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Renewable energy in fisheries and aquaculture: Case studies from the United States

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A R T I C L E I N F O

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A B S T R A C T

Fisheries and aquaculture are highly reliant on fossil fuels and must transition to renewable energy to reduce carbon emissions and meet global planetary heath goals. Here, we assessed total and renewable energy use in farmed catfish and wild-caught salmon, two of the largest seafood sectors in the United States (U.S.). Interviews were used to explore participants' views of key barriers and opportunities to replace fossil fuel use. Modeled scenarios were used to assess changes in grid source energy and electricity costs for the farmed catfish sector using the U.S. EIA National Energy Modeling System. We found that renewable energy makes up 5% of direct energy use in catfish aquaculture in Mississippi and Alabama. Catfish industry interviewees indicate that cheap electricity costs and diurnal energy use are barriers to onsite implementation of renewables. Projected renewable energy use for the catfish sector could be as high as 41% of total direct energy use in 2050 under modeled scenarios, which would result in 86% lower CO_2 emissions but 34% higher electricity costs. For wild-capture pink salmon from Prince William Sound, Alaska (AK) and sockeye salmon from Bristol Bay, AK, renewable energy makes up 2% and 0% of direct energy use, respectively. Wild-caught salmon industry interviewees identified the short duration of the fishing season as a barrier for onsite renewable energy, though there is a desire for more regional renewable energy technologies to lower electricity costs and increase reliability. Proposed renewable energy projects at utilities in fish processing towns in AK would only make modest improvements in the share of direct energy from renewables due to fuel use by fishing vessels. This is the first study to characterize current and potential renewable energy use among parts of the fisheries and aquaculture sectors in the U.S. We found that energy needs for fisheries and aquaculture are influenced by their often-remote location, production methods, and seasonal energy demands, which require context-specific solutions. There is the need for federal and state policies and incentives to shift energy sources used in these sectors to meet national and international climate change goals while supporting food security.

1. Introduction

Food systems depend on large quantities of energy, particularly fossil fuels, for their productivity (Neff et al., 2011; IRENA & FAO, 2021; Khan and Hanjra, 2009; Namany et al., 2019) and are responsible for one-third of global anthropogenic greenhouse gas (GHG) emissions (Crippa et al., 2021). Meeting national and international climate goals is not possible without reducing emissions from the food and agriculture sectors (Parker et al., 2018; Clark et al., 2020). The challenge lies in transforming the food and energy sectors in an equitable and environmentally sustainable way while maintaining food security (IRENA & FAO, 2021). Replacing fossil fuels with renewable energy sources is one of the most promising options to improve food system sustainability and address climate change (IRENA, 2017).

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Globally, 178 million metric tonnes of aquatic animals and plants were produced in 2020 (FAO, 2022). Capture fisheries and aquaculture (aquatic farming) contribute roughly equal shares of global production, and each have distinct energy requirements. Capture fisheries mainly use energy to power vessels and consumed an estimated 40 billion liters of fuel globally, which generated 179 million tonnes of CO_2-equivalent greenhouse gasses (GHG) in 2011 (Parker et al., 2018). Aquaculture uses energy during grow-out phases and to produce inputs (i.e., feed, hatchery), which contributed 245 million tonnes of GHG in 2017 (MacLeod et al., 2020). The rising energy costs and associated carbon footprint in the seafood sector is of growing concern (FAO, 2008; FAO, 2020; Tsakiridis et al., 2020; Gephart et al., 2021) and includes both production and downstream stages of the supply chain including processing, distribution and retail (Crippa et al., 2021; Murali et al., 2021; Liu et al., 2020). Onsite renewables are being considered as an approach to become less reliant on fossil fuels (Rahman et al., 2022) as is decarbonization of the electricity grid (Niles et al., 2017).

The aim of this study is to characterize energy use in the U.S. seafood sector and identify opportunities for diversification of conventional energy supply systems to reduce reliance on fossil fuels. In this paper, we assess direct energy use in farmed catfish and wild-caught salmon, two of the largest seafood sectors in the U.S. Using interviews we seek to understand business operators' views of key barriers and opportunities to replace fossil fuel use. Using modeling we explore changes in grid source energy and electricity costs for these sectors. To our knowledge, this is the first study to characterize current and potential renewable energy use among parts of the fisheries and aquaculture sectors in the U. S. Given the diversity of methods, geographies, and other factors within fisheries and aquaculture, sector- and geography-specific case studies like this one are required to effectively address the energy use challenge in seafood.

2. Materials and methods

2.1. Overview of study sites

We assessed renewable and nonrenewable energy use and modeled the economics of future energy scenarios in farmed catfish and the Alaskan wild-caught pink and sockeye salmon fisheries (Fig. 1). In addition, we conducted qualitative interviews with businesses operators to understand perceptions of energy use and constraints and opportunities for penetration of renewables within the sectors. Below is a description of the study sites and rationale for their selection.

2.1.1. Farmed catfish in Alabama and Mississippi

Farmed catfish is the largest aquaculture species by volume and value in the U.S., averaging 157.4 thousand tonnes annually between 2010 and 2019 (Kumar et al., 2020; Posadas, 2020). Catfish is one of the top-10 most consumed species in the US (Love et al., 2020) and 6th most sold species at retail (Love et al., 2022). We selected Mississippi and Alabama as the regional focus because these states represent approximately 88% of U.S. commercial catfish production (USDA, 2018) and consist of four stages (fish hatcheries, feed mills, grow-out farms, and processing plants). Catfish production typically occurs in 4–5 ha ponds (Hanson et al., 2020), and during the typical 18 month grow out period, the ponds require mechanical aeration to increase dissolved oxygen when levels become critically low at night. The timing and intensity of energy use depends on factors such as the catfish species, feed quantities, stocking density, and environmental conditions (Boyd et al., 2018; CAES, n.d.; Chapman, 2018).

2.1.2. Wild caught pink salmon in Prince William Sound, Alaska

Prince William Sound (PWS), Alaska annually produces 10.1 thousand tonnes of pink salmon (*Oncorhynchus gorbuscha*), which is a major economic driver in the region (Knudsen et al., 2021;ADFG, n.d.a). Pink salmon are caught using purse seine gear, which is a large net sealed at the bottom that encircles the fish (ADFG, 2020; ADFG, n.d.b; NOAA, 2019). Post-capture, the fish are processed into frozen headed and gutted forms for export or canned onsite (ADFG, n.d.b). Canned salmon is the second most sold form of canned seafood behind tuna at retail in the U.S. (Love et al., 2022).

2.1.3. Wild caught sockeye salmon in Bristol Bay, Alaska

The Bristol Bay, Alaska sockeye salmon (*Oncorhynchus nerka*) fishery is the largest and most valuable wild salmon fishery globally. From 2015 to 2019, Bristol Bay fishers harvested an average 98.9 thousand tonnes of sockeye salmon annually, equating to a first-wholesale value of $571 million USD (McKinley Research Group, 2021). The fishery uses two types of fishing gear, driftnets and setnets. Driftnets are operated by 9.8 m fishing vessels and are responsible for approximately 78% of sockeye salmon harvests. Setnets are deployed along the shoreline and represent approximately 22% of sockeye salmon harvests (McKinley Research Group, 2021). Fish harvests are delivered by tender vessels to floating or shoreside processing plants. Because of the remote location of Bristol Bay, primary processing is performed near where the fish are caught and occurs during the tight timeframe that aligns with the sockeye fishing season (late-June to mid-July). Sockeye salmon are processed into fresh and frozen headed and gutted fish and fresh and frozen fillets, with a smaller fraction that is canned (Knapp et al., 2013; McKinley Research Group, 2021). Salmon has the second highest sales at retail (Love et al., 2022), the second most common species group on restaurant menus (Love et al., 2021), and the top consumed species group behind shrimp in the U.S. (Love et al., 2020).

2.2. Data collection

2.2.1. Life cycle inventory data

Life cycle inventory data for direct energy use by catfish and salmon

Fig. 1. Map of study sites for United States farmed catfish (a), wild-caught pink (b), and wild-caught sockeye salmon (c).

producers and processors was collected as previously described in Brown et al. (2022) and Viglia et al. (2022). The farmed catfish businesses were in Alabama and Mississippi (n = 3 hatcheries; n = 9 farms, n = 3 processors), with one of the catfish processors, whose business operations were similar, recruited from outside of the Alabama and Mississippi study region. Five Bristol Bay processors of sockeye salmon and four Prince William Sound pink salmon processors were recruited. We computed the weighted average direct energy intensities for each fuel type (petrol, diesel, natural gas, and electricity) used in each phase of catfish production (i.e., hatchery, grow-out, and processing) and salmon capture and processing based on reported consumption by individual business operators (Brown et al., 2022a). The electricity component of the direct energy data was used to determine the mix of renewable and nonrenewable energy consumed by each phase.

2.2.2. Renewable energy data

Because electricity was the only direct energy resource reported by the sectors that had a renewable energy component, the percent generation categorized as renewable or nonrenewable energy was determined by averaging the energy sources from electric utilities for each sector. We adhered to the definition of renewable energy defined by the U.S. Energy Information Agency (EIA) as energy resources that are able to be naturally restored, yet are limited in the amount of energy that is able to be supplied at any one point in time, such as biomass, hydropower, geothermal, solar, wind, and ocean/tidal energy (U.S. EIA, n.d. a).

Electric utilities serving each study region were identified using the EIA Energy Mapping System (U.S. EIA, n.d.b) and matched with plant-specific generation and resource mix data from the U.S. Environmental Protection Agency (U.S. EPA) Emissions & Generation Resource Integrated Database (eGRID) for the most recent year available (2019) (U.S. EPA, 2021). For the southeast U.S., only plants labeled as an “Electric Utility” in eGRID for Alabama and Mississippi were incorporated into resource mix calculations to reflect generation across the regional grid supplying electricity to the catfish sector.

For two utilities that were not present in eGRID, Alegnagik, AK and Egegik, AK, electricity generation and resource mix data were obtained from the Alaska Energy Authority Fiscal Year 2020 Power Cost Equalization Program Statistical Report (AEA, 2021). A complete list of electric providers used to calculate the resource mix of each study site can be found in supplementary materials SM1 and SM2.

2.3. Qualitative interviews

Business operator perceptions of the use of energy and the challenges and opportunities relevant to renewable energy across the sites were collected via qualitative interviews conducted between July 2019 and November 2021. We conducted five interviews with catfish business operators who first provided quantitative data and also agreed to an interview. The interviews covered four stages of the catfish supply chain, including the feedmill, hatchery, grow-out, and processing, and some interviewees spanned more than one stage and provided information covering all of their operations. Additionally, nine interviews were conducted with Alaskan salmon producers and processors recruited through industry contacts and snowball sampling.

Semi-structured interviews were conducted by phone or Zoom (Zoom Video Communications, Inc., San Jose, CA) using an interview guide and ranged between 30 and 60 min. A notetaker participated in all interviews to accurately capture interviewee responses, and interviews were audio recorded to allow us to check the accuracy of notes, as needed. The qualitative interviews had a broader focus and included other sustainability topics in addition to energy (e.g., water use and waste). The analysis of qualitative data for this study only included interviewee responses relevant to energy.

Qualitative analysis was performed using grounded theory methods to identify themes and interpret data. We developed a codebook based on the initial review of interview notes, which was continually revised as subcategories developed over the period of analysis (fall 2021). The codes included descriptive information on strategies and recommendations, areas of energy usage, and the barriers, challenges, and motivations applicable to renewable energy (see supplementary material SM3 for list of codes). Interview notes were coded and analyzed using MaxQDA (VERBI Software, Berlin, Germany). The analysis emphasized direct references to electricity obtained from local utilities, energy costs, and renewable energy technologies that have been regarded as successful, desired, or infeasible within the study regions. After coding was completed, emerging themes were noted, and we compared responses from different participants and across study sites.

2.4. Energy models and scenarios

2.4.1. Farmed catfish

To evaluate the impacts of energy development on future electricity costs for farmed catfish production and processing, published scenarios were employed using data from the EIA National Energy Modeling System (NEMS) for the 2020 Annual Energy Outlook (U.S. EIA, 2020c). NEMS is a modular energy-economy modeling system that the EIA uses annually to project energy supply and demand changes in the U.S. through 2050. The projections in NEMS are estimates based on the assumptions and methodologies reflected in the model (U.S. EIA, 2019). The Electricity Market Module (EMM) of NEMS provides electricity prices to the industrial sector and emissions and generation projections to the electric power sector based on regional energy market characteristics (U.S. EIA, 2019; Frazier et al., 2019). The supply regions used to represent Alabama and Mississippi were Midcontinent ISO/South (6) and SERC Reliability Corporation/Southeast (15), shown in supplementary material SM4.

The EIA models various scenarios in NEMS to consider the impacts of economic growth, oil prices, fuel demand, and alternative domestic policies on future electricity costs and energy generation in the EMM regions (U.S. EIA, 2020a). Seven scenarios from NEMS were evaluated in this analysis and are listed in supplementary material SM5.

The electricity direct energy intensities calculated for each catfish supply chain phase (kWh/kg) were applied to the NEMS industrial electricity cost projections (2019 $/kWh) to project future electricity costs under current electricity usage and production estimates. Weighted averages of electricity generation by fuel or renewable energy source and carbon dioxide emissions in the electric power sector were calculated to determine the associated regional generation and environmental impacts under each scenario.

2.4.2. Wild-caught salmon

NEMS projections were not available for Alaska (U.S. Energy Information Administration personal communication). Alternatively, we performed a document review to identify renewable energy feasibility studies that have been conducted across Prince William Sound and Bristol Bay, Alaska. Projected estimates of electricity generation from proposed renewable energy projects in Prince William Sound and Bristol Bay identified through the document review were applied to the data provided by individual business operators to estimate the percent of future direct energy that could consist of renewable energy.

3. Results

The results are presented in three domains: (1) generation mix of nonrenewable and renewable direct energy, (2) industry perceptions of renewable energy use obtained through qualitative interviews, and (3) modeling and feasibility studies to assess the current and future potential of renewable energy implementation among the study sites.

3.1. Direct energy use

3.1.1. Farmed catfish

The farmed catfish sector in Mississippi and Alabama, which includes fish hatcheries, grow-out ponds and processing plants, reported that direct energy use consisted of a combination of electricity (75%), diesel (18%), petrol (6%), and natural gas (<1%) to produce catfish (Fig. 2a). Within electricity supplied by the utilities, 60% came from fossil fuel sources (natural gas: 42%, coal: 18%), 33% from nuclear, and 7% from renewable sources (hydropower: 7%, solar: <1%). By stage (Fig. 3), hatcheries reported using direct energy primarily in the form of electricity (83% of direct energy use) to aerate ponds and support operations, as well as diesel (13%) to run tractors and backup aerators and petrol (3%) to operate vehicles. Grow-out farms also primarily used electricity (79%) to support electric aeration, diesel (13%) to operate tractors and backup aerators, and petrol (9%) to operate trucks. Aeration requires a large share of energy, and in the past few decades farms have shifted from diesel to electricity-powered aerators to improve efficiency. Processing plants reported using a combination of electricity (66%), diesel (31%), natural gas (3%), and petrol (<1%) to operate plants. Because of the large share of electricity use and other factors, the ability of the catfish sector to transition towards renewable energy sources will rely in large part on the energy source mix used by regional utilities.

3.1.2. Wild-caught salmon

Alaskan salmon fisheries reported using diesel and to a lesser extent electricity as the main forms of direct energy in the harvest, delivery, and processing of salmon. In Prince William Sound, Alaska, diesel represented 97% of total direct energy use, which was mainly used to power fishing vessels and tenders (boats used to deliver fish) (79%) and operate generators at processing plants (18%). Electricity was 3% of total direct energy usage, which was the other main energy source to power salmon processing plants (Fig. 2b). Electric utilities in Prince William Sound rely primarily on hydroelectric power (75%), which was supplied by four hydroelectric plants, with the remaining electricity (25%) from diesel powered generators.

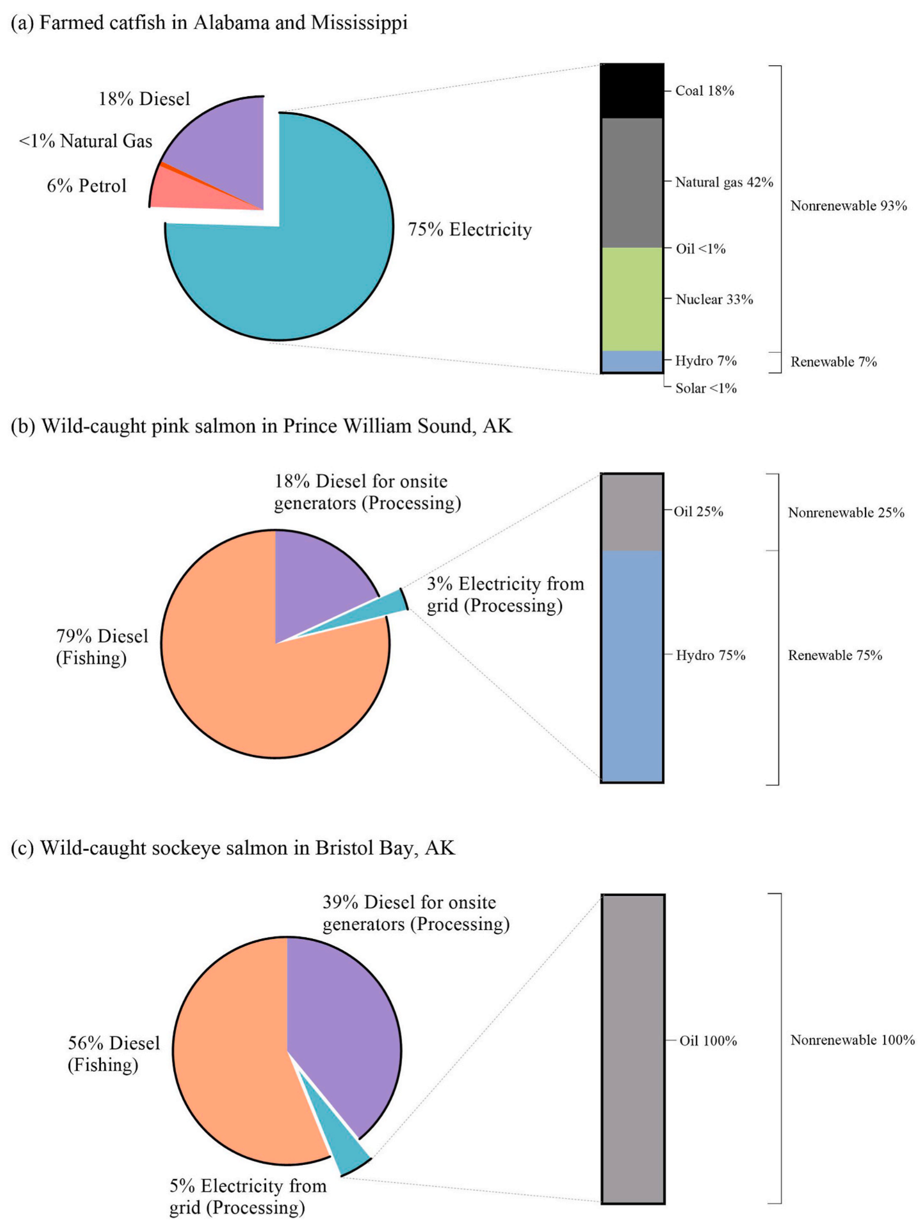

Fig. 2. Percentage of direct energy resources used in United States seafood production and processing for farmed catfish (a), wild-caught pink salmon (b), and wild-caught sockeye salmon (c). Electricity broken out by fuel source.

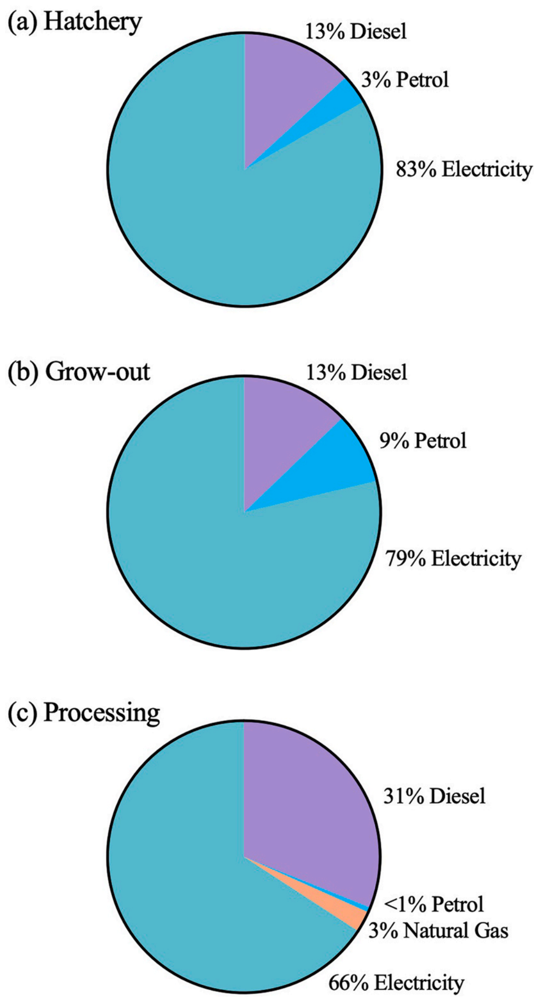

Fig. 3. Percentage of direct energy resources used in United States farmed catfish in Alabama and Mississippi for the hatchery (a), grow-out (b), and processing (c) stages.

In Bristol Bay, Alaska, there are currently no hydroelectric plants, and diesel was the main fuel source to power fishing and tender vessels (56%) and to run generators at utilities in the villages of Togiak, Dillingham, Aleknagik, Naknek, and Egegik (Fig. 2c). In the processing sector, the local utilities were unable to provide all of the electricity needs due to high peak demand in the short (~6 week) fishing season, therefore, most processing plants also had onsite diesel-powered generators (39% of total direct energy use) that supplement power obtained from the electric utilities (5% of total direct energy use). Due to the remote location of many fishing villages, short fishing seasons, and diesel powered fishing fleet, it appears that diesel will likely remain the main energy source for the Alaska salmon fishing sector in the near-term. Increasing renewable energy use is possible in processing towns with favorable natural conditions.

3.2. Qualitative interviews

3.2.1. Farmed catfish

Catfish industry interviewees report being highly reliant on electricity. One catfish farmer put it succinctly, “we are totally dependent and have to be on the grid” as electric aerators are essential to supplement depleted oxygen levels, particularly at nighttime.

Interviewees reported that onsite renewable energy sources such as solar and wind are not able to provide power during periods of higher demand. Large capital projects, such as onsite renewable energy, are less likely to be pursued because regional electricity costs are cheap and there is a need to limit downtime in farm production. Battery storage technologies for on-site were regarded as cost prohibitive. As stated by one catfish processor:

> “Generally, the southern states are cheaper than the northern states, but we’re still for the most part under $0.10/kWh while there are other places in the country over $0.20/kWh … It also makes a big difference in trying to find other energy solutions, whether solar or wind, or something else. It’s a much easier way to pay back an expensive installation of solar panels if you’re at a $0.16 to $0.18 per kWh situation than if you’re at an $0.08 or $0.09 per kWh.”

For onsite renewables such as solar to be considered, catfish industry interviewees said that “net metering” or the ability to send power back to local power companies for credit to offset use at nighttime would be important. In states such as Alabama, net metering is not required by state law, making options for net metering up to the utility (Davis-Sramek, 2021).

Current cost-saving strategies are focused primarily on energy conservation, including maintaining machinery, purchasing new equipment, switching fuel types in operations, or taking advantage of cost savings by using off-peak electricity (e.g., processors making ice at night). Catfish farmers switching to newer, more productive farming methods, such as high-intensity aeration, also require more electricity usage. Almost all catfish industry interviewees mentioned major weather events, such as hurricanes, tropical storms, ice storms, or tornadoes, as causes of power outages that result in downtime and concerns related to maintaining fish health. Interviewees shared that their operations are vulnerable if a power outage occurs, with their only options being backup diesel powered equipment and/or waiting until the power returns.

3.2.2. Wild-caught salmon

The Alaska salmon fishing sector is highly reliant on diesel to power fishing vessels. Alaska salmon producers mentioned that potential alternatives to diesel could include hydrogen fuel cells, electricity, biodiesel, solar energy, diesel hybrids, and battery storage technologies, though widespread use was viewed as future (not current) potential. One Alaska salmon producer mentioned concerns that engines may not be as powerful when implementing alternatives such as solar, and another discussed the need for a clear cost/benefit before penetrating the fishing market with diesel hybrid fishing vessels. A challenge reported with electric boats was that low access to charging stations in remote areas would make implementation almost impossible, and if successful, backup generators would still be needed.

Diesel is also the main source of power for many utilities and processing plants in this sector, but processing is one stage where shifting to renewable energy has been accomplished with changes by utilities. The main barrier to renewables in the processing stage is the short duration of the Alaskan salmon fishing season, which makes the period of most electricity usage very intense, creating a short window of time to acquire return on investments. During the short season, focus is placed on processing at peak capacity and using as much power as is needed to keep up with the salmon catch. For example, the Bristol Bay sockeye salmon run lasts just a few weeks with millions of salmon processed daily. Interviewees reported that electricity issues occur frequently, including power surges and demand charges from usage during peak billing times, which were regarded as “very detrimental to the business.”

In terms of renewable energy options, the local geography is an important factor. Wind energy generation had been evaluated in Dillingham and Egegik in Bristol Bay, but one processor reported challenges with the ground not being firm enough to hold wind generators in place due to the alluvial plain that makes up the geographic area. A failed renewable energy project in the area may have resulted in higher power costs which were off-putting for one processor.

Alaskan salmon processors generally spoke positively about hydropower, though there were concerns about ensuring salmon runs would not be impacted when considering these types of projects. Processors reported that hydroelectricity is being evaluated in Bristol Bay and exists in two towns in Prince William Sound (Valdez and Cordova, AK). In Valdez, interviewees reported that hydroelectricity had allowed for more efficient, cleaner processing and electricity costs lower than diesel power generation during the summertime when the electricity demand is highest.

Interviewees mentioned that the Nuyakuk River Project in Dillingham will greatly benefit the region in reducing electricity costs, decreasing reliance on diesel, and making the area more competitive like areas such as Kodiak, Alaska that operate on non-diesel energy sources. As stated by one processor, "This hydroelectric plant that Dillingham is working on … It will hugely reduce the amount of diesel that they spend making electric power … It'll be what Kodiak did 4–7 years ago when they put in the Terror Lake Dam and they put in the wind generators on top of Pillar Mountain. Kodiak is pretty much non-diesel now … So those kinds of projects, Alaska is right for that kind of stuff, if, for example, you can find hydroelectric options … Kodiak's power rate dropped in half … I think it's going to drop in half again. That's huge savings, and that's very motivating because it makes a town like Kodiak a lot more competitive than places where you are making power by using diesel."

Because power surges are a frequent issue during the peak of the salmon processing season, interviewees reported a desire for technologies such as battery banks to help supplement the inconsistent power needs and prevent outages that lead to lost production and damaged equipment.

3.3. Modeling and feasibility studies

3.3.1. Farmed catfish

The catfish industry is heavily reliant on electricity from the grid, and participants in the industry appear hesitant about investing in onsite renewables. Therefore, the largest opportunity for increasing renewable energy in the catfish sector may be from changes at the utility-level. With that in mind, we studied energy supply and demand scenarios, modeled by NEMS, to assess the current and future (2050) potential electric power mix of farmed catfish production in Alabama and Mississippi (Fig. 4). Modeled renewable energy use could be as high as 55% or as low as 5% depending upon the range of scenarios. The scenario that provided the largest share of renewable energy (% of total) in 2050 was in the "$35 carbon fee" scenario (55%) followed by "low oil and gas supply" (46%), "low renewable cost" (37%), "carbon-free generation standard" (25%), "reference case" (21%), "high oil and gas supply" (12%), and "high renewable cost" (5%) scenarios. Solar photovoltaic was the largest renewable energy technology implemented in 2050 under all scenarios.

Next, we modeled the current and future (e.g., 2050) electricity costs for the farmed catfish sector using NEMS data and found that fossil fuel availability and policies promoting renewables can have a significant impact on both electricity costs and CO_2 emissions for the sector. The scenario with the highest shares of renewables (e.g., "$35 carbon fee" scenario) resulted in 34% higher electricity costs and 86% lower CO_2 emissions than the 2050 "reference case" for the U.S. catfish sector (Table 1, Fig. 4). The scenario with the lowest share of renewables (e.g., "high renewable cost") had 6% higher electricity costs and 22% higher CO_2 emissions than the 2050 "reference case" for the catfish sector. Electricity cost footprints ($/kg) under the scenarios for the hatchery, grow-out, and processing stages are provided in supplementary material SM6.

To put unit costs into context, we calculated the total cost differences between the scenarios using hypothetical production amounts from the weighted average of production data reported by participants (Table 1). For example, after accounting for inflation, a catfish farmer producing an average of two million kg of catfish in 2050 would pay approximately $11,500 less in 2050 than in 2020 under the "reference case" scenario.

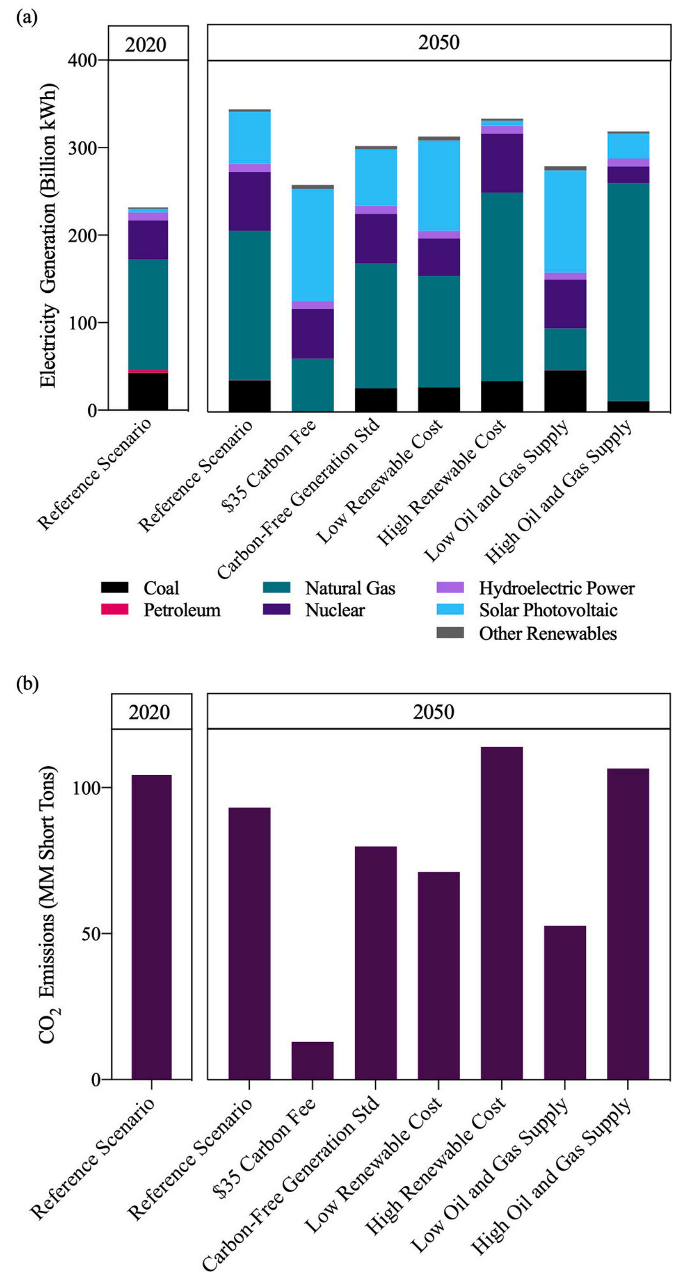

Fig. 4. Alternative energy supply and demand scenarios and their impact on the electric power sector generation and carbon dioxide emissions in the southeast United States. Regional generation resource mix of electricity (a) and regional carbon dioxide emissions (b).

Lower real electricity costs in 2050 reflect factors such as domestic resource availability resulting in higher production at lower costs, capital costs for electric power generating technologies, macroeconomic growth, inflation, and other key assumptions used in the NEMS model (U.S. EIA, 2020d). Compared to the 2050 "reference case," a "high oil and gas supply" scenario would save the average catfish farmer ~$9800 in electricity costs, whereas a "$35 carbon tax" scenario would increase annual electricity costs by ~$41,000.

Catfish processors were found to have the highest total electricity cost increases among the business types because they are processing large volumes of catfish and operating multiple types of machinery that require continuous sources of electricity (i.e., cold storage units, ice-making machines, dryers, lighting, etc.) (Murali et al., 2021). Using an average processing amount of nine million kg of catfish product, catfish

Table 1
Alternative energy supply and demand scenarios and their impact on United States farmed catfish electricity costs.

	2050 Electricity Cost (2019 $) [a]		
Scenario	Hatchery [b]	Grow-out [c]	Processing [d]
Reference Case in 2050	$102,786	$122,202	$424,525
	Difference from 2050 Reference Case		
High Oil and Gas Supply	-$8247	-$9805	-$34,063
Carbon-Free Generation Standard	-$1931	-$2296	-$7977
Low Renewable Cost	-$270	-$321	-$1115
High Renewable Cost	$6238	$7417	$25,766
Low Oil and Gas Supply	$20,093	$23,889	$82,988
$35 Carbon Tax	$34,718	$41,276	$143,390

[a] The electricity pricing included in calculations takes into account applicable taxes, capital investments, and the average cost to build, operate, and maintain transmission and distribution systems under each scenario (U.S. EIA, 2020b).
[b] Based on 1.4 MM kg hatchery production.
[c] Based on 2 MM kg grow-out production.
[d] Based on 9 MM kg processor production.

processors would pay $40,000 less and have 11% lower electricity-related carbon dioxide emissions in 2050 than in 2020 under a “reference case” scenario. Under a “high oil and gas supply” scenario, we found electricity costs and electricity-related carbon dioxide emissions for processors would be approximately $34,000 lower and 14% higher, respectively, than the “reference case” in 2050 and over $143,000 greater and 86% lower, respectively, under the “$35 carbon tax” scenario.

Finally, we assessed the current and future renewable energy use in the catfish sector under different scenarios (Fig. 5). The catfish sector currently uses renewable energy for 5% of direct energy use. In 2050, renewable energy could be 4%–41% of direct energy use, depending upon the scenario, however, in most scenarios renewable energy use is projected to increase.

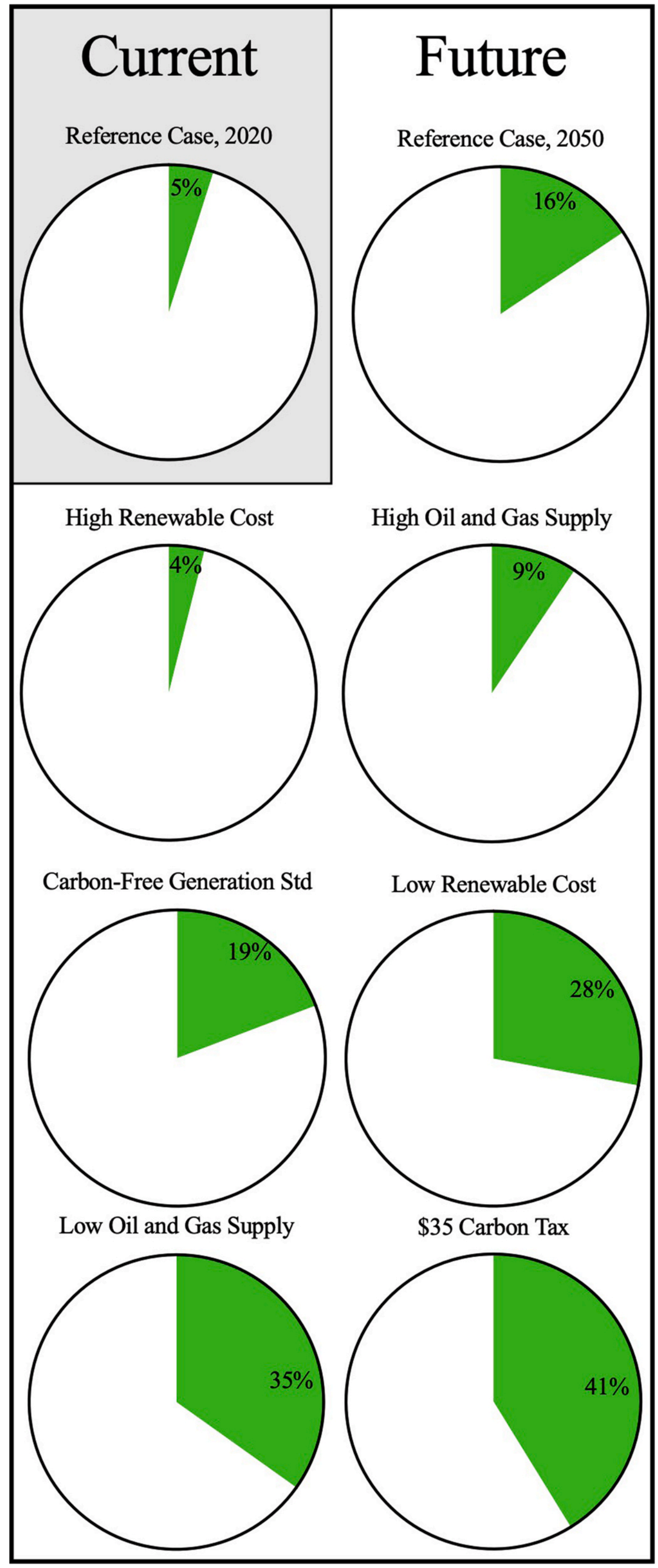

Fig. 5. Current and future scenarios and their impact on the percent renewable direct energy (in green) for United States farmed catfish in Alabama and Mississippi.

3.3.2. *Wild-caught salmon*

NEMS energy supply and demand scenarios were not available for Alaska, therefore, to better understand the renewable energy futures we performed a document review of feasibility studies in the study region. We found that wind energy, biomass, hydropower, and geothermal are the main renewable energy resources that have been evaluated across the study regions. However, only a few renewable energy projects have been completed.

In Prince William Sound, one feasibility study on wind and three feasibility studies on biomass have been conducted, which would add additional renewable energy capacity beyond the four currently operating hydroelectric plants in the region. For wind, a four-year monitoring study was performed to evaluate wind energy resources on Alaska Native Lands in the Cordova region as a source of power during the winter months when local hydropower resources are reduced. The project was conducted by the Native Village of Eyak in cooperation with the Cordova Electric Cooperative (Whissel and Piche, 2016). Cordova is one of the two main towns in Prince William Sound for processing pink salmon, and the Cordova Electric Cooperative is the main supplier of electricity for these processing plants. The study found that the 27-mile, Meals Reservoir, and Pt. Whitshed/Camp Hill all have potential for developable wind resources, though each area possesses its own challenges (i.e., lack of transmission lines, close proximity to the airport, etc.) (Whissel and Piche, 2016). At least three biomass feasibility studies were also found to have been performed in the region of Cordova. One of the studies found that lands near the airport owned by Eyak Corporation possessed a net growth of over 4500 cords annually, the equivalent displacement of over 500,000 gallons of diesel, making biomass a potentially economically feasible option for the area (Pape, 2013).

In Bristol Bay, no renewable energy projects are currently in operation, however, there have been a series of hydroelectric, wind, and geothermal energy proposals. The closest to reach fruition is the

Nuyakuk River Project in Bristol Bay, a proposed hydroelectric project that has the potential to generate up to 12 MWs of power and deliver electricity and optical fiber to Dillingham, Aleknagik, Koliganek, and other communities in the surrounding area. Dillingham has two large processing plants for sockeye salmon. The project is estimated to annually replace up to 1.5 million gallons of diesel fuel, as well as provide potential dual benefits like improving fish passage through the reduction of high-water velocities in the Nuyakuk river (NETC, 2019). Furthermore, findings from a pilot study conducted in the village of Egegik from 2014 to 2016 found that replacing one diesel generator from Egegik's power plant with a small wind generating unit could provide a viable source of cost-effective power for the highly variable demand that is greatest during the summer fish processing season (Vaught, 2017).

Additionally, the geographic landscape of Togiak has a history of volcanic activity that makes it a potential site for geothermal energy (U. S. FWS, 2013). In July 2021, the Bristol Bay Native Corporation was awarded $89,650 by the Bureau of Energy Affairs to conduct surveys of the volcanic formation surrounding the communities of Togiak and Twin Hills to identify potential heat sources for geothermal energy. The awards are part of an Energy and Mineral Development grant program that aims to identify projects supporting energy, mineral, and natural resources that will enhance the energy and economic self-sufficiency of tribes and Alaska Native corporations (U.S. DOI, 2021). While a failed "demonstration of concept" project to determine if the area of Naknek could support geothermal resources to replace diesel was found to have caused the local utility company to file for bankruptcy (AK OMB, 2011; Loy, 2011), for fiscal year 2022 Naknek Electric Association received $103,500 to assess the feasibility of wind energy and solar power for the community (AKLEG, 2021).

Based on current and proposed renewable energy projects, we calculated the percent of direct energy that comes from and could come from renewable sources. In Prince William Sound, because the direct energy mix largely consists of diesel used to power fishing vessels, the current total direct energy mix comprising of renewable energy is approximately 2%. Because of the large amounts of diesel fuel used to operate fishing vessels, under a case of an additional renewable energy project, such as the Cordova Wind Energy Project, the percentage of direct energy coming from renewable energy could increase to approximately 3% of the total direct energy mix (Note: the Cordova Wind Energy Project would increase the current electricity resource mix from 75% to 100% renewable energy). In Bristol Bay, there is currently no renewable energy in the total direct energy mix, and when the Nuyakuk River Hydoelectric Project is completed, the total direct energy mix coming from renewable energy will increase to 0.6%. The low percentage of renewable energy reflects the fact that i) Naknek, an area where many sockeye processors are located, will not be an end-user of the electricity generated from the Nuyakuk River Project, and ii) diesel fuel used to operate fishing vessels dominates direct energy use in the sector.

4. Discussion

We assessed renewable energy usage, stakeholder perceptions, and modeled scenarios in the largest U.S. aquaculture sector and in two large U.S. fisheries. We found that renewable energy is a minor contributor to energy usage, representing approximately 5%, 2%, and 0% of direct energy in farmed catfish, wild-caught pink salmon, and wild-caught sockeye salmon production, respectively. In U.S. farmed catfish where electricity use is high, shifting the energy portfolio at utilities shows the greatest potential. In Alaska, diesel is the main fuel source for fishing fleets which poses a stubborn obstacle, while small gains are achievable among processing plants that have access to hydroelectric power from local utilities. Replacement of fossil fuels with renewable sources is possible but requires an understanding of the different energy needs in the fisheries and aquaculture sectors to provide context-specific solutions.

Like other agricultural sectors such as crop or livestock production, the fisheries and aquaculture sectors have different needs in terms of energy which is in part due to production methods, but also the location of production, seasonality, and access to an energy grid. Capture fisheries use the largest share of their energy at sea, while many forms of aquaculture are performed on land, with an exception for some stages of marine aquaculture. Land-based farming systems and post-harvest processing stages can tap into the electric grid and any renewable energy mix sourced by local utilities, while fisheries will remain more dependent upon fossil fuels in the near-term to power vessels as alternative fuel technologies continue development. Seasonality is also an important factor; fishing and fisheries processing is often a seasonal activity that requires intense effort over a short period, while aquaculture and aquaculture processing operates year-round and has more control over production methods and inputs (Murali et al., 2021). In Alaska, processors were reluctant to make upgrades to their plants because of the short fishing and processing seasons. Both fisheries and aquaculture often exist in remote or rural locations, which further complicates the use of onsite renewable energy.

Energy needs in aquaculture are varied, and because farms in our study were connected to the grid, these needs could be met with a wider range of energy sources. Opportunities to implement renewables in the catfish sector exist either directly on-farm or indirectly through electricity obtained from renewable resources, although interviewees were concerned about the feasibility of onsite renewables. Productivity and varying input costs such as feed and labor create low margins for capital cost investments, which impacts the adoption of onsite renewables in some parts of the industry (Kumar et al., 2020). In recent years, more intensive production technologies with higher aeration rates have been implemented, and some farmers are switching from stocking ponds with channel catfish (*Ictalurus punctatus*) to faster-growing hybrid catfish (*I. furcatus* x *I. punctatus*) (Hanson et al., 2020). These new techniques have the potential to reduce production costs, increase productivity (Engle et al., 2022; Kumar et al., 2020), and reduce energy use. This study did not assess indirect energy used in producing feed for catfish. Catfish feed comes mainly from corn, soy, wheat, and animal byproducts, which is a large component of total energy use (Gephart et al., 2021; FAO, 2018).

Parker and colleagues estimate fuel use in global fisheries is 489 L per ton of fish caught, which varies based on the species, gear type, and vessel type (Parker et al., 2018). Current efforts to increase fuel efficiency on large fishing vessels are primarily focused on behavioral, technological, and managerial interventions such as advanced engine designs, upgraded hydraulics, upgraded compressors for refrigeration, reduced vessel speeds at appropriate intervals, and other techniques to reduce (in contrast to replace) fossil fuel use (Denham et al., 2015; Parker et al., 2018; Parker and Tyedmers, 2015). Alternatives to replace fossil fuels on fishing vessels include biodiesel, hybrid electric, diesel electric, battery electric, fuel cells, and solar energy, though most applications have either been adopted on small vessels or are in early stages of development (FAO, 2018). Rebuilding fish stocks and reducing over-capacity of fishing fleets are seen as long-term approaches to reduce fuel use (Parker and Tyedmers, 2015).

It is also important to note that energy use in fisheries is management system dependent. Many fisheries are managed so that there is significant over-capacity to catch large amounts of fish in a short period of time (Birkenbach et al., 2017), and the short season that characterizes Alaska salmon serves as a good example. Valderrama and Anderson (2010) show that participation in the salmon fishery changes significantly with the price of salmon, with little impact on quantity landed. As over-capacity in terms of the number of vessels is often more than 200% (Asche et al., 2014), there is scope for significant reduction in energy use just by reducing the number of vessels.

The U.S. is transitioning towards the national goal of 100% clean electricity by 2035 and a net-zero economy by 2050 (U.S. DOS; EOP, 2021). Our results show that proposed policies such as a carbon tax (U.S. House of Representatives, 2020) would be effective in support of a framework to reduce emissions across the electric power sector (NASEM, 2021). Our modeling analyses showed that a "$35 carbon fee" scenario would lower carbon dioxide emissions. At the same time, it would significantly increase direct energy costs in the catfish sector, which could be unsustainable without the addition of programs and policies to support an equitable transition (NASEM, 2021). A similar effect would be observed in the fisheries sector, as rising fuel costs as a result of a carbon fee would create a financial burden on fishing vessels, which are limited in options to simultaneously reduce fossil fuel use and maintain productivity (Roll et al., 2022). U.S. fisheries and aquaculture sectors can be a part of the renewable energy transformation but cannot do it by themselves. Increased costs could drive processing to other countries or increase the share of imported seafood. Our analyses help to establish the current use of renewable energy, stakeholder views and perceptions, as well as opportunities in both onsite and grid applications to transition towards renewable energy.

5. Conclusions

Fisheries and aquaculture are highly reliant on fossil fuels and must become more energy efficient and climate friendly to meet global planetary heath goals and a national goal of a net-zero economy by 2050. There are specific energy challenges for fisheries and aquaculture because of their often-remote geographic locations, seasonal patterns in energy use, and low ability to invest in new technology. Rising fuel costs and political interventions to reduce carbon emissions will place burdens on these sectors and the overall food system, with ramifications for food prices and the health of domestic industries. These issues will require context specific solutions and informed discussions by stakeholders to balance the needs of domestic producers, food security, and sustainability.

CRediT authorship contribution statement

Rachel E. Scroggins: conceived of the project, Formal analysis, conducted the analysis, Writing – original draft, wrote the original manuscript, All authors were involved in editing and revision. **Jillian P. Fry:** conceived of the project, Data curation, provided data, All authors were involved in editing and revision. **Mark T. Brown:** Data curation, provided data, All authors were involved in editing and revision. **Roni A. Neff:** conceived of the project, All authors were involved in editing and revision. **Frank Asche:** conceived of the project, All authors were involved in editing and revision. **James L. Anderson:** conceived of the project, All authors were involved in editing and revision. **David C. Love:** conceived of the project, All authors were involved in editing and revision.

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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