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Wild caught Alaska sockeye salmon: A case study of the food energy water nexus for a sustainable wild catch fishery

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ABSTRACT

There is a gap in information in the literature regarding the energy and water embodied is seafood, especially wild catch fisheries. This work draws on primary and secondary data to assess, through a life cycle approach, the energy and water consumed to catch and process wild sockeye salmon in Bristol Bay, Alaska (USA). The Bristol Bay sockeye salmon fishery is a very remote wild catch fishery. All material inputs and labor are either barged or flown in from other parts of Alaska, and the lower U.S. states. In addition, a large monitoring and enforcement effort by the State of Alaska is conducted to sustainably manage the fishery. We therefore expanded the system boundary to include energy and water for commuting laborer's and regulators to depict the system within a wider context. Structured interviews were conducted to elicit information from fishers and processors related to their use of water and energy and to ascertain potentials for reducing energy and water demand of the fishery. The energy associated with fishing and processing sockeye ranges between 24.6 and 33.8 MJ kg^{-1} with fishing effort accounting for 43% of the total energy embodied in products. The water embodied in final sockeye salmon products ranged between 10 and 23 L/kg, mainly the result of processing and packaging. Combined, labor transport and fishery management contributed 8% to the embodied energy in sockeye products, while contributing less that 1% of the water embodied in sockeye products. While not insignificant, the energy costs of fishery management are inconsequential and should provide adequate justification for continued sustainable management and forceful information for consumer choice. The combination of governmental regulations and the remote location results in few opportunities for lowering energy and water demand of this already efficient fishery.

1. Introduction

In this study, we use a Life Cycle approach to evaluate the seafood, energy, water nexus in the Alaskan sockeye salmon fishery. Part of a larger study funded by the United States Department of Agriculture under the National Science Foundation's Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) program, our study is investigating energy and water consumption in the USA seafood supply chain to identify strategies for increased efficiencies and reduction of wastes. In this paper, we address the relative proportions of energy and water use in the Bristol Bay, Alaska sockeye salmon fishery from catching to gate of processing facility. In addition, we expand the system boundary to include the energy consumed for governmental monitoring and enforcement efforts, and for transport of laborers from the lower 48 states of the USA to Alaska.

1.1. Study motivation

United Nations (UN) Food and Agriculture Organization statistics on global fisheries provide both optimism and warning signs for the future of a sustainable seafood system. In 2018, global seafood captures reached 96.4 million tonnes, an increase of over 5% from the previous 3 years. Yet, as of 2017, 34.2% of global fish stocks were overfished, an increase of 142% since 1974 (FAO, 2020). Worldwide, seafood accounts

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for 17% of animal protein consumption and 7% of all protein foods (FAO, 2020).

Increased global demand for seafood has led to more production and technological developments in processing, handling and transport (Costello et al., 2020) which, in turn, has translated into increased energy and water demands (Tlusty et al., 2019; Tyedmers, 2004). Recent consumer awareness of the link between climate change and energy use and the fragility of global water systems has resulted in demands for 'green' products and accounting systems that make choices more transparent (Hameed and Waris, 2018). Clearly, accounting and highlighting the energy and water consumption along the seafood supply chain will not only provide consumers the information with which to make informed decisions, but potentially help the industry to increase efficiencies along the value chain (Tlusty et al., 2019).

If global seafood systems, especially marine capture fisheries, are to meet Agenda 21 UN Sustainable Development Goals, monitoring and enforcement may need to become more commonplace (Zhang, 2021; FAO, 2020: United Nations, 2021). In areas with intensive fisheries management, fish stocks are above target levels or rebuilding, while unmanaged fisheries are in poor shape (Hilborn et al., 2020). Effective management of fisheries could result in more productive, profitable, and sustainable fish stocks (Gaines et al., 2018; Costello et al., 2016), but could increase demand for energy. In most cases the benefits of fisheries management exceed the costs (Mangin et al., 2018), yet, the perceived costs of monitoring have been one of the largest barriers to implementation (Fujita et al., 2018*)* and there is little data on the energy costs of monitoring and enforcement (Avadí and Fréon, 2013).

The fisheries sector is a major source of employment, employing over 39 million workers worldwide in 2018 (FAO, 2020). Some fisheries, because of their remoteness are burdened with considerable costs in transporting laborers from their place of residence to points of fishing and processing. Little is known about the relative proportion of total energy demand for labor transport to these remote fishing and processing locations.

In a study of Corporate Social Responsibility (CSR) of the seafood industry, Packer et al. (2019) found that the largest gap in information necessary to bolster CSR by the industry was robust and consistent accounting practices. While there are many studies documenting the energy (and to a lesser extent, water) used in aquaculture (Bohnes et al., 2019), there are fewer studies that document energy use in wild catch fisheries (Avadí and Fréon, 2013; Avadí et al., 2020) and the majority of those studies are for purse seining and trawling technologies. There is only one study documenting energy use by salmon fishers (Fulton, 2010) and no studies that document energy and water use using driftnet technology for any target species. This study helps to fill the gap in accounting by documenting energy and water use in a wild catch salmon fishery that uses driftnet technology.

The novelty of this research effort lies in the fact that there are only a few studies of energy consumption in wild catch fisheries, and no studies of water consumption. In addition, there are no studies of the energy costs of transporting labor to remote fishing locations, and no studies of the energy demands for management and monitoring of wild catch fisheries. Finally, this analysis not only focuses on documenting the energy and water use through the first 3 stages of food production, but also completes in-depth interviews with stakeholders to elicit information from fishers and processors related to their use of water and energy, seeking their contributions to potential strategies to improve efficiency.

In all, these factors have precipitated the following questions that have motivated this study:

In order to bench mark the current energy and water use and provide insight into where the biggest opportunities for increases in efficiency might lay, we posed the following question:

1. What is the energy and water demand of the Bristol Bay, Alaska sockeye salmon fishery and how is it partitioned between catching, processing, and packaging the finished product?

   Because sustainable wild catch fisheries are subject to overfishing without some level of management, it is important to evaluate the energy and water costs of monitoring and enforcement, we therefore posed the second question:
2. What proportion of total energy demand is attributable to governmental management and monitoring?

   Many global fisheries are in remote locations that require time and energy for transport of both products and labor, making evaluating transport costs an important component of developing pathways toward resilient and sustainable wild catch fisheries. This led to the third question.
3. Due to the remoteness of the Bristol Bay, Alaska sockeye salmon fishery, how much does transport of inputs including labor contribute to the overall energy demand of the final product?

Finally, in keeping with the vision of this VSI, *"A Resilient and Sustainable World: Contributions from Cleaner Production, Circular Economy and Eco-innovation",* we elicited information from fishers and processors related to their use of water and energy, seeking their contributions to potential strategies to improve efficiency, which provided a fourth question.

4. How do stakeholders in the Alaska sockeye salmon fishery view the potential for energy and water savings in the future?

2. Materials and methods

2.1. Life cycle approach

This analysis uses a life cycle approach to assess the energy and fresh water that is embodied in sockeye salmon product, starting with raw material acquisition from the environment and ending at the gate of the processing facility as packaged canned, filet or head and gut sockeye salmon. We have estimated both direct (foreground) and indirect (background) energy and water consumption. Along the production chain we have considered several functional units according to the three stages under consideration:

1) 1 kg (live weight) of unprocessed and landed sockeye salmon,
2) 1 kg of processed sockeye salmon,
3) 1 kg of packaged (canned, fillet, and head and gutted (H&G)) sockeye salmon.

As our main focus is placed on energy and water requirements, to assess the magnitude and significance of these selected environmental impacts, we have focused on Fossil Depletion Potential (FDP) and Water Depletion Potential (WDP) impact categories, calculated in kg of oil equivalent (or MJ) and m^3 of water, respectively. The study has been performed utilizing the SimaPro software version 9.0.0.30 (https://simapro.com/), the Ecoinvent database version 3.6 (Wernet et al., 2016), and the ReCiPe Midpoint (H) v.1.13 method (Goedkoop et al., 2013) for impacts assessment has been chosen.

2.2. Background

Bristol Bay, Alaska, is the location of one of the world's largest (and most valuable) sockeye salmon (*Oncorhynchus nerka*) fishery. Beginning in late June or early July, and extending for 4–6 weeks, an average of 39 million salmon return to spawn in the rivers that flow into Bristol Bay (ADFG, 2020a) after spending anywhere from 1 to 4 years feeding in the North Pacific Ocean (Groot and Margolis, 1991). The Bristol Bay sockeye salmon fishery is one of the most monitored and regulated fisheries in the world. Monitoring includes stock assessment and aerial surveys of salmon abundance. Enforcement of regulations during the season, uses helicopters, planes, rigid hull inflatables, and undercover boats to transport biologists and wildlife troopers (Boenish et al., 2020).

Supplying 53 percent of the world's sockeye salmon (McKinley Research, 2021), the fishery is Alaska's largest private employer, employing nearly 14,700 people for summer, seasonal and year-round employment (8200 fishers, 5700 workers in seafood processing and 700 in fishery management and other support industries) (Wink, 2018), of which most workers are nonresidents (Seung, 2016).

The fishery consists of both driftnet and setnet fishers (referred to as "driftnetters" and setnetters"). Up to 1500 driftnet vessels with crews of up to 4 participate each year in the relatively short 4–6 week salmon run (Wand, 2018). About 900 shore-based "setnetters" also harvest salmon from shore-based riverside locations.

Bristol Bay sockeye harvest is processed locally by a total of 33 processing companies in both shore-based and floating processing facilities with the 15 largest accounting for over 99% of the total catch (McKinley Research Group, 2021). During the period 2015–2019, an average of 71 million kg of sockeye were processed into four products: fresh & frozen headed and gutted (67%), fresh and frozen fillets (16%), canned (13%), and salmon roe (4%).

2.3. System description

Fig. 1 is a systems diagram of the main life cycle stages for salmon fishing and processing. Circles are sources of energy, water, regulations, and labor from outside the system. The bullet shaped symbol represents environmental production (processes happening in the ecosphere). Rectangles represent processes under human control, and the arrow symbols represent transport processes.

This analysis is focused on driftnet fishing boats, shore based setnetters and salmon processing in both land-based and floating processing facilities in Bristol Bay. We ignore the environmental production (Fig. 1) and consequently the analysis begins with the extraction of raw materials (fishing) and ends with the processing of live fish into canned, fresh, and frozen products at the processing-gate.[1] The assessment constitutes a "cradle to processing gate" analysis divided into two main stages, fishing and processing.

In the first stage (Fig. 1), salmon fishing, the sockeye salmon are caught with driftnet vessels and transferred to tender vessels for delivery to processing facilities. The second stage, processing facility, is divided into two sub-stages. The first, an initial processing stage, where salmon are slaughtered, gutted, and turned into three different products, 1) salmon for canning 2) fresh and frozen head and gut (salmon trimmed of head and eviscerated) or 3) fresh and frozen salmon fillet. Additionally, there is a by-product termed "offal" which consists of all the trimmed salmon parts and gut contents which can be ground and dumped in the ocean or processed into fish meal and fish oil, depending upon the equipment in a plant and whether the processor is permitted to dump offal.

In the second processing sub-stage, the salmon products are packaged in polystyrene, plastic, cardboard, and/or metal cans for shipment to USA, Canada, and Europe and Asia. The quantity of offal produced from each product was different, 35%, 50% and 60% for H&G, canned, and filet respectively. Therefore, each product form required a different quantity of whole fish to produce 1 kg of product (1.54 kg, 2.0 kg, and 1.67 kg for H&G, canned, and filet respectively). We then assigned energy and water inputs based on the quantities of fish required to produce the 1 kg of product.

2.4. System boundary expansion

Because of the remoteness of Bristol Bay (there are no roads that connect the Bay to other parts of Alaska), all laborers, materials, and energy must be imported by either air or sea transport. Therefore, to the outside observer, it appears that significant quantities of energy are consumed in transport of laborers and materials to the fishing grounds and processing facilities. Also, the State of Alaska invests considerable time and effort in management of the fishery; in fact, it is often cited as a success story in fisheries management (Hilborn et al., 2003, 2020) and has been certified by the Marine Stewardship Council as well managed (Phillips et al., 2003). Because of these two factors, we expanded the system boundary to include transport to and from the lower 48 USA states and to include the energy required by State agencies for monitoring and enforcement of regulations.

2.5. Data collection and inventory

All primary data are based on averages of a 3-year period (2016–2018) obtained from 3 seafood companies (which represented over 24% of total systemwide harvesting and processing) and the Alaska Departments of Fish and Game and Public Safety. The energy and water embodied from background processes in boats, buildings, equipment, and infrastructure materials, were obtained from the Ecoinvent® v3.6 database.

2.5.1. Fishing stage

The main inputs considered for the fishing stage were energy consumption related to catching wild fish (fuels for driftnet, setnet and tender vessels) and construction and maintenance of the vessels and equipment amortized over 25 years. Total fuel consumption of the fleets of 3 seafood companies representing 598 contract driftnet vessels, 84 tender vessels and 323 setnet vessels were obtained. Direct water consumption in the fishing stage was negligible. The energy and water embodied in fishing and tender vessels were derived from major materials content of the vessels (fiber glass, aluminum, and steel) and weights computed using vessel-specific data (length, beam, depth) according to (Bower, 1985). Ecoinvent® v3.6 database (Wernet et al., 2016) was used to estimate energy and water required to produce the mass of vessels.

Driftnet crewmember data and transport distance to and from the fishery for the 2017 fishing season were derived from permit holder information that includes the residence state of permit holders (CFEC, 2019). We assumed that crewmembers and permit holder were from the same state. We computed the air distance from home airport to Dillingham, Alaska through Anchorage, Alaska. We allocated transport distance (person-kilometers) based on average 2017 season catch by dividing the total person kilometers for driftnet crews by the total sockeye catch, then using that ratio and energy per person-kilometer data from Ecoinvent 3.6 we assigned labor air transport energy to the fishing stage.

2.5.2. Governmental inputs

Direct energy use for government monitoring and enforcement was obtained from each agency involved in the 2018 fishing season. Based on previous experience, we assumed the energy and water embodied in equipment (a total of 3 helicopters, 7 aircraft, 35 boats of varying size and 12 pickup trucks) when amortized over 25 years was negligible.

2.5.3. Processing and packaging

Data for fish processing facilities were collected from 4 shore based and 2 floating facilities. Direct energy use by processing facilities is both diesel used on site for electricity generation and electricity from local grids (which is based on diesel generators). Direct water consumption is water that is evaporated plus any ground water that is pumped used and discharged to the sea. Surface water (rivers) that is used in processing was not considered consumed water since the river surface water would have discharged to the sea naturally. We considered developing an algorithm that would evaluate the portion of fresh water that was "used" based on changes to water quality between inflow and outflow, however, this was not possible because the State of Alaska does not require

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[1] In a companion paper in this volume, using Emergy Analysis, we include environmental production and the energy embodied in labor to give a fuller perspective of their relative contributions to the salmon value chain.

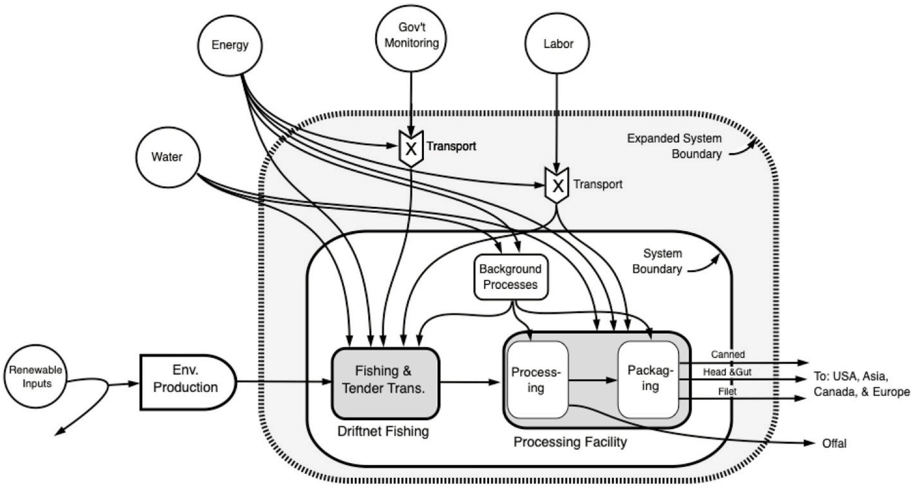

Fig. 1. System diagram of the stages of Bristol Bay, Alaska USA sockeye salmon fishery and processing. The solid boundary line denotes the system initially evaluated and the dashed outer boundary line shows the expanded system that includes energy required for government monitoring of the fishery and for labor transport to and from Bristol Bay.

water quality monitoring of discharge waters from processing plants.

Energy and water use for packaging was derived from Ecoinvent/Simapro as background consumption to produce the packaging materials. Materials were allocated as follows for canned, fillets and H&G: 100% of energy and water consumed to produce cans was assigned to canned salmon product. Polystyrene packaging and plastic film were assigned to fresh H&G and fillet. Cardboard boxes and wooden pallets were assigned to each of the product forms produced based on their percent of the total product.

2.5.4. *Material and product transport*

All materials used in processing as well as diesel energy used in fishing and processing plants are primarily transported by barge from Seattle, Washington. Because of the diverse nature of the materials used, we could, not accurately estimated transport costs from place of manufacture to Seattle and so estimates of transport costs are under estimates. Sea and Air distances from Seattle, WA to Dillingham, AK were obtained from ports.com (http://ports.com) and air miles calculator (https://www.airmilescalculator.com) (sea distance = 4100 km; air distance = 2700 km).

2.5.5. *Labor transport*

Energy use for the air transport of workers at processing plants was computed from the number of workers at each plant and distance from Seattle WA. While workers are from many locations including the lower 48 states, Eastern Europe, and Latin America, we could not, with any degree of certainty, consider these longer distances since we had no data on actual place of workers' origin. Therefore, estimates of transport costs of processing plant workers is most likely an underestimate. Transport of fishing vessel crews was computed from the closest international airport of their home residence to Dillingham, AK.

2.5.6. *Life cycle inventories*

The material and energy inputs of the fishing, processing, and packaging phases are detailed in the inventory analysis given in Tables 1 and 2. The inventory data were computed per kg of product from each of the three stages of the value chain.

Table 1
Inventory for fishing and processing phase to produce 1 kg of salmon product.

Activity name	Unit	Amount[a]
Fishing phase		
Driftnet vessels (aluminum and fiberglass)	kg	1.0E-02
Tenders (steel)	kg	1.2E-02
Diesel	kg	2.4E-01
Labor (Air Transport)	p[a]km	6.2E-01
Monitoring/Enforcement activities (Diesel)	kg	3.8E-03
Sockeye (live weight)	kg	1.72
Processing phase		
Building (steel and concrete)	m^2	6.7E-05
Sodium chloride	kg	3.9E-02
Water	m^3	9.75E-03
Diesel	kg	1.3E-01
Electricity (USA)	kWh	1.2E-01
Labor (Air Transport)	p[a]km	6.1E-01
Processed fish	kg	1.00
Offal	kg	0.72

[a] Data are based on weighted mean of 598 contract driftnet vessels, 84 tender vessels and 5 processing plants.

Table 2
Inventory for packaging phase to produce 1 kg of packaged salmon product.

Activity name	Unit	Amount[a]
Packaging phase		
Processed fish	kg	3.00
Wooden pallets	kg	2.1E-02
Fiber boxes	kg	2.3E-02
Tin plated chromium steel sheet (only for canned)	m^2	8.8E-03
Plastic	kg	2.1E-03
Packaging transport (ship)	ton[a]km	4.51E-01
Sockeye salmon products		
- H&G	kg	1.00
-Canned	kg	1.00
-Frozen fillet	kg	1.00

[a] Data are based on weighted mean of 5 processing plants.

2.6. *Stakeholder interviews*

To collect information about stakeholders' views on the use of water and energy and challenges facing the sockeye salmon sector, qualitative interviews were conducted on the phone or using Zoom (Zoom Video Communications, Inc, San Jose, USA). The interviewees included fishers, processor managers or executives, and stakeholders with expertise on the sockeye salmon sector in Bristol Bay, Alaska. Additional information on these topics was collected through informal conversations with supply chain actors and other stakeholders in person, by phone, or via Zoom. For the main interviews, a notetaker participated in the calls to capture responses, and most interviews were audio recorded to allow the research team to check for accuracy as needed. The interviews were conducted between February 2020 and May 2021. An interview guide (see Supplemental Material) was used to ask interviewees the same set of main questions, and the responses were analyzed and summarized by topic and type of stakeholder. The interview data were managed and analyzed using MAXQDA (VERBI Software, Berlin, Germany).

3. Results

3.1. Estimating energy and water use in sockeye salmon production and processing

The contribution analysis of processes and raw material inputs involved in fishing, processing, and packaging stages are shown in Figs. 2–4 respectively. The data represent the weighted mean of all the driftnet, setnet and tender vessels and weighted means of the processing facilities. Fig. 2 shows the total and relative portions of the energy and water associated with 1.0 kg of wild-caught sockeye salmon (live weight) related to the fishing phase. Total energy embodied in the salmon (both direct and indirect energy) was 8.98 MJ kg^{-1} while embodied water was 1.06 L kg^{-1}. About 77% of the total energy use was due to the direct energy (diesel) consumed by the vessels to catch and transport the fish to the processors. The contribution of infrastructure (vessels and nets) was nearly 14 percent. The energy spent on surveillance and control (monitoring) activities by government was only 2% of the total energy associated with the fishing phase. The energy costs of air transport of the fishers to Alaska accounted for about 6% of total energy.

Since very little water is used directly in the fishing stage, the embodied water was mainly affected by the background water used to produce and transport the inputs. In particular, 76% was embodied in the infrastructure, 20% in the diesel, and only 3% and 1% respectively for worker transport and monitoring activities.

Energy and water consumption change dramatically during the processing stage (Fig. 3). While energy consumption increased by 144% to 22.4 MJ kg^{-1}, compared with the non-processed fish, the consumption of water increased more than 11 times to 12.6 L kg^{-1} because of the amount of direct water used during the processing stage. Direct energy used in processing accounts for about 33% of the total, while the infrastructure and labor transport account for 3% and 4% respectively. The remaining 60% is accounted for by the salmon input.

Direct water use accounts for 77% of total embodied water. The water embodied in the salmon during the fishing phase accounted for 13% of the embodied water, while indirect water embodied in infrastructure and energy used in processing accounted for 4% each. Water embodied in the air transport of laborers amounted to less than 1% of total embodied water.

Each of the three product forms require different materials and quantity of packaging (Fig. 4). The mean total energy required for catching, processing, and packaging 1 kg of the three product forms examined was 25.0 MJ, 34.5 MJ, and 33.9 MJ for H&G, fillet, and canned, respectively. Packaging represented about 33% of total energy to the processing gate for canned products and 19% and 20% for fillet and H&G respectively. Mean total water consumed for producing and packaging 1 kg of H&G, fillet, and canned salmon was 10.0 L, 23.0 L, and 22.1 L respectively. Water embodied in the packaging materials was about 32% of canned water use and 30% and 19% consumed in producing packaging materials for H&G and fillets respectively.

3.2. Visualizing relative contributions

Fig. 5 shows a Sankey diagram that represents all energy flows into the supply chain of sockeye salmon from fishing to processing and finally to packaging. The widths of the bands are linearly proportional to the energy used, directly, and embodied in the nonenergy inputs. The indirect energy in background process to produce infrastructure accounted for about 8% of total energy demand. By far, the largest demand for energy is the direct energy used in fishing and processing (58%), while the background energy in packaging accounts for about 27% of total input, primarily embodied in the tin-plated chromium steel used in producing the salmon cans. The transport of laborers from points of origin to Bristol Bay accounted for about 6% of total energy.

At the processing stage, a mass allocation was applied to allocate energy to the 3 product forms (canned, fillet, H&G). The “waste product’ during the processing phase, called offal, represents a considerable quantity of the liveweight of salmon processed. Using a weighted average of Crapo et al. (1993) conversion efficiencies and percent of product forms from McKinley Research Group (2021), we computed total products meant for human consumption were 70% of round weight and therefore offal was 30% of mass output at the processing gate.

We did not assign energy or water use to offal, instead, assigning 100% to the products. Currently, only a few companies use offal to make fish meal and oil or petfood while the majority grind up offal into a slurry and return it to the ocean waters of Alaska.

The largest use of water is in the processing stage as shown in the

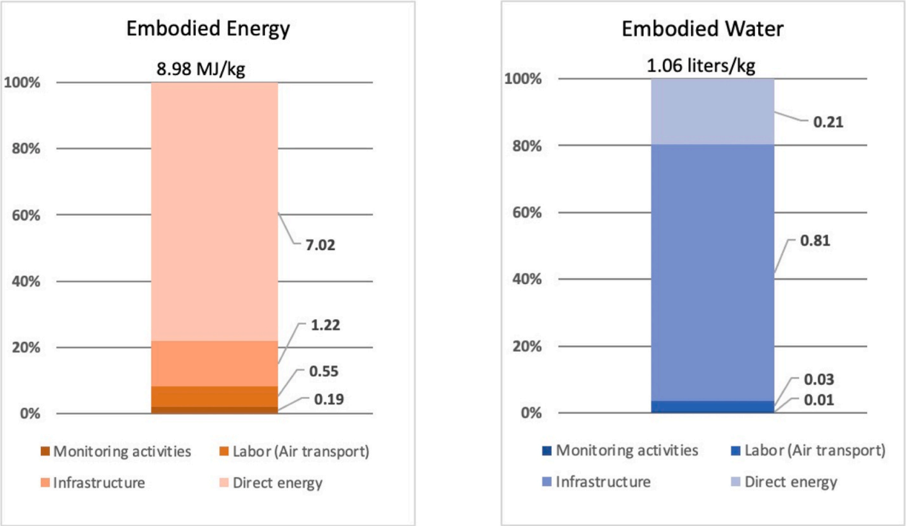

Fig. 2. Weighted mean energy (orange) and water (blue) embodied in landed sockeye salmon during the fishing phase.

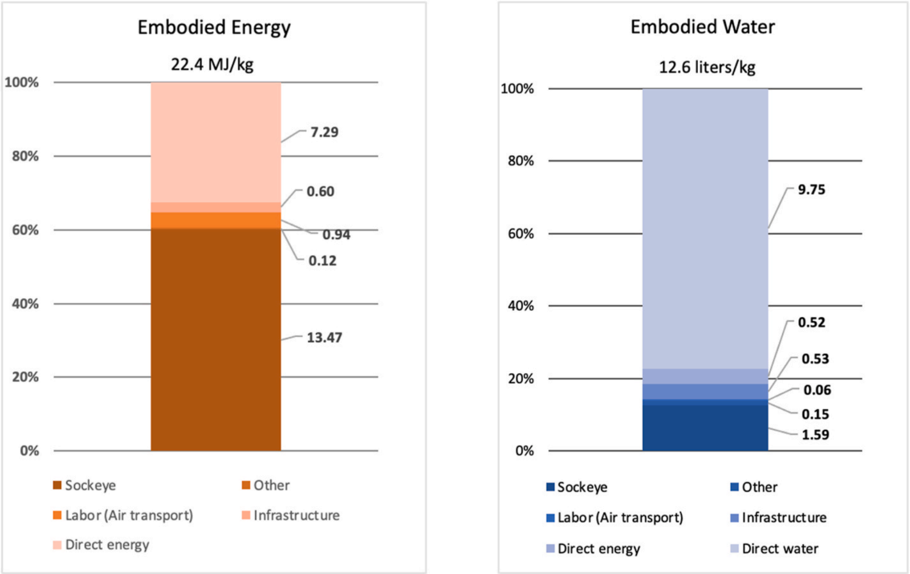

Fig. 3. Weighted mean energy (orange) and water (blue) embodied in an average kilogram of processed sockeye salmon.

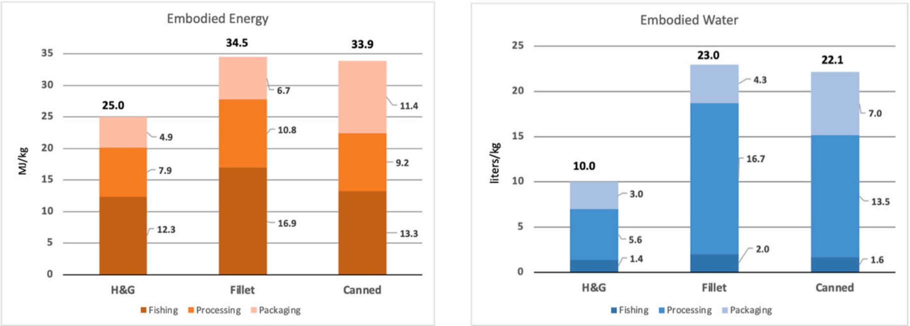

Fig. 4. Weighted mean energy (red) and water (blue) embodied at the processing gate following packaging (per kg of sockeye salmon product).

Sankey diagram in Fig. 6. Seventy-seven percent of all water embodied in the salmon product forms at the gate of the processing stage is processing water, while the remaining 23% is contributed from background processes producing facility infrastructure and fuel. At the packaging gate, water embodied in packaging is about 28% of the total water consumption, the largest contributor of which is the water used in can production.

3.3. Qualitative stakeholder interviews

3.3.1. Energy

Reducing diesel use was not a top priority for sockeye salmon fishers, for three main reasons: i) the importance of moving quickly to open fishing areas during the short, intense fishing season, ii) there is no suitable equipment or technology available to fishers that could be used to reduce fuel use, and iii) fuel is not the largest economic expense for sockeye salmon fishers, typically about 15% of total operating costs.

In recent years, many sockeye salmon vessels have been equipped with refrigerated sea water (RSW) systems to cool and store fish because processing companies pay higher prices for fish that are immediately cooled onboard fishing vessels. While RSW would appear to increase the energy used on vessels, interviewees discussed potential tradeoffs which we did not evaluate. The most important of which is that if the RSW is powered separately from the main engine, energy saving could accrue while waiting to off load catch by shutting down the main engine. Additionally, to the extent RSW improves cooling effectiveness, it prevents seafood loss, with all its embodied energy.

There was general agreement among fishers that the State of Alaska's regulations governing driftnet vessel length is inadvertently contributing to boats that are less efficient than they would be with a longer size limit. The purpose of the length limit is to prevent fewer, larger boats from dominating the fishery. Interviewees recognized that narrower, longer boats with the same capacity to hold fish would be, energetically, more efficient.

Processors reported challenges with their energy supply including high prices, surge pricing (higher prices during high demand periods, which is hard to avoid during the peak of the season), and some power surging that has damaged processing plant equipment. Energy saving strategies that processing plants use include installing LED lights, using variable speed motors, and keeping motors properly maintained. Most local electric power grids use diesel fuel to provide electricity, and many processors use diesel powered generators. There could be significant energy savings if alternatives were available. It was reported that there is one hydroelectric plant planned for the Nuyakuk River to supply Dillingham, but the timing was not clear. Wind and geothermal sources of energy have been explored in the past, but interviewees reported that neither were viable. In all, it appears there are few alternatives for saving energy within the processing sector of sockeye salmon fishery.

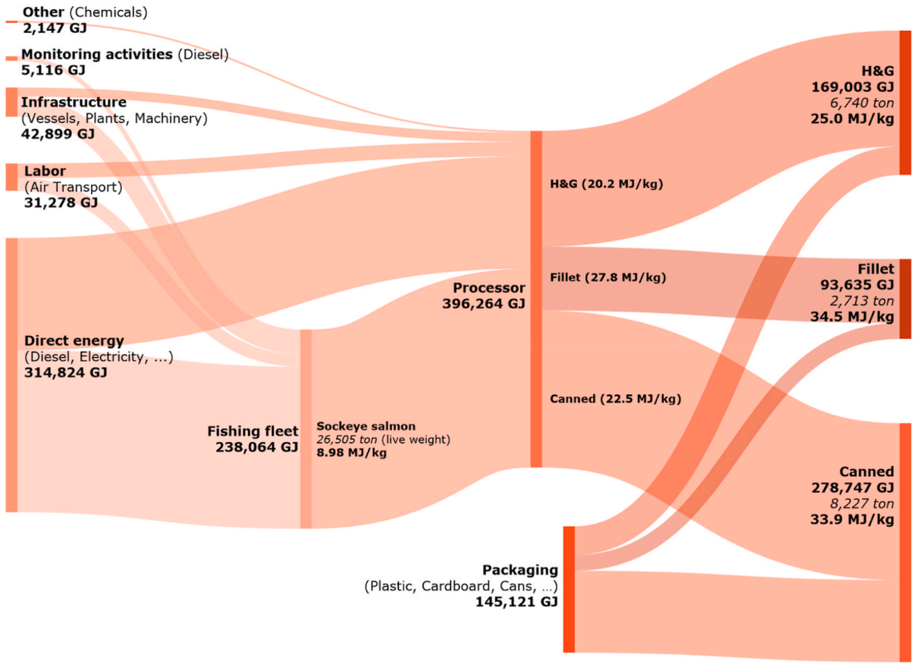

Fig. 5. Sankey diagram of energy flows, showing direct energy use in the fishing and processing stages and the indirect energy contributions through monitoring, labor transport, infrastructure, and packaging. Energy intensities of the final products are based on weighted averages of the 5 processing plants in this study.

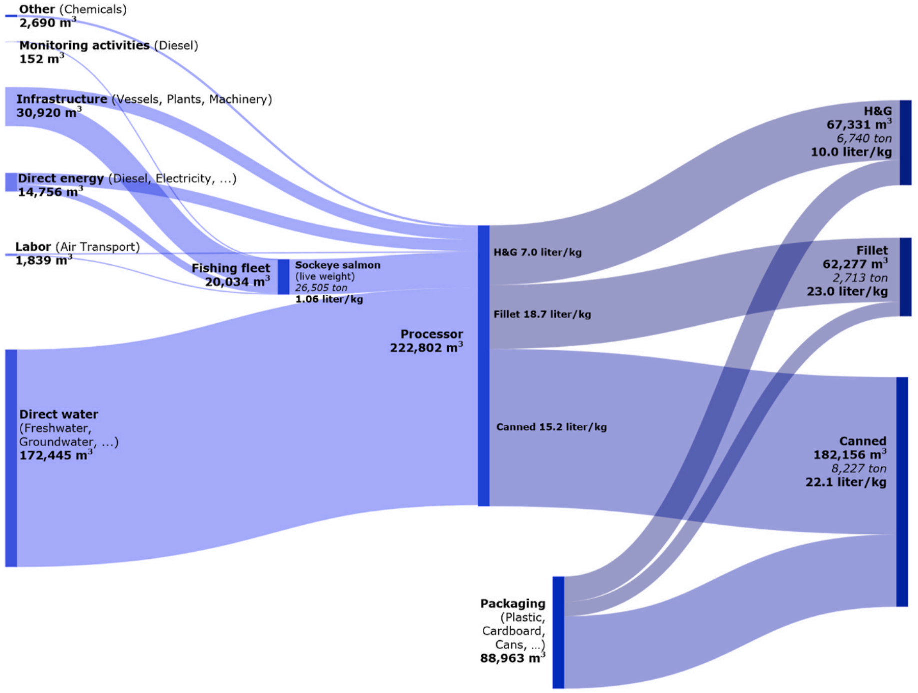

Fig. 6. Sankey diagram of water flows showing direct water use in the fishing (negligible) and processing stages. Contributions to indirect water consumption result from monitoring, labor transport, infrastructure and packaging inputs of material and energy. Water intensities of the final products are based on weighted averages of the 5 processing plants in this study.

3.3.2. *Water*

Freshwater is used by processing companies for ice (to cool and store fish) and for cleaning in the processing plants. The supply of freshwater in the region as plentiful, so allocating time and effort to reduce water use was generally not a priority, except for simple measures like making sure hoses are off when not in use.

4. Discussion

4.1. *Energy: baseline evaluation*

In this study we document the current demand for energy and water use in the wild catch Alaska sockeye salmon fishery that fills a large gap in data availability for wild catch fisheries and to provide baseline information for the sockeye fishing industry. Energy embodied in Alaska sockeye salmon increased from 8.5 MJ kg^{-1} for fish caught and transported to the processing facility, to between 19.7 and 27.1 MJ kg^{-1} for the three product forms after initial processing. Packaging results in increasing embodied energy to between 24.6 and 33.8 MJ kg^{-1}depending on type of packaging for each product form.

To place the Bristol Bay fishery into perspective, Parker and Tyedmers (2015) computed an average fuel use efficiency of global fisheries since 1990 of 639 l t^{-1} which translates into about 24.7 MJ kg^{-1} as compared to 8.5 MJ kg^{-1} in the Bristol Bay. Obviously, the sockeye fishery of Bristol Bay is more efficient, using less than 33% of the global averages. Pagani et al. (2020), using a variety of data sources for the USA food supply chain, computed embodied energy of "fish" equal to 48 MJ kg^{-1} and meat equal to 23.6 MJ kg^{-1}, which increased to 62.1 MJ kg^{-1} and 43.3 MJ kg^{-1} respectively following processing. Compared to the final Bristol Bay sockeye products, which had an embodied energy of between 24.6 and 33.8 MJ kg^{-1} the protein from processed sockeye salmon appears to be on the low end of protein sources.

Fulton (2010) computed an energy intensity for Alaskan pink salmon caught using purse seine gear of about 2.53 MJ kg^{-1} (including boat and gear) and cumulative energy intensity of 10.0 MJ kg^{-1} for average processed pink salmon fillets (disregarding allocation to offal). These energy intensities are somewhat lower than Bristol Bay sockeye and while the lower energy intensity of landed pink salmon is probably the result of gear type, there is no apparent reason for the considerably lower energy intensity of processed pink salmon. It may be the result of the difference in source of electricity. In Bristol Bay all electricity is generated using diesel powered generators, while the pink salmon processing used electricity from the Alaska grid, some of which comes from hydroelectric power.

Given that the data for Alaska sockeye salmon are roughly half of the energy required and a very small percentage of the water required for global fish and meat as estimated by Mekonnen and Hoekstra (2012) and Gleick and Cain (2004) suggests that the sockeye salmon fishery of Alaska is a relatively efficient means of producing fish for human consumption. It should be mentioned that a large part of the lower energy demand results from two factors. First is the fact that the Bristol Bay sockeye salmon fishery is a very short duration (4–6 weeks) and highly concentrated in space which contribute to higher efficiency since fishing effort is related to both time (i.e., duration) and space (concentrated fish equals less effort). Second, drift net fishing requires less energy that trawling In addition, during years of higher than normal harvest, which, in fact, was the case for one of the three years in this study, efficiencies would obviously be higher. To get a more accurate representation of the energy required, a longer time series of data would be warranted.

4.2. Energy: opportunities and constraints for improvement

Perception by stakeholders was that there are few options and incentives for increasing energy efficiency in the capture phase of the fishery. While nearly all the vessel owners understood that the government regulations that specify size of boats and type of gear used in Bristol Bay actually result in inefficient boat designs that use much more energy (because of the length restriction, to maximize quantity of fish in the vessel hold, boats are designed with wider beams and deeper depths, creating much more drag than a sleeker design would exhibit). There is no indication that government will change regulations and further, if they were changed, most vessel owners said that scrapping their current vessel in favor of a more efficient one was out of the question.

There is the potential for some energy savings if the entire fishing fleet were to begin using refrigerated sea water (RSW) systems to cool catch in the hold. RSW systems circulate water from the ocean through a system of pipes into a chiller then into a vessel's fish hold. This helps to preserve the fish without needing ice. The energy savings that result is from lower fuel consumption without the ice load typically needed to chill fish. Additionally delivered fish to processors are more likely to be of a higher quality with less loss.

Since the processing phase represents over 50% of the total embodied energy in salmon products, the potential for energy and water savings during this phase is relatively large. Processors were almost unanimous in saying that they have installed energy efficient lighting and machinery whenever possible, but that the biggest problem is that there is not an electrical grid. All electricity is generated using relatively small-scale diesel generators, which are typically very inefficient. Considering that Alaska has a fairly large potential for hydroelectric generation, considerable energy savings (as much as 50% of the energy associated with processing), could accrue with investments in regional electric grids. However, it must be understood that building a hydroelectric grid is not the responsibility of the industry.

Packaging requires considerable amounts of energy and water (between 20 and 35 percent). It is most interesting that in canned salmon, about 34% of the total embodied energy results from the can, while the plastic packaging for H&G and filets represents about 20% of total embodied energy in both product forms. The energy in cans is quite high and an estimated 20% energy savings in packaging could accrue if plastic pouches were substituted for cans (Franklin, 2022).

4.3. Water: baseline evaluation

Capture fisheries by their very nature, do not require significant quantities of fresh water (Gephart et al., 2014, 2016; Hoekstra, 2003) yet processing, as seen in the present analysis, can add to embodied water. Water used in the processing and packaging of Alaska sockeye salmon increased from 0.8 l kg^{-1} for fish caught and transported to the processing facility, to between 7.0 and 18.7 l kg^{-1} depending on product form after initial processing. Packaging resulted in increasing embodied water to between 10 and 23 l kg^{-1}depending on type of packaging. These quantities of water include direct water usage and indirect embodied water in infrastructure and energy used. Still, water consumption of processed sockeye salmon is considerably lower than global estimates of water footprint by Mekonnen and Hoekstra (2012) for other animal-sourced foods, such as 15,400 l kg^{-1} for beef, 4300 l kg^{-1} for chicken and 6000 l kg^{-1} for pork. It must be noted that the Mekonnen and Hoekstra (2012) study includes all water use (i.e., rainfall, irrigation, and processing) regardless of water source.

4.4. Water: opportunities and constraints for improvement

Our lower water intensities may result in part because of definition of consumptive use. We considered consumptive use as water that either evaporates or is included in a product or is returned to another body of water, in keeping with the "blue water concept' (Chapagain and Hockstra, 2008). Processing uses a considerable quantity of water (50–75% of total embodied water), primarily for washing equipment which is returned to the river from which it was drawn. Consumptive use, a much smaller quantity (about 15% of total with drawls) results from evaporation, incorporation into products, and production of ice which melts into the ocean from fishing vessels.

Because the location of land-based processing facilities is in remote areas and usually next to large fresh water rives, there are no incentives to reduce water consumption. Additionally, most consumption, as defined, is not subject to conservation measures since little opportunities exist to reduce in plant evaporation or packaging requirements. With increases in RSW systems in the fishing fleet, there may be a slight decrease in the amount of ice required for cooling of catches.

4.5. Allocation of energy and water

Allocation of the energy and water used to catch, process and package Alaska sockeye salmon has its issues. Allocation has been a persistent methodological issue for both LCA and water footprint approaches for many years. In this study, we assigned energy and water to the three product forms based on industry wide averages of the quantities of final product obtained from round weight of captured fish (Crapo et al., 1993) as follows: H&G, 74%; fillet, 53% and canned 67%. Thus, it required 1.35 kg of landed fish to produce 1 kg of H&G, 1.89 kg to produce 1 kg of fillet, and 1.49 kg to produce 1 kg of canned salmon. Additionally, we were able to assign energy and water embodied in packaging materials to the various product forms based on primary data from the 5 processing plants.

Where allocation becomes an important issue revolves around how to handle the offal produced in the processing phase. Allocation of roughly half of the energy and water required to catch and process salmon to offal is problematic. At present the offal at most plants in Bristol Bay is not used but disposed of in the ocean. The Clean Water Act requires floating and shore-based seafood processing facilities to grind seafood waste to a maximum size of ½ inch to increase dispersion of solids into the ocean (Tetra Tech, 2009). Recently there has been an interest by some companies to collect the ground offal from floating and shore-based processors for conversion into fish meal and oil, however it is not a widespread practice. Major impediments to offal use in this way result from the remoteness of the Bristol Bay sockeye fishery which leads to transport costs of low value (offal) products and the fact that the sockeye run is very short so building a meal/oil plant that is used only a few weeks a year is probably rather inefficient.

If energy and water were allocated to products and offal based on mass, the energy and water per kg of offal would be 30% of total energy and water input and the energy assigned to products would be 70% of inputs (see section 3.2). An economic allocation of energy and water to products and co-products would result in assigning, at present, near zero energy and water to offal since the offal has only minor economic value. Based on the fact that at present the offal has relatively minor economic value and that it is disposed of in the ocean which may increase marine productivity, we did not allocate to offal and have assigned all energy and water to the salmon products intended for human consumption.

4.6. *Energy costs of fishery management*

Much is written and discussed about the fact that the Alaskan sockeye fishery is one of the most intensely regulated and monitored fisheries in the world (Clark et al., 2006) and it is often cited as one of the great successes in fisheries management (Hilborn et al., 2003; Hilborn, 2006). Mangin et al. (2018) using a country level database of the economic costs of fishery management concluded that for most nations the benefits of increased management outweighed the costs. Studying northern Europe fisheries, Arnason et al. (2000) estimated economic costs of management in Newfoundland, Iceland, and Norway ranged between 3% and 28% of landed value. Our analysis, while not an economic study, showed that the energy associated with management, monitoring and enforcement amounted to about 2% of the total energy consumed in the fishing stage and represented less than 1.0% of total energy of the finished products after processing and packaging.

4.7. *Expanding system boundary to include labor transport*

We were surprised that the energy required to transport labor to the Bristol Bay was not larger. Not included in this evaluation (but maybe should be) is the energy embodied in laborers (see the companion paper in this volume "Quantifying the Environmental Support to Wild Catch Alaskan Sockeye Salmon and Farmed Norwegian Atlantic Salmon: an emergy approach**")**. Overall, the energy required to fly laborers from Seattle WA, and fishers from their home states to Bristol Bay was about 31,300 GJ, which represented about 8.0% of total embodied energy in the final products. Since we did not include the energy required to transport laborers in the processing stage from their homes, using instead, only costs from Seattle (many are from Latin America and Eastern Europe), this number is a conservative estimate.

4.8. *Final remarks*

When viewed from a global perspective, the energy and water demand of the Bristol Bay, Alaska sockeye salmon fishery is small compared to other capture fisheries and animal-sourced foods. Water demand is nearly nonexistent during the fishing phase and when evaluated at the processing gate amounts to far less than 1% of the water demand for terrestrial meat sources. From the standpoint of embodied energy and water, wild caught sockeye salmon from Alaska's Bristol Bay is, on average, more efficient than most animal sourced proteins.

Considering the low energy demand of the capture phase of the sockeye salmon fishery compared to other fisheries, and explanations from sockeye salmon fishers that reducing fuel use is impractical and not a top concern, it is reasonable to prioritize developing fuel-saving strategies and technologies for other, more fuel-intensive fisheries. A pressing energy issue identified by processors was a need to develop reliable, more affordable, and cleaner sources of electricity for plants and nearby towns and would result in significant decreases in the energy demand of processing.

Because Bristol Bay is relatively remote, transport of labor and supplies for processing were thought to require significant energy demand. Labor transport was by air and supplies by barge. Overall, transport required about 8% of total energy demand, and while not insignificant, it was somewhat smaller than we first imagined. The remoteness of Bristol Bay makes reducing energy demand of transport difficult and in reality out of the hands of the sockeye industry and into the hands of the transport industry. One way to limit the transport footprints is for fishers or processing plant workers to stay in Alaska and work in other fisheries after the 4–6 week Bristol Bay sockeye season ends. The water demand of transport was insignificant as we expected.

Finally, effective fishery management is increasingly called for as a third of marine fisheries are overfished (note: the Bristol Bay sockeye fishery is not in the overfished group). The energy demands for regulation of the Bristol Bay sockeye fishery amounted to very small percentage (1–2%) of the total energy demand. Which was surprising, considering the number of times during our field visit that the intensity of monitoring by the state of Alaska was mentioned. It is an open question whether these energy estimates for management are transferable to other fisheries because of differences in spatial and temporal scales. Alaskan sockeye salmon management is tightly focused on times when salmon return from the oceans to spawn in rivers, which may not be transferable to open ocean fishing or other migratory species.

CRediT authorship contribution statement

Silvio Viglia: Conceptualization, Writing – original draft, Methodology, Formal analysis. **Mark T. Brown:** Writing – original draft, Validation, Formal analysis, Writing – review & editing. **David C. Love:** Investigation, Writing – review & editing. **Jillian Fry:** Investigation, Writing – review & editing. **Roni A. Neff:** Supervision, Funding acquisition. **Ray Hilborn:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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