = ferry miles per gallon = 0.28mpg; Casco Bay Island transit in Portland Maine vessels operate at 0.28 MPG[6]
V = ferry vehicle capacity = 5; Vessel is Captain Neal Burgess which holds 5 vehicles8

Truck – regular gas is assumed to have 12mpg when towing a boat and 16mpg when not towing, based on the mpg of the truck make & model used. Personal car is assumed to have 25 mpg, based on the average mpg of a 2015 vehicle.

Refrigerated rental box truck weight and milage data was provided by ASF. Total ton-miles were calculated using number of trips, distance per trip, and average weight of kelp per trip.

Equation 12.
Refrigerated truck tonmi =EM*Wp+Σ ((N*D)/2)*Wk

Where:
EM = Empty truck miles
Wp = weight of empty pallets
N = number of trips traveled from dock to wharf for harvest
D = total round trip distance from dock to wharf
Wk = average weight of kelp per trip

Table 10: Refrigerated transport of kelp from dock to cross dock location

ASF Partner	Number of Trips	Round trip distance (mi)	Total distance (mi)	Total distance with kelp (mi)	Average weight per trip (tons)	Total Tonmiles
Keith /Brian/Richard	14	9	132	66	3.2	208
Mark Miller	1	9	9	5	1.3	6
Bob Baines	6	15	90	45	4.0	178
Mason & Adam	1	320	320	160	4.0	640
Scott/Greg	15	14	207	104	3.5	360
Abby Barrows	1	185	185	93	0.1	13
Karen Cooper	1	26	26	13	0.8	10
Alex/Jodi	2	132	263	132	4.4	582
Josh & Shey	1	50	50	25	3.4	85
Greg Perkins	4	106	425	212	1.0	211
Elijah	1	364	364	182	2.1	374
ASF ->MFD -> ASF	3	202	606	303	1.3	404
Mason & Adam	1	160	160	160	5.0	798
Empty miles	-	-	1614.8		0.1	161

Table 11: Kelp farming refrigeration emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Kelp harvest							
Scope 1-fugitive	Post-harvest refrigeration (diesel powered refrigeration truck)	571,161	lbs	12,337 lbs of kelp sent to a drying trial and excluded from scope 1/5 of total harvest was stored in a diesel powered refrigeration truck for 24 hours	50,687	kg*day	359
Scope 3-category 4	Post-harvest 24hr refrigeration (refrigerated warehouse)	571,161	lbs	12,337 lbs of kelp sent to a drying trial and excluded from scope 1/4 of total harvest was stored in a refrigerated warehouse for 24 hours	79	kWh	25

Kelp Farming | Refrigeration

2% of kelp was transported offsite for a drying trial and is excluded from the scope. Of the remaining kelp, approximately one fifth was held onsite at the wharf in a diesel-powered refrigerated truck for 24 hours, and one quarter was held onsite at the wharf in a refrigerated warehouse. The remaining 55% of harvest was transported directly to ASF or dehydrators for processing and is included in ready-cut kelp and Maine kelp powder production emissions.

Refrigeration emissions were calculated using emissions, including fuel production and combustion emissions. Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate fuel production emissions, unless otherwise noted. EPA Emissions Factors Hub is used to calculate fuel combustion emissions, unless otherwise noted.

Diesel powered refrigeration truck emissions were calculated using Ecoinvent datasets and IPCC 2021

GWP 100yr. Total kgday were calculated based on the amount of kelp stored and storage duration time.

Equation 13.
Diesel refrigeration,kgday = K*(lbs/kg)*D

Where:
K = mass of kelp in cold storage = 11,765 (calculated from data provided by ASF = (571,161lbs kelp farmed – 12,337lbs kelp sent to drying trial) *20% stored in diesel refrigeration)
Lbs/kg = unit conversion; 1 lb / 2.205 kg
D = total days stored in diesel powered refrigeration truck

Refrigerated warehouse storage emissions were calculated using US EPA eGRID2021 subregion specific emission factor. Total kwh were calculated based on the amount of kelp stored storage duration provided by ASF, and energy consumption data from AC Portland, one of ASF's offsite storage locations.

Equation 14.
Energy for offsite cold storage, kWh = K*M*V*E*T*(1/U)

Where:
K = mass of kelp in cold storage = 11,765 (calculated from data provided by ASF = (571,161lbs kelp farmed – 12,337lbs kelp sent to drying trial) *25% stored in diesel refrigeration)
M = mass of kelp per pallet = 1000lbs (ASF)
V = pallet volume, in m3 = 40" x 48" x48" (ASF)
E = annual electricity consumption per m3 of cold storage = 68.53 kWh/m3/yr; AC Portland freezer is 1,587,630 cubic feet, annual electricity consumption of frozen storage = (1560 *freezer volume m3)0.7083 = 68.53 kWh/m3/yr[7]
T = average storage time in years = 1/365 (ASF)
U = warehouse utilization = 0.5; not all warehouse space is used for product storage and a logistics company recommends 50% utilization for food grade products that stack neatly and turn 10-15 times per year[8]

Kelp Farming | Waste

The only waste resulting from the farming process is seawater sent to wastewater treatment. Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate waste emissions.

Table 12: Kelp farming waste

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Kelp cultivation							
Scope 3 - Category 5	Wastewater treatment of seawater down the drain	47,600	gal	1 CCF = 748.052 gal	64	ccf	51

READY CUT KELP PRODUCTION

Ready Cut Kelp production includes trucking harvested kelp from the wharf to ASF for processing; blast freezing half fresh kelp in a rental container at ASF; blast freezing remaining fresh kelp at ASF; trucking frozen kelp to and from offsite cold storage to ASF; washing, shredding, blanching and packing kelp at ASF; waste kelp resulting from processing at ASF; storing Ready Cut Kelp prior to sale; and trucking Ready Cut Kelp to Boston for distribution.

Table 13: Summary of processing emissions

Total Ready Cut Kelp produced during study period	235,034	pounds
Total Ready Cut Kelp sold during study period	5,706	pounds
Emissions during study period	175,615	kg CO2e
Fresh kelp needed to produce 1lb Ready Cut Kelp	1.05	pounds
Emissions per lb Ready Cut Kelp, processed to end of ASF's processing line & packed in 55gal drums, includes processing only (excludes farming & distribution)	0.74	kg CO2
Emissions per lb Ready Cut Kelp, processed to end of ASF's processing line & packed in 55gal drums, includes farming & processing (excludes distribution)	0.89	kg CO2
Emissions per lb Ready Cut Kelp, processed to end of ASF's processing line, packed in 55 gal drums, cold storage, finished good packaging, shipped to Boston (excludes farming)	0.98	kg CO2e
Emissions per lb Ready Cut Kelp, farmed kelp, processed to end of ASF's processing line, packed in 55 gal drums, cold storage, finished good packaging, shipped to Boston (includes farming)	1.13	kg CO2e

Ready Cut Kelp Processing | Fuel use

Fuel is used to transport harvested kelp from MFD and PFE, empty blast freezer from Florida to ASF, kelp to and from cold storage and ASF for processing, and Ready Cut Kelp to cold storage and distribution.

Fuel use emissions include fuel production and combustion emissions. Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate fuel production and combustion emissions. For the rental *refer truck*, Ecoinvent datasets combine fuel production and combustion emissions. Thus, emissions were not able to be broken out into scope 1 and 3, and all emission are categorized under scope 1 emissions.

During the study period, a blast freezer truck was used to blast freeze half of the harvest. The blast freezer was driven empty from Florida to ASF.

The weighted average distance was used for frozen kelp that is transported from cold storage to ASF and was calculated based on the number of pallets in inventory at four cold storage facilities on July 1, 2022.

Ready Cut Kelp Processing | Refrigeration

Refrigeration includes blast freezing of fresh kelp at ASF and cold storage of previously harvested and blast frozen kelp that is processed during the study period.

Table 14: Kelp processing fuel use inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Farmed kelp transport							
Scope 1- mobile combustion	Refer Truck - diesel	20	mi	Refrigerated transport (20-26' trailer) PFE -> Biddeford; 48,353 #s of kelp (half of processed kelp) Not ASF Owned	474	tonmi	451
Scope 1 - mobile combustion	Refer Truck - diesel	107	mi	Refrigerated transport (20-26' trailer) MFD -> Biddeford; 48,353 #s of kelp (half of processed kelp) Not ASF Owned	2,587	tonmi	2,463
Blast freezing							
Scope 3 - Category 4	Empty rental Blast Freezer driven to ASF from Florida	15,000	lbs	40' freezer shipped from Florida to Biddeford, ME	11,078	Tonmi	2,724
Cold storage							
Scope 3 - Category 4	Frozen transport of kelp to and from cold storage to ASF for processing	172,026	lbs	172,026 lbs of frozen kelp processed; weighted average of miles to cold storage facility = 137 mi; account for transport to and from cold storage	23,568	tonmi	9,982
Shipping and distribution							
Scope 3 - Category 4	Frozen transport of Ready Cut Kelp to distribution hub	240	lbs	Biddeford Maine -> Boston MA, 20-26' trailer, 240lbs twice per month Not ASF Owned	282	tonmi	269

Table 15: Kelp processing refrigeration inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Blast freezing							
Scope 1- fugitive	ASF blast freezing - R404A recharge	6	lbs	Data from Spark Records (3.7.23)	3	kg	10,672
Scope 1- fugitive	ASF blast freezing - R404A recharge	15	lbs	Data from Spark Records (5.24.23)	7	kg	26,680
Cold storage							
Scope 3- Category 4	Energy required for offsite cold storage of frozen Kelp processed during study period	172,026	lbs	Storage duration: Low: 19 months High: 34 months Avg: 30 months	89,014	kwh	27,910
Scope 3- Category 4	Refrigerant required for off-site cold storage of frozen Kelp processed during study period	172,026	lbs	Storage duration: Low: 19 months High: 34 months Avg: 30 months	331	kg	770

Blast freezing energy at ASF is included in the total utility bill and is found in Ready Cut Kelp Processing | Utilities. Blast freezing R404 recharge amount at ASF was provided by purchase records. The GWP of R404A is 3922 kg CO2e/kg from the EPA Emissions Factors Hub.

Energy required for offsite cold storage is calculated based on the amount of frozen kelp required (calculated by Pure Strategies from yield, waste, and farmed kelp provided by ASF), storage duration provided by ASF, and storage capacity data from one of ASF's offsite storage locations.

Equation 15.
Energy for offsite cold storage, kWh = (K/M)*V*E*T*(1/U)

Where:
K = mass kelp in cold storage = 172,026lbs (calculated from data provided by ASF = 235,034lbs Ready Cut Kelp + 11,435lbs processing waste – 77,443lbs fresh kelp)
M = mass of kelp per pallet = 1000lbs (ASF)
V = pallet volume, in m3 = 40" x 48" x48" (ASF)
E = annual electricity consumption per m3 of frozen storage = 68.53 kWh/m3/yr; AC Portland freezer is 1,587,630 cubic feet, annual electricity consumption of frozen storage = 1560 *(freezer volume m3)-0.2917 = 68.53 kWh/m3/yr[9]
T = 2.5 = average storage time in years = 2.5 (ASF)
U = warehouse utilization = 0.5; not all warehouse space is used for product storage and a logistics company recommends 50% utilization for food grade products that stack neatly and turn 10-15 times per year[10]

Refrigerant required for offsite cold storage is calculated based on the amount of frozen kelp required (calculated by Pure Strategies from yield, waste, and farmed kelp provided by ASF), storage duration provided by ASF, and literature.

Equation 16.
Refrigerant for offsite cold storage, kg = K*M*D*A*L*(1/U)

Where:
K = mass kelp in cold storage = 172,026lbs (calculated from data provided by ASF = 235,034lbs Ready Cut Kelp + 11,435lbs processing waste – 77,443lbs fresh kelp)
M = mass of kelp per pallet = 1000lbs (ASF)
D = average storage time in days, 2.5 years = 912.5 (ASF)
A = kg ammonia needed per pallet per day of refrigerated storage = 0.021 kg ammonia/pallet/day; DataSmart dataset for refrigerated warehouse storage requires 0.021 kg ammonia/pallet/day
L = average leak rate = 5%; trigger rate for commercial refrigeration is 20%[11] and many industry sources mention taking action at 5%
U = warehouse utilization = 0.5; not all warehouse space is used for product storage and a logistics company recommends 50% utilization for food grade products that stack neatly and turn 10-15 times per year[12]

Ready Cut Kelp Processing | Utilities

Utilities include the energy at ASF to wash and blanch kelp, energy to operate the cooler, freezer, and temporary blast freezer, and water use.

Upstream emissions for natural gas, diesel, and purchased electricity are included in total emissions. Upstream emissions include the production of natural gas and diesel, the generation of electricity, and the transmission and distribution losses.

For electricity, the NPCC New England (NEWE) regional grid data set was used, as ASF's facility is located within that eGRID region. For upstream emissions from electricity generation, a US country level factor from the International Agency Energy (IEA) Life Cycle Upstream Emission Factors pilot dataset for 2023 was used. Regional or state-level data is not currently available.

ASF is located in a shared facility and does not have its own energy metering. During the study period, ASF was charged 88% of the total facility energy bill, and the total is 293,980 kWh. To partition the bill into different operations, an ASF electrician estimated the following allocations: 200,000 kWh freezer, 20,000 kWh cooler, 11,000 kWh fermentation room, and remaining 62,980 kWh includes blanching, washing, and packaging kelp as well as building operations, such as lights, computers, and restrooms. Fermentation is outside the scope of the study and is excluded. The entirety of the remaining 62,980 kWh has been allocated to kelp processing, as it is expected that other building operations will contribute an insignificant amount of energy. The amount of freezer energy allocated to Ready Cut Kelp sold during the study period has been calculated using Equation 17 below and is 2,799 kWh.

Equation 17.
Energy for RCK sold during the study period = (RCU*SD) + (RCD*SD)

Where:
RCU = pounds unsold Ready Cut Kelp stored at ASF, 135,260 pounds
SD = storage duration in years; unsold RCK is stored for 1 year, sold RCK is stored for 4 months
RCD = pounds sold Ready Cut Kelp stored at ASF; 5,760 pounds

Table 16: Kelp processing utilities inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 2	Electricity - kelp washing & blanching, general building needs (excludes fermentation)	62,980	kwh	ASF electrician	62,980	kwh	15,540
Scope 2	Electricity - ASF cooler	20,000	kwh	ASF electrician	20,000	kwh	4,935
Scope 2	Electricity - ASF freezer	200,000	kwh	ASF electrician	2,799	kwh	691
Scope 3 - category 3	Electricity - upstream emissions	282,980	kwh	Includes total upstream emissions for all electricity in ASF facility	282,980	kwh	18,903
Scope 1 - stationary combustion	Natural gas - combustion emissions	4,014	therms	Utility bills based on meter	401	mmBtu	21,320
Scope 3 - category 3	Natural gas - upstream production emissions	4,014	therms	Utility bills based on meter	423,504	MJ	8,433
Scope 3 - Category 1	Tap water	637	HCF	Utility bills, based on 73.5% shared facility	1,806,553	kg	648
Scope 1 - stationary combustion	Diesel - onsite blast freezer - combustion emissions	408	gal	ASF Onsite Trailer used 6 weeks during study period, gallons fuel from diesel delivery bills	408	gal	4.237
Scope 3 - category 3	Diesel - onsite blast freezer - upstream fuel production emissions	408	gal	ASF Onsite Trailer used 6 weeks during study period, gallons fuel from diesel delivery bills	408	gal	834

Ecoinvent datasets and IPCC 2021 GWP 100yr were used to calculate emissions for water use and the production of natural gas. The EPA Emission Factors Hub was used to calculate emissions from the stationary combustion of natural gas.

Similar to electricity, ASF does not have it's own water meter. During the study period, ASF was charged 73.5% of the total facility water usage, for a total of 63,725 cubic feet.

ASF has an onsite natural gas meter and the natural gas usage during the study period is 4014 therms.

Ready Cut Kelp Processing | Waste

Waste includes process water sent to treatment, kelp waste from processing, and general waste resulting from processing.

Table 17: Kelp processing waste inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 3 - Category 5	Waste water treatment	637	HCF	Amount equal to process water input	637	CCF	506
Scope 3 - Category 5	Organic Waste - Kelp - landfill (80%)	900	lbs	Employee estimate: 900 lbs/ month total kelp sent to waste	8,640	lbs	2,381
Scope 3 - Category 5	Organic Waste - Kelp - incineration (20%)	900	lbs	Employee estimate: 900 lbs/ month total kelp sent to waste	2,160	lbs	32
Scope 3 - Category 5	General municipal waste - landfill (80%)	59,007	lbs	Waste hauler bills & employee estimates	47,205	lbs	13,183
Scope 3 - Category 5	General municipal waste - incineration (20%)	59,007	lbs	Waste hauler bills & employee estimates	11,801	lbs	2,715
Scope 3 - Category 5	Waste to recycling	12,690	lbs	Transport impact only, 6.1 mi from ASF to recycling center	39	tonmi	75

Waste emissions were calculated using Ecoinvent datasets and IPCC 2021 GWP 100yr. For waste sent to recycling, the only impact is the transport to the facility, as the energy impact is allocated to the enduser of the final product. Emissions from transport of waste include both fuel production and combustion emissions.

For calculating wastewater treatment emissions, it was assumed that all process water is sent to wastewater treatment.

It is assumed that 80% kelp and general waste disposed via trash are sent to landfill and 20% are incinerated without energy recovery. This 80% landfill/20% incineration is based on US EPA Municipal Waste Statistics.[13]

Waste records and ASF estimates were used to calculate mass of general municipal waste disposed.

Equation 18.
General municipal waste,lbs = GW-KW-FW

Where:
GW = mass waste collected = 84,327lbs, via waste hauler bill
KW = kelp organic waste = 10,800lbs, ASF estimates 900lbs/month; this is included in "Organic Waste – Kelp"
FW = ferments & veggies ferments = 14,520lbs, ASF estimates 1210lbs/month; fermentation is outside the scope of the study and this is excluded

The impact of waste sent to recycling includes waste transport only.

Ready Cut Kelp Processing | Packaging

Packaging includes all finished goods packaging materials.

Packaging mass and materials were provided by ASF for the study period. Note that some packaging materials are for all Ready Cut Kelp produced during the study period, while other materials were used only for kelp sold during the study period.

Ecoinvent, USLCI, and DataSmart datasets and IPCC 2021 GWP 100yr were used to calculate material production emissions. Where available, processing emissions (ie. extrusion, blow molding, metal working) are included.

Pallets are purchased used and have no environmental impact. Pallet waste is included in the general municipal waste.

Table 18: Ready Cut Kelp packaging inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Packaging for Ready Cut Kelp sold during the study period (5,760lbs)							
Scope 3 - Category 1	Corrugated Cardboard	1,006	lbs	USA, Sales by item record 0.6906 lbs each, 1456 units sold	1,006	lbs	553
Scope 3 - Category 1	Vacuum Bag	276	lbs	China, Sales by item record 0.1896 lbs each, 1456 units sold	276	lbs	346
Scope 3 - Category 1	Case Label	91	lbs	Sales by item record	91	lbs	87
Scope 3 - Category 1	Tape	91	lbs	Sales by item record	91	lbs	108
Packaging for Ready Cut Kelp produced during the study period (235,034lbs)							
Scope 3 - Category 1	Pallet	2,912	lbs	All used pallets. And the 60% that they reuse; use for 2 years.	2,038	lbs	0
Scope 3 - Category 1	55 Gallon Drum w/ lid & ring	520	lbs	USA, Uline purchasing records 25lbs each, 32 drums, lifespan of 2 years	260	lbs	415
Scope 3 - Category 1	Lid Replacement	74	lbs	USA, Uline purchasing records 2.48lbs each, 30 lids	74	lbs	119
Scope 3- Category 1	Ring replacement	47	lbs	USA, Uline purchasing records 2.37 lbs each, 20 rings	47	lbs	105
Scope 3 - Category 1	Drum Liner	353	lbs	USA, Uline purchasing records Based on total kelp processed in a year	353	lbs	442
Scope 3 - Category 1	Pallet	5,876	lbs	All used pallets. And the 60% that they reuse; use for 2 years.	4,113	lbs	0

MAINE KELP POWDER PRODUCTION

Fresh harvested kelp is shipped directly via refrigerated truck from the wharfs to the processors. Kelp is dried, milled, and packaged at the processors and is now Maine Kelp Powder. Powder is trucked to storage at NEPW and ASF, where it remains for an average 24 months. Maine Kelp Powder is trucked to Chicago and Atlanta distribution hubs.

Maine Kelp Powder | Fuel Use

Fuel use includes refrigerated transport of wet kelp from the wharf directly to the dehydrators, as well as unrefrigerated transport of Maine Kelp Powder from the dehydrators to ASF and NEPW, and from ASF to Chicago and Atlanta distribution hubs.

Table 19: Summary of Maine Kelp Powder production carbon emissions

Total Maine Kelp Powder produced during study period	49,247	pounds
Total Maine Kelp Powder sold during study period	5,520	pounds
Emissions during study period	213,675	kg CO2e
Emissions per lb Maine Kelp Powder produced & sold (excluding farming)	4.5	kg CO2e
Fresh kelp needed to produce 1 pounds Maine Kelp Powder	9.4	pounds
Emissions per lb Maine Kelp Powder, includes farming, processing, distribution	5.7	kg CO2e

Table 20: Maine Kelp Powder fuel use inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 3 - Category 4	Refrigerated transport of wet kelp from Portland Fish Exchange to PA	14,509	lbs/ trip	53' trailer, 450 miles 1 way, 14,509 lbs transported each trip 9 trips	29,381	tonmi	12,445
Scope 3 - Category 4	Refrigerated transport of wet kelp from Portland Fish Exchange to WI	6,670	lbs/ trip	53' trailer, 1200 miles 1 way, 6,670 lbs transported each trip 4 trips	16,008	tonmi	6,780
Scope 3 - Category 4	Refrigerated transport of wet kelp from Mussel Farm Road to PA	20,325	lbs/ trip	53' trailer, 531 miles 1 way, 20,325 lbs transported each trip 14 trips	75,548	tonmi	31,999
Scope 3 - Category 4	Refrigerated transport of wet kelp from Mussel Farm Road to WI	10,156	lbs/ trip	53' trailer, 1281 miles 1 way, 10,156 lbs transported each trip 2 trips	13,010	tonmi	5,510
Scope 3 - Category 4	Transport Maine Kelp Powder from PA to Portland	11,084	lbs/ trip	53' trailer, 452 miles one way, 11,084 lbs per trip, 4 trips	10,020	tonmi	1,643
Scope 3 - Category 4	Transport Maine Kelp Powder from WI to ASF	4,912	lbs	53' trailer, 1183 miles one way, 4,912 lbs per trip, 1 trip	2,905	tonmi	476
Scope 3 - Category 4	Transport Maine Kelp Powder from Portland to ASF	5,520	lbs	All inventory ships from ASF facility; 5,520 lbs of kelp sold during study period	57	tonmi	43
Scope 3 - Category 9	Transport Maine Kelp Powder from ASF to Chicago	40	lbs	53' trailer, 1066 miles, 1 case = 40lbs, 3 times per month	768	tonmi	126
Scope 3 - Category 9	Transport Maine Kelp Powder from ASF to Atlanta	1,020	lbs	53' trailer, 1163 miles 1 pallet = 1020 lbs, 4 times per year	2,373	tonmi	389

The trailer type, number of trips, and mass of product shipped per trip were provided by ASF.

Ecoinvent and IPCC 2021 GWP 100yr were used to calculate material production emissions. Transport is assumed one way and google maps is used to calculate distance.

Maine Kelp Powder | Packaging

Packaging includes all finished good packaging for the 49,247 pounds of Maine Kelp Powder produced during the study period.

Packaging materials and masses were provided by the dehydrators.

Ecoinvent and DataSmart datasets and IPCC 2021 GWP 100yr were used to calculate material production emissions. All plastics are assumed to be injection molded.

End of life of finished goods packaging materials are excluded as the scope is cradle to gate.

Table 21: Maine Kelp Powder packaging inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 3 - Category 1	Corrugated cardboard - 20#	163	lb	USA - Uline - WI	163	lb	89
Scope 3 - Category 1	Blue Tint Bags	20	lb	USA - Uline - WI	20	lb	32
Scope 3 - Category 1	Zip Ties	75	lb	China - Uline - WI	75	lb	332
Scope 3 - Category 1	Corrugated cardboard -35#	523	lb	USA - Uline - PA	523	lb	288
Scope 3 - Category 1	Blue Tint Bags - 20#	113	lb	USA - Uline - PA	113	lb	180
Scope 3 - Category 1	Zipties	461	lb	China - Uline - PA	461	lb	2,038
Scope 3 - Category 1	Blue Tint Bags - 35#	872	oz	USA - A-Pac - PA	54	lb	87
Scope 3 - Category 1	Gaylord Bottom & Lid	1,140	lb	USA - PA	1,140	lb	627
Scope 3 - Category 1	Gaylord Liner	88	lb	USA - PA	88	lb	141
Scope 3 - Category 1	Corrugated Cardboard - 20#	572	lb	USA - PA	572	lb	315

Maine Kelp Powder | Utilities

Utilities include electricity and fuels used at the dehydrators to produce Maine Kelp Powder from wet kelp and at offsite storage.

The dehydration vendors provided the amount of electricity, diesel, and propane used per mass of Maine Kelp Powder produced during the study period. Note the processors used roughly the same amount of electricity (1,460 kWh in PA and 1,643 kWh in WI), while PA processed nine times more kelp than WI. ASF reached out to PA and WI and verified the energy data they both provided is accurate.

Energy in the Portland warehouse was calculated using a combination of provided data and literature data, using Equation 19 below.

Equation 19.

Portland storage kWh = ((ASF*CF)/P)*(MKP/PW)*(1/WH)*WE*ST

Where:

ASF = portion of Portland warehouse storage space that ASF occupies = 2%, provided by Portland warehouse

CF = cubic footage = 2.3 million, provided by Portland warehouse

P = number of pallets of MKP stored = 91, provided by Portland warehouse

MKP = mass MKP sold = 5,520lbs, provided by ASF

PW = mass of MKP per pallet = 1020lbs, provided by ASF

WH = average height of a warehouse = 31 feet, per Average height of buildings in distribution center networks of logistics and warehouse providers in the United States from 2016 to 2021, 2021 data, https://www.statista.com/statistics/947267/logistics-distribution-center-network-average-height-unitedstates.

WE = average energy for non-refrigerated warehousing = 4.7 kWh/square foot/year, from 2018 CBECS Survey Data, US EIA, Table C22. Electricity consumption totals and conditional intensities by building activity subcategories, 2018 - https://www.eia.gov/consumption/commercial/data/2018/index.php?view=consumption#electricity

ST = average storage time at NEPW = 1.5 years, provided by ASF

Table 22: Maine Kelp Powder utilities inventory and emissions

Scope	Input description	ASF Provided Data	Units	ASF Notes + calculations	Study period amount	Units	Study period emissions (kg CO2)
Scope 3 - Category 1	PA - electricity	1,460	kWh	Spring 2023 data provided by co-packer	1,460	kWh	545
Scope 3 - Category 1	PA - diesel	4,640	gal	Spring 2023 data provided by co-packer	4,640	gal	57,671
Scope 3 - Category 1	PA - propane	12,601	gal	Spring 2023 data provided by co-packer	12,601	gal	89,927
Scope 3 - Category 1	WI - electricity	1,643	kWh	Spring 2023 data provided by co-packer	1,643	kWh	894
Scope 3 - Category 1	WI - gas	106	Therms	Spring 2023 data provided by co-packer	11,163	MJ	906
Scope 3 - Category 4	Portland	2,300,000	ft3	see Equation 19 below for details	622	kwh	194

PRODUCT CARBON FOOTPRINT RESULTS SUMMARY

Results represent the product carbon footprint of ASF farmed kelp, ready cut kelp, and Maine kelp powder from cradle to distribution hub from July 1, 2022 through June 30, 2023. The scope includes farming off the coast of Maine, processing at ASF and contract facilities, storage at ASF and contract facilities, and transport of a small sub-set of exemplar sales to distribution hubs. Impacts at retail and transport to the end customer are excluded from the scope.

Product carbon footprint results are presented both as an annual footprint and per pound of farmed kelp, ready cut kelp, and Maine kelp powder. A summary of the data included for each stage follows:

1. Farmed kelp includes consumables, fuel use from boats and trucks, 24-hour cold storage, and farming waste.

2. Ready cut kelp processing and distribution includes fuel use from transporting kelp, fuel use from blast freezing, electricity from on and off-site cold storage, utilities at ASF processing facility, waste, packaging materials, and fuel use for distribution.

3. Maine kelp powder processing and distribution includes fuel use from transporting kelp to processing facilities, energy use for drying, packaging materials, storage time and duration, and fuel use for distribution.

EMISSIONS BY ASF PROCESS

The impact of ASF farmed kelp, Ready Cut Kelp, and Maine Kelp Powder is summarized in Table 23. Product stage and input category percentage breakdowns in Table 24 and Figure 7.

Table 23: Study period and product footprint across product stages

Product stage	Study Period Footprint (kg CO2e)	Product Footprint (kg CO2e/lb) RCK & MKP includes farming, processing & distribution impacts
Farmed kelp	78,138	0.14
Ready Cut Kelp processing & distribution	165,356	1.08
Maine Kelp Powder processing & distribution	213,675	5.74
Total Footprint	**457,169**	**NA**

Table 24: ASF lifecycle stages and associated emissions

Category	Category annual emissions, kg CO2e/yr	Percent of Study Period Emissions
Farming	**78,138**	**17%**
Consumables	49,681	11%
Fuel Use	28,022	6%
Refrigeration	384	0%
Waste	51	0%
Ready Cut Kelp processing & distribution	**165,356**	**36%**
Fuel Use	15,889	3%
Refrigeration	66,032	14%
Utilities	62,368	14%
Waste	18,892	4%
Packaging	2,175	0%
Maine Kelp Powder processing & distribution	**213,675**	**41%**
Fuel Use	59,412	13%
Packaging	4,127	1%
Utilities	150,137	32%
Total Emissions	**519,001**	

Overall, Maine Kelp Powder processing and distribution has the highest impact, accounting for 41% of ASF's annual emissions. This is largely due to utilities for kelp drying which make up 70% of MKP processing and distribution emissions and 32% of annual emissions. Ready Cut Kelp processing and distribution accounts for 36% of the annual footprint, with off-site cold storage and utilities at ASF accounting for a majority of RCK emissions. Kelp farming has a much lower impact on annual footprint, with consumables accounting for 64% of farming impact. Packaging materials and waste have a minimal impact on the carbon footprint.

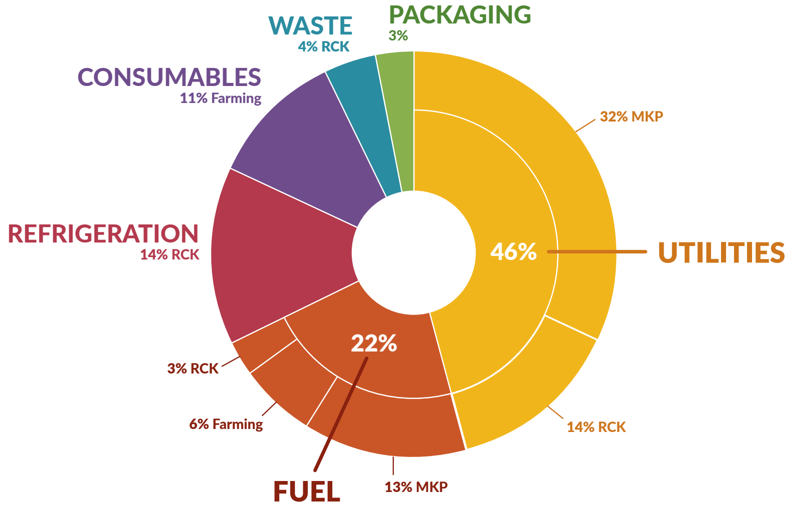

Figure 7.
Process contribution to ASF study period emissions

EMISSIONS BY SCOPE

The impact of ASF kelp production across all scopes included in this study are outlined in Table 25. Nearly 80% of ASF's annual emissions fall under scope 3 and occur within ASF's value chain, with energy from kelp dehydrators accounting for 41% of scope 3 emissions. Direct emissions from ASF owned or operated facilities and equipment account for 16% of annual emissions, while emissions from electricity purchased by ASF account for 5%. Given that a majority of ASF's emissions fall within their value chain, interventions to reduce the carbon footprint of their products must leverage their partner farms, processing facilities, warehouse facilities, and transporters.

Table 25: GHG emissions by scope

Scope	Description	Annual Emissions (kg CO2e)	Percent of total
Scope 1 - fugitive	Fugitive emissions from refrigerants during blast freezing and on-site cold storage	37,352	8%
Scope 1 - mobile combustion	Fuel use from ASF owned and rented trucks during kelp farming	5,764	1%
Scope 1 - mobile combustion	Diesel use during 24 hour post harvest refrigeration	359	0%
Scope 1 - mobile combustion	Fuel use from rented trucks for kelp transport to ASF facility	2,914	1%
Scope 1 - stationary combustion	Natural gas used at ASF processing facility	25,557	6%
Scope 2	Electricity use at ASF processing facility	21,166	5%
Scope 3 - Category 1	Consumables used during kelp farming	49,681	11%
Scope 3 - Category 1	Packaging for kelp powder	4,127	1%
Scope 3 - Category 1	Processing for kelp powder	149,943	33%
Scope 3 - Category 1	Packaging for ready cut kelp	2,175	0%
Scope 3 - Category 1	Tap water used for kelp processing	648	0%
Scope 3 - Category 3	Upstream emissions of scope 1 fuel used in kelp farming	858	0%
Scope 3 - Category 3	Upstream emissions of scope 1 and 2 fuel and electricity in kelp processing	14,997	3%
Scope 3 - Category 4	Fuel use by ASF partner farms during kelp farming	21,400	5%
Scope 3 - Category 4	Warehousing for 24 hour cold storage post harvest	25	0%
Scope 3 - Category 4	Upstream transport to and from dehydrators	59,412	13%
Scope 3 - Category 4	Warehousing for off-site storage of kelp powder	194	0%
Scope 3 - Category 4	Upstream transport for rental blast freezer, off-site frozen kelp storage, and distribution of ready cut kelp	12,975	3%
Scope 3 - Category 4	Cold storage of blast frozen kelp processed during study period	26,680	6%
Scope 3 - Category 5	Waste generated during kelp farming	51	0%
Scope 3 - Category 5	Waste generated during kelp processing	18,892	4%

HOTSPOT ANALYSIS

To better understand the primary sources of emissions, a hotspot analysis was conducted. Top emitting inputs from all emissions, farming, Ready Cut Kelp, and Maine Kelp Powder were identified and are outlined in the following sections. Some inputs have been combined to better understand the total emissions and their impact.

Study period emissions

Propane and diesel emissions at PA dehydrators are the highest emitting processes, contributing 28% of CO2 emissions. Energy for ASF's freezer along with refrigerant recharge contribute 15%. Other hot spots include refrigerated transport for wet kelp from Mussel Farm Drive to PA, galvanized mooring chains used for farming, and energy required for off-site cold storage of frozen kelp processed during the study period.

Table 26: Hot spot analysis of total carbon footprint during the study period. Inputs and processes contributing 5% or more impact are listed, all others are below 5%.

Input Category	ASF process	Input	Total emissions, kg CO2e	Percent of Study Period Emissions
Utilities	Drying	PA - propane	91,217	19%
Utilities	Drying	PA - diesel	57,671	12%
Fuel Use	Drying	Refrigerated transport of wet kelp from ASF to PA	31,999	7%
Utilities	Kelp processing	Natural gas – upstream & combustion emissions	29,753	6%
Refrigeration	Cold storage	Energy required for off-site cold storage of frozen Kelp processed during study period	27,910	6%
Consumables	Seed deployment & Farmer monitoring	Galvanized Mooring Chains	23,385	5%
Refrigeration	Blast Freezing	ASF blast freezing - R404A recharge	26,680	6%

Table 27: Hot spot analysis of kelp farming carbon footprint during the study period. Inputs and processes contributing 5% or more impact are listed, all others are below 5%.

Input Category	ASF process	Input	Emissions per lb farmed kelp, kg CO2e	Percent of Farmed Kelp Emissions
Consumables	Seed deployment & Farmer monitoring	Galvanized Mooring Chains	0.04	32%
Fuel Use	Kelp harvest	Lobster boat (30-40ft) - diesel	0.03	23%
Consumables	Seed deployment & Farmer monitoring	Marine Algae Culture Lines - Poly line ⅜", 1,000' long	0.01	9%
Consumables	Seed deployment & Farmer monitoring	Moorings - Concrete blocks	0.01	8%
Consumables	Seed deployment & Farmer monitoring	Mooring Lines - 3-strand nylon rope	0.01	7%

Farmed Kelp

Galvanized mooring chains contributes 30% of farming impact and lobster boats used for seed deployment and harvest contributes over 20%. Polyline, concrete blocks, and nylon rope are also hot spots. Extending the life of consumables will reduce their impact.

Ready Cut Kelp

Producing Ready Cut Kelp includes farming, processing, and shipping and distribution. Electricity to operate the ASF freezer includes blast freezing a portion of fresh kelp before shipping it offsite for storage as well as storage of finished Ready Cut Kelp.

Kelp farming is the highest emitting category, with cold storage of the 172,026 pounds of previously farmed help processed during the study period and refrigerant at ASF for blast freezing identified as other hot spots. Additional minor hotspots include corrugated cardboard for packaging finished Ready Cut Kelp, and natural gas and electricity use at ASF.

Table 28: Hot spot analysis of Ready Cut Kelp carbon footprint during the study period. Inputs and processes contributing 5% or more impact are listed, all others are below 5%.

Input Category	ASF process	Input	Emissions per lb Ready Cut Kelp, kg CO2e	Percent of Ready Cut Kelp Emissions
All categories	Kelp farming	All impacts associated with kelp farming	0.16	14%
Refrigeration	Cold storage	Energy required for off-site cold storage of frozen kelp processed during study period	0.12	10%
Refrigeration	Blast Freezing	ASF blast freezing - R404A recharge	0.11	10%
Utilities	Kelp processing	Natural gas - combustion emissions at ASF	0.09	8%
Packaging	Kelp Processing	Corrugated Cardboard	0.10	8%
Utilities	Kelp processing	Electricity - upstream emissions for ASF utilities	0.08	7%
Utilities	Kelp processing	Electricity - kelp washing & blanching, general building needs (excludes fermentation)	0.07	6%
Waste	Kelp processing	General municipal waste to landfill	0.06	5%
Packaging	Kelp processing	Vacuum bag	0.06	5%

Table 29: Hot spot analysis of Maine Kelp Powder carbon footprint during the study period. Inputs and processes contributing 5% or more impact are listed, all others are below 5%.

Input Category	ASF process	Input	Emissions per lb Maine Kelp Powder, kg CO2e	Percent of Maine Kelp Powder Emissions
Utilities	Drying	PA - propane	1.83	32%
All categories	Kelp farming	All impacts associated with kelp farming	1.28	22%
Utilities	Drying	PA - diesel	1.17	20%
Fuel Use	Drying	Refrigerated transport of wet kelp from Mussel Farm Road to PA	0.65	11%

Maine Kelp Powder

Propane and diesel used at PA Dehydrator contribute more than half of the carbon impact. About 90% of all Maine Kelp Powder is produced at PA Dehydrator and the process is energy intense. Kelp farming and refrigerated transport from Mussel Farm Road, Maine to PA Dehydrator are additional minor hot spots.

ISO 14067 EMISSION REPORTING CATEGORIES

ISO 14067 7.2 requirements for Carbon Footprint of Products study report requires the emissions in Table 30 to be reported. There are no GHG emissions and removals from direct land use change as there is no land use change during farming, processing, and storage and distribution or aircraft transport as no materials are transported via air.

Table 30: ISO 14067 emission reporting categories

GHG emission category	GHG emissions per study period, kg CO2e	Description	Application to this study
GHG emissions and removals linked to main life cycle stage in which they occur, including relative and absolute contribution of each	See Inventory data and footprint section	Absolute and relative GHG emissions for each stage are reported	The CO2e for each material and process in the life cycle is reported in the Inventory Data and Results sectio
Net fossil GHG emissions and removals	470,342	Carbon that is contained in fossilized material	Total emissions
Biogenic GHG emissions and removals	0	Carbon derived from biomass, material of biological origin, excluding material embedded in geological formations and material transformed to fossilized material	The biogenic carbon content of kelp has not been calculated, as kelp has a short life cycle, and the biogenic carbon will be released from the kelp when eaten or disposed.
GHG emissions and removals resulting from direct land use change	0	Change in the human use of land within the relevant boundary; land use change happens when there is a change in the land-use category as defined by IPCC (ie. from forest to cropland)	No direct land use change from kelp farming, production, or storage and distribution
GHG emissions and removals resulting from aircraft transportation	0	GHG emissions from aircraft transportation	No materials are transported via aircraft; kelp is distributed via truck

SENSITIVITY ANALYSES & RECOMMENDATIONS

The goals of sensitivity analyses are to understand how assumptions in data and methodology and uncertainty in the data may affect the PCF results. Sensitivity analysis results are important as they help understand the relative importance of assumptions made and quality of the data.

Table 31: Sensitivity analysis for short and long kelp storage durations for storage excluded in the study period

		Short storage time (19mo cold, 12mo dry)		Long storage time (34mo cold & dry)	
Kelp storage excluded from study	**Total pounds stored**	**Study period Emissions (kg CO2e)**	**Percent change in emissions**	**Study Period Emissions (kg CO2e)**	**Percent change in emissions**
Off-site cold storage of blast frozen farmed kelp	22,263	2,814	1%	5,035	1%
Off-site cold storage of unsold RCK	94,014	11,881	3%	21,261	5%
Cold storage of unsold RCK at ASF	135,260	97,901	21%	175,191	38%
Off-site dry storage of unsold MKP	43,727	1,022	0%	2,897	1%
Total excluded kelp storage	**295,264**	**113,618**	**25%**	**204,384**	**45%**

SENSITIVITY ANALYSIS: KELP STORAGE EXCLUDED FROM THE SCOPE

Emissions from offsite cold storage of farmed kelp not processed during the study period and unsold Ready Cut Kelp and Maine Kelp Powder were excluded from the scope of this study. This includes emissions from transport of kelp to and from storage facilities, energy requirements for storage, and refrigerants for cold storage. To asses the impact of storage duration on total study period emissions, sensitivity analysis were conducted for both short and long storage times. The short storage durations for cold and dry storage are 19 months and 12 months, respectively. The long storage time was 34 months for both cold and dry storage. Estimated storage durations were provided by ASF.

Sensitivity analysis results are shown in Table 31. The cold storage of unsold Ready Cut Kelp has the greatest impact and would result in a 38% increase in study period emissions if stored for the long storage time. Including all additional kelp storage would have at least a 25% increase in study period emissions and up to a 45% increase for a 34 month storage period.

SENSITIVITY ANALYSIS: VARIABILITY IN PRODUCT STORAGE TIMES

For the off-site cold and dry storage included in the study, storage duration can significantly vary. This study currently assumes an average storage duration of 30 months for harvested kelp prior to kelp processing and an 18 month storage period for Maine Kelp powder prior to distribution. Sensitivity analyses were conducted to assess the impact of shorter and longer storage durations. Long and short storage times are 34 months and 19 months for cold storage and 34 months and 12 months for dry storage. Both study period emissions and per pound emissions are reported in Table 32.

Each additional month of off-site cold storage of harvested kelp processed during the study period results in ~1,000 kg CO2e. Each additional month of off-site dry storage of sold MKP results in 11 kg CO2e. If the storage time of harvested kelp was 19 months rather than 30 months, the carbon footprint of ready cut kelp would decrease by 7%.

Table 32: Sensitivity analysis for short and long kelp storage durations for storage included in the study period.

		Short storage time (19mo cold, 12mo dry)			Long storage time (34mo cold & dry)		
Kelp storage excluded from study	**Total pounds stored**	**Study period Emissions (kg CO2e)**	**Per pound emissions (kg CO2e/lb)**	**Percent change in per lb emissions**	**Study Period Emissions (kg CO2e)**	**Per pound emissions (kg CO2e/lb)**	**Percent change in per lb emissions**
Off-site cold storage of harvested kelp for RCK	172,026	21,740	0.13	-7%	38,904	0.23	2%
Off-site dry storage of sold MKP	5,520	129	0.02	0%	366	0.07	1%

SENSITIVITY ANALYSIS: ALL MAINE KELP POWDER PRODUCED USING ELECTRICITY

Currently 90% of Maine Kelp Powder is processed at PA dehydrators and 10% is processed in WI. The emissions intensity of each dehydrator is shown in Table 33. PA Dehydrator emissions intensity is 9 times more than WI. WI uses electricity and natural gas for drying. PA uses electricity, propane and diesel for drying. The impact per gallon of diesel is more than 1.5 times that of propane and natural gas. Drying all kelp in WI results in a savings of 132,000kg CO2e from processing energy and an increase of 48,000kg CO2e due to transporting wet kelp more than double the distance to WI instead of PA, for a net savings of 84,000kg CO2e. This is equal to a reduction of 1.7kg CO2e per pound of Maine Kelp Powder, a 30% savings.

SENSITIVITY ANALYSIS: KELP FARMING YIELD

A sensitivity analysis was performed for both an increase and decrease of 20% harvested kelp. Per ASF, the 2022/2023 growing period was an abnormally low yield, down 56% from the expected kelp yield. This can be due to a variety of reasons, namely weather conditions during the growing period. A sensitivity analysis was also conducted for the expected yield by modeling a 56% increase in kelp yield.

Results show that a 20% increase in yield results in a 17% savings of carbon emissions per pound of kelp farmed. A 20% decrease in yield results in 25% more carbon emissions per pound of kelp farmed. If kelp yields were expected (56% higher), the carbon footprint of kelp farming would decrease by 36%. The yield impact on per pound emissions are shown in Table 34 on the following page. Kelp yield has a greater impact on Maine Kelp Powder as ~9lbs of wet kelp are required to produce 1 lb powder. This highlights the importance of yield and how fluctuations in yield affects the carbon footprint.

Table 33: Emissions intensity of drying kelp at each of ASF drying contractors

Dehydrator	Total emissions (kg CO2e)	Wet kelp processed (lbs)	Emissions per lb (kg CO2e/lb)
PA	148,143	415,126	0.36
WI	1,800	46,992	0.04

Table 34: Sensitivity analysis of yield impact on per pound emissions

Yield Scenario	Kelp product	Scenario per pound emissions (kg CO2e/lb)	Percent change from baseline
Baseline	Farmed Kelp	0.14	n/a
	Ready Cut Kelp	1.08	n/a
	Maine Kelp Powder	5.74	n/a
Expected yield (56% increase)	Farmed Kelp	0.09	-36%
	Ready Cut Kelp	1.03	-5%
	Maine Kelp Powder	5.28	-8%
20% yield increase	Farmed Kelp	0.11	-17%
	Ready Cut Kelp	1.06	-2%
	Maine Kelp Powder	5.53	-4%
20% yield decrease	Farmed Kelp	0.17	25%
	Ready Cut Kelp	1.12	3%
	Maine Kelp Powder	6.06	6%

SENSITIVITY ANALYSIS: 10% REDUCTION IN FUEL USE

An across the board 10% reduction in fuel use for boats and trucks through increases in efficiency, minimizing idling, or using more efficient makes/models of equipment, has the potential to reduce annual carbon emissions by over 10,000kg CO2e.

SENSITIVITY ANALYSIS: ADOPT RENEWABLE ENERGY

ASF purchased electricity, made up of the average Maine grid mix, contributes 6% of the study period carbon footprint. Adopting 25% wind energy and 25% solar energy has the potential to reduce emissions by over 13,000kg CO2e, and doubling the adoption to account for 100% renewable energy has the potential to reduce emissions by over 26,000kg CO2e.

Emissions from purchased electricity within ASF's value chain due to off-site cold storage of kelp and processing of Maine Kelp Powder accounts for 6% of the study period carbon footprint. Encouraging and supporting suppliers to adopt renewable energy or purchase renewable energy certificates (RECs) is one strategy for reducing ASF's scope 3 footprint. Adoption of 50% renewable energy by partners within ASF's value chain has the potential to reduce emissions by over 14,000kg CO2e. Adoption of 100% renewable energy would reduce emissions by over 28,000kg CO2e.

If renewables are adopted for 100% of electricity for both ASF and partners within its value chain, this would reduce the footprint of Ready Cut Kelp by 0.23 kg CO2e/lb and Maine Kelp Powder by 0.03 kg CO2e/lb, 21% and 0.4% reduction, respectively.

SENSITIVITY ANALYSIS: INCREASE THE LIFESPAN OF MOORING CHAINS IN KELP FARMING

Galvanized mooring chains account for half of farming consumable emissions and 32% of kelp farming emissions. They have an estimated lifespan of 2.5 – 3.5 years. Sensitivity analysis were conducted for increasing lifespan to 5 and 10 years. Results are shown in Table 35. Investigate the use of other materials that may be more durable and less impactful.

Table 35: Sensitivity analysis for increasing the lifespan of mooring chains in kelp farming

Lifespan scenario	Annual emissions savings (kg CO2e)	Farming emissions savings (kg CO2/lb)	Ready Cut Kelp emissions savings (kg CO2e/lb)	Kelp powder emissions savings (kg CO2e/lb)
5 years	6,285	0.01	0.01	0.10
10 years	10,006	0.02	0.02	0.16

SENSITIVITY ANALYSIS: ASF ELECTRICITY ALLOCATION

ASF's processing building's electricity is not sub-metered, therefore there is no data to determine how much electricity is used by the cooler, freezer, and general building electricity. Therefore, allocation of electricity in this study is based on estimates by ASF's electrician. There is uncertainty specifically around the amount of electricity used by the freezer.

Total building electricity for the study period is 282,980 kWh, and ASF's electrician estimates 20,000 kWh is used by the cooler, 200,000 kWh is used by the freezer, with the assumption the freezer evaporator heaters ran 50% of the time with a 50% duty cycle, and the remaining 62,980 kWh is general building electricity. This energy allocation is used throughout the study.

ASF's electrician provided a different estimate of 98,000 kWh used by the freezer (40% duty cycle with the heater on episodically). Because the total energy use remains the same, when freezer energy decreases, general building electricity increases by an equivalent amount. In this scenario, the general building electricity increases to 164,980 kWh, resulting in an increase of total study emissions by 31,534 kg CO2e. Ready Cut Kelp emissions increase by 0.13 kg CO2e/lb or 12%.

Table 36 shows the allocation of electricity and corresponding emissions at different duty cycles and heater running times. This analysis illustrates the importance of energy allocation and how estimates can dramatically affect results.

Table 36: Sensitivity analysis of electricity allocation for kelp processing and freezing

	Allocation Scenarios	
	50% duty cycle; 50% heater run time	**40% duty cycle; intermittent heater run time**
Total building electricity[a] (kWh)	282,980	282,980
Total electricity allocated to freezer (kWh)	200,000	98,000
Electricity from freezing and on-site storage of distributed RCK[b] (kWh)	2,799	1,372
Electricity from freezing and on-site storage of non-distributed RCK[c] (kWh)	197,201	96,628
Electricity allocated to cooler (kWh)	20,000	20,000
General building electricity (kWh)	62,980	164,980
Electricity included in the study[d] (kWh)	**85,779**	**186,352**
Total emissions (kg CO2e)	**26,896**	**58,430**

a. excludes electricity from the fermentation room
b. included in the system boundary
c. excluded from the system boundary
d. sum of electricity from freezing and on-site storage of distributed RCK, electricity allocated to cooler, and general building electricity

RECOMMENDATIONS

Figure 8 below shows the reduction in impact associated with the recommendations in the sensitivity analyses in this section. The biggest reduction opportunity is processing all Maine Kelp Powder using electricity. This intervention alone can reduce the annual impact by 18%. Furthermore, adopting 100% renewables both at ASF facilities and within their value chain has the potential to decrease annual emissions 11%. Adoption of all interventions could decrease ASF's study period emissions by 37%.

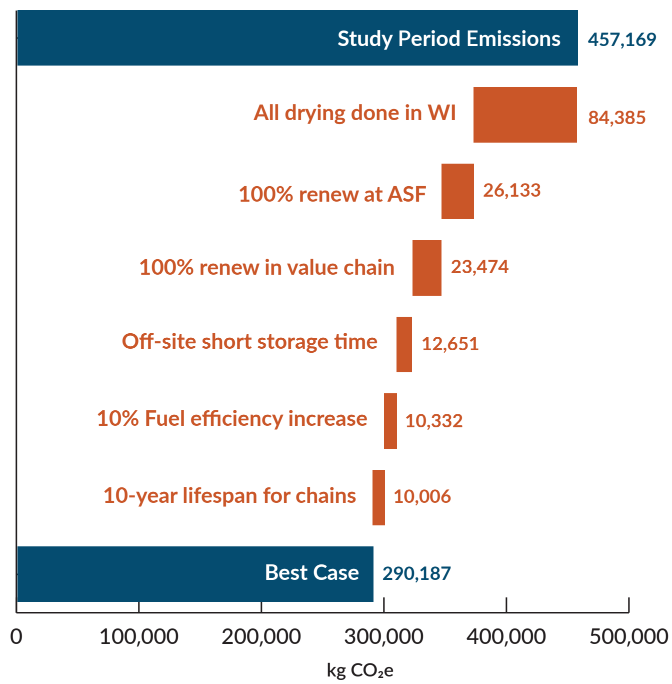

Figure 8.
Sensitivity analysis results

CONCLUSIONS

The goal of the study was to calculate the product carbon footprint (PCF) of ASF's farmed kelp, Ready Cut Kelp, and Maine Kelp Powder and identifying hot spots within their production. This allows for the identification of specific reduction strategies within ASF's operations.

Utilities at ASF and dehydrators, fuel use for boats and transport, and refrigeration of kelp and Ready Cut Kelp represent more than 80% of ASF's study period carbon footprint. On a per pound basis, mooring chains and diesel use in lobster boats contribute more than half of farmed kelp emissions, all cold storage and freezing as well as farming contribute more than a third of Ready Cut Kelp emissions, and more than half of all Maine Kelp Powder emissions are from propane and diesel use at PA dehydrators.

The biggest opportunity for impact reduction is producing all Maine Kelp Powder in WI, saving just under 20% of annual carbon emissions. Adopting 100% renewable energy at ASF and along the value chain reduces annual emissions by an additional 11%.

ENDNOTES

1 Carbon emissions vary by type of renewable energy. NEWE grid energy emits 0.25 kg CO2/kWh, wind energy emits 0.003 kg CO2/kWh, and solar energy emits 0.01 kg CO2/kWh.

2 Czyżewski, B., & Kryszak, Ł. (2018). Impact of different models of agriculture on greenhouse gases (GHG) emissions: A sectoral approach. Outlook on Agriculture, 47(1), 68-76.

3 https://www.ipcc.ch/assessment-report/ar6/

4 Ulrich, et. al., Tailpipe greenhouse gas emissions from tank trucks transporting raw milk from farms to processing plants, International Dairy Journal, 31:1, 2013, https://doi.org/10.1016/j.idairyj.2012.09.009

5 https://ferrygogo.com/route/rockland-northhaven/

6 Table 1:
https://mdpi-res.com/d_attachment/energies/energies-04-00239/article_deploy/energies-04-00239.pdf
https://www.maine.gov/mdot/ferry/assets/docs/2020/tarrifs/Tariff9.1.pdf

7 Watcharapong Tachajapong, Kengkamon Wiratkasem, Niti Kammuang-lue, Somchai Pattana, Preliminary study on specific energy consumption of cold storage room in Thailand's cold chain, Energy Reports, 8:10 10, 2022, 336341, https://doi.org/10.1016/j.egyr.2022.05.171

8 https://www.spartanlogistics.com/warehouse-space-calculator

9 Watcharapong Tachajapong, Kengkamon Wiratkasem, Niti Kammuang-lue, Somchai Pattana, Preliminary study on specific energy consumption of cold storage room in Thailand's cold chain, Energy Reports, 8:10 10, 2022, 336-341, https://doi.org/10.1016/j.egyr.2022.05.171

10 https://www.spartanlogistics.com/warehouse-space-calculator

11 US EPA Stationary Refrigeration Leak Repair Requirements, https://www.epa.gov/section608/stationaryrefrigeration-leak-repair-requirements

12 https://www.spartanlogistics.com/warehouse-space-calculator

13 https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-andfigures-materials

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