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Economic Impacts of Offshore Wind Farms on Fishing Industries: Perspectives, Methods, and Knowledge Gaps

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Abstract
Offshore wind farms (OWFs) are rapidly developing as an alternative energy source globally and in the Greater Atlantic region of the United States. Despite the pace of development, there are still many uncertainties surrounding best practices in assessing the economic impacts of offshore wind on regional fishing industries. This work aims to provide an overview and assessment of industry perceptions, methods, results, and knowledge gaps pertaining to economic areas of concern related to interactions between OWFs and fishing industries in the region. We provide a compilation of studies focusing on industry perceptions and impacts of OWFs on the fishing industry, focusing on four key economic areas of interest: fuel expenditures; insurance costs; fishing industry revenues, income, and livelihoods; and fishing support businesses. Our findings suggest four overarching knowledge gap themes that persist across all economic areas of focus: (1) a lack of economic data or economically centered data collection efforts, (2) minimal works aiming to quantify the economic impacts of key areas of concern, (3) a lack of peer-reviewed models and methods in quantifying economic impacts, and (4) limited syntheses containing best practices or lessons learned associated with quantifying the comprehensive economic impacts posed by OWFs on fisheries. This article aims to build awareness in areas where interdisciplinary collaboration can take place as well as serve as a foundation for informing best practice guidance as it pertains to assessing economic impacts imposed by OWFs on the fishing industry.

The intersection of the U.S. offshore wind and fishing sectors is expected to result in economic implications given the roles that both industries play in contributing to the national economy. In 2018, the American Blue Economy,[1] including goods and services, contributed about US$373 billion to the nation's gross domestic product (GDP) and supported approximately 2.3 million jobs (NOAA 2021). From 2017 to 2018, marine-related GDP grew by 5.8%, 0.4% faster than the total U.S. GDP, which grew by 5.4%. From 2014 through 2018, the economic activity from America's seaports alone grew by 17% to $5.4 trillion, comprising nearly 26% of the nation's $20.5 trillion in GDP.[2] If American coastal counties were combined to create an individual country, they would rank third in the world in GDP, surpassed only by the United States and China (NOAA 2021). Commercial landings (edible and industrial) across the entire United States totaled 4.2 million metric tons (930 billion lb), valued at $5.5 billion in

[1]According to the World Bank (2017), the Blue Economy includes the sustainable use of ocean resources for economic growth, improved livelihoods and jobs, and ocean ecosystem health.

[2]Measured in 2021 dollars.

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2019. Of these landings, the Atlantic region[3] made up 13% of the total U.S. commercial harvest and 39% of exvessel value (NMFS 2021). Like American offshore fisheries, offshore wind development along the U.S. Atlantic coast has a trajectory of becoming a major contributor to the U.S. economy. The potential for offshore wind in the United States is around 5,000 GW, and the Biden Administration aims to capture a portion of this potential by producing 30 GW by 2030 and 110 GW by 2050 in energy from offshore wind farms (OWFs; GWEC 2021). With these new developments, the administration also expects increases in OWF-related job opportunities, with the potential for 25,000 development and construction jobs from 2022 to 2030 and up to 4,000 operations and maintenance jobs annually between Long Island and the New Jersey coast (White House, Office of the Press Secretary 2021).

As of 2021,[4] the Bureau of Ocean Energy Management (BOEM) issued 27 proposed offshore lease areas on the Atlantic coast (as seen in Figure 1) and considerations for additional wind areas off the Atlantic coast, along Pacific state coastlines, and in the Gulf of Mexico (Figure 2). The authorization to issue corresponding leases, easements, and rights of way for renewable energy development on the Outer Continental Shelf was given to BOEM in 2005 under the Energy Policy Act (Energy Policy Act 2005). The Energy Policy Act also outlines the need for compliance with the National Environmental Policy Act, which requires federal agencies to assess the environmental impacts of their proposed action(s) that may arise from the construction, operation, and decommissioning of OWFs. As such, BOEM must assess environmental impacts, which include socioeconomic impacts—whether direct, indirect, or cumulative—prior to development decision making (National Environmental Policy Act 2022). Unsurprisingly, the construction and operation of OWFs have introduced many uncertainties, including how OWFs will impact fishing communities and the fishing industry's contributions to the national economy. Assessing and understanding the socioeconomic externalities stemming from offshore wind energy areas (WEAs; offshore locations where wind power is harvested and developed) remains essential to mitigating negative impacts on the fishing industry. Implementing strategic policies and plans stemming from research findings can ensure that direct and indirect costs are minimized while monetary and nonmonetary benefits are maximized.

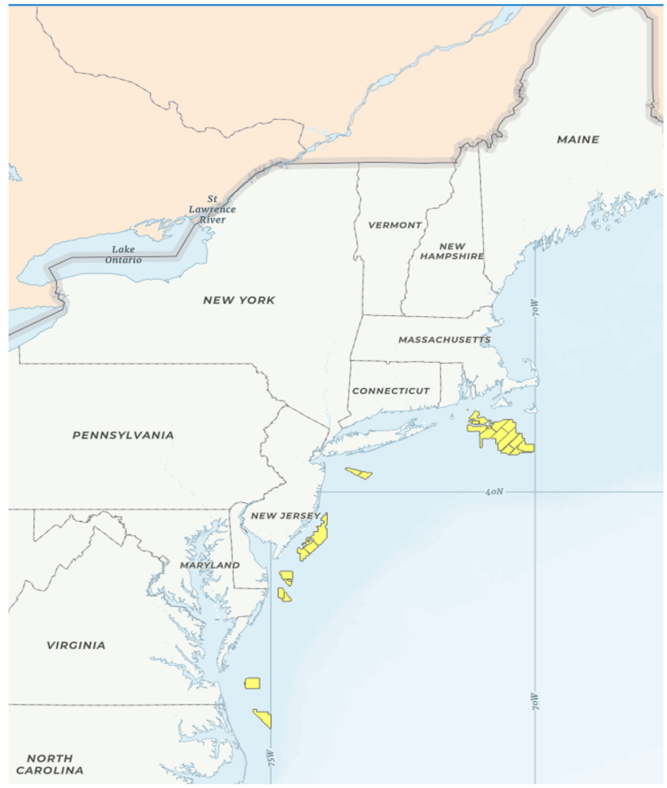

FIGURE 1. Lease areas (yellow) in the Greater Atlantic region as of 2022. Lease areas were obtained from the Bureau of Ocean Energy Management's GIS website (https://www.boem.gov/renewable-energy/mapping-and-data/renewable-energy-gis-data).

There is a handful of published works that focus on identifying economic areas of concern when assessing OWFs and the fishing industry (Moura et al. 2015; Haggett et al. 2020; Methratta et al. 2020), and some works provide best practices for fishing industry liaisons (FLOWW 2014). Here, we aim to merge and expand upon existing works by not only highlighting major economic areas of interest, but also summarizing studies that quantify these economic impacts, discussing the methods used, and identifying areas where additional information, research, or both are still needed. Despite the rapid increase of OWF proposals in the Greater Atlantic region, the region has few standardized protocols or studies that outline recommended methods for capturing and estimating the economic impacts imposed by OWFs on the regional recreational and commercial fishing sector. The goal of this article is to expand upon the existing literature and generate a foundation for building a better understanding of existing studies as well as identifying the knowledge gaps that require further investigation to inform best practices for assessing and measuring the economic impacts of OWFs on fishing industries.

[3]Data from the east coast of Florida are included in the Atlantic, while Florida's west coast data are included in the Gulf Coast. Data from Puerto Rico were not available for 2019.

[4]Lease areas were obtained from BOEM's GIS website (https://www.boem.gov/renewable-energy/mapping-and-data/renewable-energy-gis-data).

FIGURE 2. Proposed (blue) and leased (yellow) wind development areas in the United States as of 2022, obtained from the Bureau of Ocean Energy Management's GIS website (https://www.boem.gov/renewable-energy/mapping-and-data/renewable-energy-gis-data).

METHODS

In this article, we summarize industry perspectives, methods, results,[5] and knowledge gaps from reports and studies focusing on economic areas of concern stemming from OWF development and operation on the commercial and recreational fishing sectors. Initial economic areas of focus were informed by a collaboration of offshore wind and fishing industry experts. This initiative included members of the Responsible Offshore Development Alliance (RODA), Responsible Offshore Science Alliance (ROSA), academic partners, BOEM, and the National Oceanic and Atmospheric Administration (NOAA) National Marine Fisheries Service (NMFS) collaborators and aimed to compile a cross-disciplinary synthesis of OWF impacts. The workshops were held in October 2020, focusing on stakeholder engagement, which brought academics, researchers, wind, and fishing industry representatives together to discuss ecological, economic, and social impacts related to OWFs. Once the economic research topics were identified, an expert review of references and methods was initiated, starting with a search of published works, followed by white papers and interactive data tools. Specifically, the review focused on summarizing the following sections across studies: (1) perspectives from the fishing industry pertaining to the economic areas of focus; (2) the methods used to quantify the economic impacts of OWFs pertaining to the area of focus; and (3) the direct monetary result of OWFs on the fishing industry as it pertains to the economic area of focus. We place specific emphasis on sections 2 and 3, as these are particularly underexamined areas of focus. The search period spanned from November to April of 2020.[6] Due to the rapid increase of OWF exploration in the Greater Atlantic region, existing research pertaining to this area was the principal focus of the economic literature review. Relevant research from other regions was also included to help form a basis for potential adaptation in the Greater Atlantic region. A schematic of the literature search processes is displayed in Figure 3. For recreational studies, there are initiatives aiming to gather baseline angler effort and preference data pertaining to offshore wind (Dalton et al. 2020; Kneebone and Capizzano 2020); however, studies assessing the economic impacts of OWFs on the recreational fishery are less common. This may be due to limited species-specific recreational demand models coupled with the uncertainty of recreational effort displacement. The lack of recreational studies may also be driven by a lack of spatial primary, on-water catch data, such as Marine Recreational Information Program data. Given the lack of recreationally focused studies, this article captures the perspectives of commercial harvesters more fully than those of recreational anglers. Although there are potential externalities on OWFs posed by the fishing industry, this work aims to capture the unilateral economic impacts of OWFs on fisheries. In addition, this work attempts to isolate and evaluate the literature pertaining to the *economic* factors stemming from OWFs rather than other social or ecological topics of concern, despite a significant overlap between these fields of study.

Given the number of economic areas of focus identified in the workshops, multiple keyword searches were conducted using Google Scholar and the NOAA library

[5]All monetary results are reported in nominal dollars unless indicated otherwise.

[6]We have updated any reference that was cited as “in press” during the literature search period that has since been published.

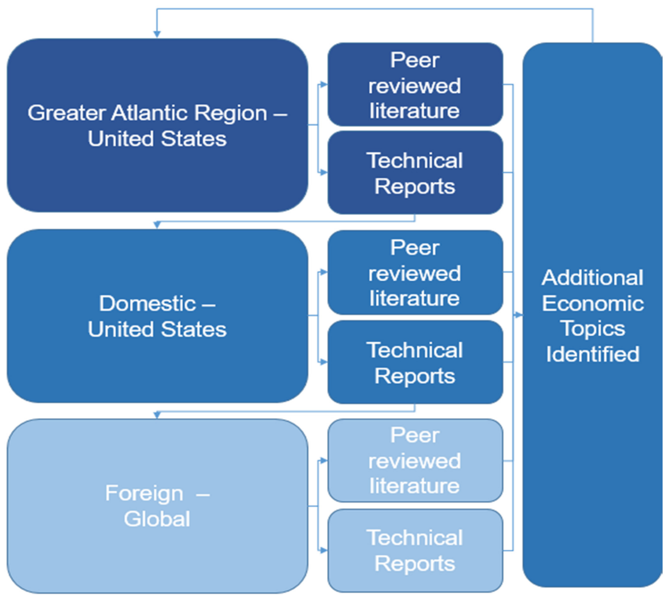

FIGURE 3. A schematic of the literature search conducted in this study and the order of review.

databases to ensure that the appropriate published works were considered in this review.[7] The literature review underwent a blind peer review, which was conducted by academic and industry experts. Ultimately, there were few peer-reviewed works published that focused on quantifying and monetizing the economic impacts of offshore wind on fishing industries during our literature search period. The lack of peer-reviewed works caused us to deviate from the traditional literature review methodologies. There was, however, a suite of technical reports and tools developed specifically to answer the economically focused research questions presented in this paper. To enhance the utility and completeness of the present work, findings from white papers, technical reports, and data query tools are also summarized in this review. As the review progressed, additional economic areas of concern were identified and incorporated into the analysis based on the topic's prevalence and significance in the literature, such that this paper highlights the top economic areas of concern that emerged from workshop results as well as those that surfaced from the literature review exercise. Using these methods, we aim to inform emerging and pre-existing frameworks used in assessing and mitigating negative externalities imposed on the fishing industry in the wake of expanding offshore wind activity.

[7]There is a large number of studies pertaining to offshore wind development business practices, which often do not consider the economic implications of OWFs for the fishing industry. For this reason, the majority of records yielded by each keyword combination was deemed potentially misleading.

RESULTS

Through our research, we identified four main economic areas of concern relating to the impacts of offshore wind on the fishing industry, including (1) fishing industry fuel expenditures; (2) fishing industry revenues, income, and livelihoods; (3) the cost of insurance; and (4) impacts on fishing support businesses. In the following sections, we present each of the four economic areas of focus, first by describing the grounds for concern through summarization of fishing industry perspectives. We then summarize the various methods used to quantify the economic impacts pertaining to each economic area, along with the monetized burden placed on industry resulting from pertinent studies. We close each section by discussing suggested mitigation techniques, knowledge gaps, and future research recommendations to improve assessments of OWFs' economic impacts on the fishing sector. An overview of each economic area of focus is presented in Tables 1–4, including the pertinent research studies, methods, economic implications, and knowledge gaps.

Fuel Expenditures

Fuel usage accounts for about 80% of at-sea operational costs for commercial fishing vessels in the Greater Atlantic region, making it the single highest trip-level cost for the average vessel (Das 2014). Despite the large role that fuel costs play in at-sea operation, there are still many uncertainties in how commercial and recreational fuel expenditures will be impacted by offshore wind and the extent of such impacts (Berkenhagen et al. 2010; Hattam et al. 2015). Increases in fuel usage either have been observed, or are anticipated to occur, given disruptions in vessel navigation and changes in fishing location (i.e., displacement) as a result of wind areas (Perry et al. 2012; EEI 2014). The largely qualitative study by Gray et al. (2016) found that UK fishers encountered increases in steam times and in overall distances to fishing areas due to established OWF areas, which translated into higher rates of fuel consumption. In the study, the majority of fishermen from northwest England agreed that the cost of fuel directly impacted their fishing effort.

Only a handful of studies have focused on assessing and quantifying the increases in fuel usage and costs driven by OWF-induced changes. The BOEM funded a study investigating wind development on the Atlantic Outer Continental Shelf in which a location choice model was generated to identify the probability of commercial harvesters operating in particular ocean patches (Kirkpatrick et al. 2017). From this model, the relative difference in trip-level net revenues (revenues minus variable costs, including fuel)[8] was estimated; however, a quantification

[8]Variable costs included fuel, ice, bait, and an average measure of gear damage or loss.

TABLE 1. An overview of studies assessing fishing industry perspectives, methods, results, and knowledge gaps in relation to the economic implications of offshore wind farms (OWFs) on fishing fuel expenditures.

Author	Approach	Economic implications	Primary knowledge gaps[a]
Greater Atlantic United States			
Kirkpatrick et al. (2017)	Commercial fishing location choice model	Not explicit	II, III, IV
Samoteskul et al. (2014)	Cost effectiveness analyses and Coastal and Marine Spatial Planning modeling frameworks	Nearshore wind development caused rerouting, increasing per-transit distance by 18.5 km. In turn, cumulative annual industry costs increased by US$9.76 million (2012 dollars), of which fuel accounted for 54% of the total increase in expenditures (an additional $5.29 million [2012 dollars]).	III, IV
Foreign global			
Gray et al. (2016)	Telephone interviews with fishers, developers, and regulators	UK fishers encountered increased steam times and distances to fishing areas. The majority of fishermen from northwest England agreed that the cost of fuel directly impacted their fishing effort.	V

[a]Primary knowledge gaps are as follows: I = a lack of economic data and data collection efforts; II = minimal works aiming to quantify the economic impacts of OWFs on the fishing industry; III = a need for peer-reviewed methods when quantifying economic impacts; IV = limited guidance on best practices or lessons learned associated with quantifying the economic impacts posed by OWFs on fisheries; and V = not applicable because the study pertains to the identification of economic areas of concern rather than quantifying the magnitude of the impact.

of the changes in fuel usage and costs was not individually summarized in that report (Table 1).[9]

An analysis by Samoteskul et al. (2014) combined cost effectiveness analyses and Coastal and Marine Spatial Planning modeling frameworks to identify optimal locations for wind development in relation to routes used by mid-Atlantic U.S. transport vessels. The report modeled 1,500 commercial shipping vessel transports, calculating direct and indirect costs pertaining to each trip. The direct costs included fuel expenditures, operational costs, and capital costs and the indirect costs pertained to greenhouse gas emissions. For the calculation of direct costs, fuel usage was estimated for each trip using the vessel's main and auxiliary engines. The price of fuel was assumed to be $1,000 per metric ton based on marine diesel oil or marine gas oil global prices (2012 dollars). The Samoteskul et al. (2014) study found that on average, nearshore wind development caused an additional 18.5 km per transit, which increased the total annual costs by $9.76 million. Of the additional costs, fuel accounted for 54% of the total increase in expenditures (an additional $5.29 million to the fleet's total fuel expenditures). Although Samoteskul et al. (2014) investigated large deep-draft ships exclusively, similar methods could be applied to model costs incurred by fishing industry participants (e.g., commercial and recreational fishing vessels) under various wind area closure scenarios.

Multiple methods have been proposed to minimize or avoid increases in fishing industry fuel expenditures as a result of OWFs. Gray et al. (2016) suggested developing fuel depots to increase fuel supply to offset increases in fuel expenditures by the fishing industry. Government-funded fuel subsidies are a best practice suggested by Moura et al. (2015); however, there is a lack of consensus around using subsidies due to potential negative externalities.[10] These works, however, do not offer methods on how to accurately estimate the level of subsidization required to offset possible increases in fuel expenditures due to offshore wind sites. Vessel engine replacement programs have also been suggested to reduce costs associated

[9]The work by Kirkpatrick et al. (2017) is discussed further in the Revenues, Income, and Livelihoods section.

[10]Some studies have found evidence that fuel subsidies are linked to overfishing (Martini and Innes 2018; Sumaila et al. 2019), while other studies (Sakai 2017) suggest otherwise.

TABLE 2. An overview of studies assessing fishing industry perspectives, methods, results, and knowledge gaps in relation to the economic implications of offshore wind farms on fishing industry revenues, income, and livelihoods.

Author	Approach	Economic implications	Primary knowledge gaps[a]
Greater Atlantic United States			
Kirkpatrick et al. (2017)	Multiway fixed-effects model estimating exposure and fishing location discrete choice model (random utility model) identifying fishing activity likelihood in wind energy areas based on various parameters	Identified US$14 million in commercial revenue exposure and $23.9 million (6%) in average annual for-hire gross revenue exposure. Commercial net revenues decreased across permit clusters between −$6,588 and −$516,984 (2012 dollars).	III, IV
NMFS (2018b)	Vessel monitoring system (VMS) effort data and modeled vessel trip data using statistical methods to increase the precision of reported catch	Total exposure of $334.8 million in revenues combining the New York Bight wind areas from 2012 to 2016 (2014 dollars). The most exposed fishery management plans (FMPs) were Atlantic sea scallop *Placopecten magellanicus* ($268 million), and Atlantic surfclam *Spisula solidissima* and ocean quahog *Arctica islandica* ($48 million).	III, IV
RI DMF (2017)	Fishing density weighting techniques informed by VMS data	Total exposure across all FMPs equaled over $39 million in revenue from 2011 to 2017. The three highest FMPs based on revenue exposure were Atlantic sea scallop ($23.1 million); longfin inshore squid *Doryteuthis (Amerigo) pealeii*, Atlantic Mackerel *Scomber scombrus*, and Butterfish *Peprilus triacanthus* ($5.7 million); and Goosefish (also known as Monkfish) *Lophius americanus* ($3 million) when assessed over the 6-year time period.	III, IV
RI DMF (2018)	Fishing density weighting techniques informed by VMS data	Results suggested that over $222 million in revenues were exposed in the New York Bight call areas from 2011 to 2016. The following FMPs were identified to have the highest exposure: Atlantic sea scallop ($211 million); Goosefish ($3.3 million); longfin inshore squid, Atlantic Mackerel, and Butterfish ($3.3 million); and Summer Flounder *Paralichthys dentatus*, Scup *Stenotomus chrysops*, and Black Sea Bass *Centropristis striata* ($2.8 million).	III, IV

TABLE 2. Continued.

Author	Approach	Economic implications	Primary knowledge gaps[a]
RI DMF (2019)	Autoregressive integrated moving average	Cumulative exposure of $30–35 million in revenues derived from the Vineyard Wind areas over an aggregated 30-year time period.	III, IV
Methratta et al. (2020)	Synthesis of key challenges related to offshore wind from published works	Potential decreases in revenues and incomes across multiple commercial fisheries groups stemming from overcrowding and displacement.	V
ten Brink and Dalton (2018)	Primary data collection via semi-structured interviews and thematic coding	Loss of fishing grounds and crowding concerns expressed by fishermen in the Block Island Wind Farm area.	V
BOEM (2020b)	Qualitative assessment of cumulative impacts	Reported cumulative impacts of proposed alternatives were "moderate" to "major" for commercial fisheries and for-hire recreational fishing, in addition to short-term losses as a result of the proposed cable placement/maintenance and construction noise.	V
		Foreign global	
Mackinson et al. (2006)	Primary data collection via questionnaire	Majority of participants expected negative impacts on fishing income as a result of restricted access to high-value fishing areas, navigation around wind areas, and the crowding of alternative fishing locations as a consequence of displacement.	V
de Groot et al. (2014)	Primary data collection via a questionnaire and workshops and thematic coding methods	Socioeconomic data were the third leading area of challenge shared by participants, after ecological data and environmental monitoring. More research is needed in (1) understanding the realized or estimated economic impacts due to the displacement of fishers, (2) capturing the economic contributions of each fishing location, (3) estimating the potential loss of employment, and (4) generating supply chain analyses.	V
Alexander et al. (2013)	Primary data collection via interviews and thematic coding	Loss of commercial fishing livelihood was identified as one of the top-three concerns reported by industry members.	V
Gray et al. (2005)	Primary data collection via interviews	Regulators and wind developers identified wind development as a possible source of major negative impacts on harvesters' incomes.	V

TABLE 2. Continued.

Author	Approach	Economic implications	Primary knowledge gaps[a]
Gray et al. (2016)	Primary data collected via a questionnaire paired with secondary landings and vessel movement data	The majority of fishermen claimed that wind farms resulted in a "negative" or "very negative" impact on their income.	V
Hooper et al. (2015)	Primary data collection via structured interviews	70% of participants had been impacted by previous wind projects, and 77% expected to be impacted in the future.	V

[a]Primary knowledge gaps are defined in Table 1.

with increased fuel expenditures (Perry et al. 2012; EEI 2014). Designated transit lanes are another suggested tool to increase vessel safety as well as a method to decrease fuel expenditures. Efforts to better understand vessel transit have been initiated by various organizations in the United States, including RODA, which utilized commercial fishermen survey data to map vessel navigation through the proposed New York Bight WEA (RODA 2019). The U.S. Coast Guard initiated the Massachusetts and Rhode Island Port Access Route Study in March 2019 to investigate various components of vessel transit lanes off the coasts of Massachusetts and Rhode Island (USCG 2020). This ongoing study relies on extensive stakeholder engagement as well as Automatic Identification System density data to explore vessel navigation patterns near wind areas in exploring vessel routing measures. These studies, however, have not yet reported results pertaining to fuel cost savings when comparing transit lanes to navigation around wind areas.

To understand how fuel costs are or could be impacted by OWF locations, data are needed to create a baseline of fishing industry costs. In the Northeast and mid-Atlantic, U.S. trip-related costs (including fuel expenditures) are collected on a subset of commercial fishing vessels (~4% of trips annually) by onboard observer programs. The trips are sampled based on a stratified sampling design created to satisfy biological rather than economic data needs, which can lead to bias in econometric models relying on these data. Trip costs have been modeled using methods to correct for selection bias and to predict trip costs for the entire regional fleet; however, verifying the accuracy of these model predictions is difficult due to the nature of selection bias (Werner et al. 2020). These models are also currently designed to predict total trip costs rather than each cost component individually. Estimating fuel costs for each trip would require additional research and modeling. A comprehensive, mandatory economic cost data collection effort would aid in generating a foundation for estimating how changes imposed by wind areas could impact fuel and other trip-related expenses. If trip cost data collection efforts were implemented, methods similar to those employed by Samoteskul et al. (2014) could be used to improve our understanding of increases in fuel expenditures driven by offshore wind development in the Greater Atlantic region. Lastly, changes in fuel costs can cause business owners to change their fishing habits or reconsider their at-sea operations altogether, given that a large percentage of at-sea operation consists of fuel expenses. Similar to Kirkpatrick et al. (2017), understanding harvester or angler choice in fishing location, along with the decision not to fish at all, would need to be examined to capture the net changes in fuel expenses. The combination of cost data collection efforts and location choice models could allow for the initial quantification of increased fuel expenditures driven by OWFs. Ultimately, quantifying the impacts of OWFs on the fishing industry's fuel expenses is necessary to ensure that appropriate allocations are used for adequate mitigation and to capture the financial burden placed on fishing businesses.

Fishing Industry Revenues, Income, and Livelihoods

Common concerns expressed by the fishing community are related to the impacts of offshore wind development and operation on fishing revenues, earnings, income, and/or livelihoods. Methratta et al. (2020) suggested possible decreases in commercial fishing revenues and incomes stemming from overcrowding and displacement driven by OWF areas. Property loss or damage due to OWF areas may also decrease overall profits (EEI 2014). In the UK, Mackinson et al. (2006) used questionnaire data to

TABLE 3. An overview of studies assessing fishing industry perspectives, methods, results, and knowledge gaps in relation to the economic implications of offshore wind farms (OWFs) on fishing industry insurance.

Author	Approach	Economic implications	Primary knowledge gaps[a]
Greater Atlantic United States			
Hall and Lazarus (2015)	Data collection via public meetings and ethnographic field note techniques with theme identification	Fishermen expressed concerns related to insurance costs as a result of OWFs. They also expressed confusion on whether insurance companies would exclude certain distances from the turbines.	V
Foreign global			
Gusatu et al. (2020)	Semi-structured interviews of fishing organization representatives	Interviewees expressed concerns over the potential for higher costs of insurance due to safety risks, such as accidents with fishing vessels, spillover effects to aquaculture farms, etc.	V
Hooper et al. (2015)	Primary data collection via structured interviews	One-third of the crab/lobster fishermen interviewed were concerned about the validity of their insurance while fishing in wind areas.	V

[a]Primary knowledge gaps are defined in Table 1.

summarize fishing industry perceptions of the socioeconomic impacts of OWF construction and operation. In that study, all but one respondent suggested that wind development would have negative impacts on fishing income as a result of restricted access to high-value fishing areas, navigation around wind areas, and the crowding of alternative fishing locations as a consequence of displacement.[11] Fishermen, however, were unable to quantify the predicted changes in expected revenues resulting from the development and operation of OWFs. The Mackinson et al. (2006) report also summarized the percentage of harvesters' total revenues earned within the various proposed wind areas, lending insights into the extent of impacts on total profits. In another UK study (de Groot et al. 2014), results from stakeholder questionnaires and workshops investigating perspectives from fishing industry representatives, academics, and offshore renewables spokespeople were thematically coded to decipher key challenges related to renewable energy developments. Results suggested that socioeconomic data are the third leading area of challenge behind ecological data and environmental monitoring. The authors indicated the need for additional research focusing on (1) understanding the realized or estimated economic impacts due to displacement of fishers, (2) capturing the economic contributions of each fishing location, (3) estimating the potential loss of employment, and (4) generating supply chain analyses (de Groot et al. 2014). Loss of commercial fishing livelihood was also identified as one of the top-three concerns reported in a study examining potential impacts to Scottish west coast fisheries (Alexander et al. 2013). Gray et al. (2005) also conducted a study on wind development perceptions in the UK through interviews with wind developers, regulators, and key industry members. The study reported that both regulators and wind developers identified wind development as a possible source of major negative impacts to harvester incomes and identified compensation to the industry as a method to counteract the restriction of access to fishing grounds. Hooper et al. (2015) investigated wind developer and fishing industry perceptions pertaining to co-located UK OWFs and found that the majority of interviewed fishermen expected to lose fishing grounds if the proposed OWFs are built. The study did not investigate whether this loss of fishing area would translate into decreases in gross revenues or income. A handful of fishermen in a Block Island Wind Farm study also expressed concerns about the loss of fishing grounds and crowding, which can ultimately lead to decreases in harvester revenues (ten Brink and Dalton 2018). Concerns around fishing income and revenues were cited as the main issue motivating the BOEM environmental study update on the North

[11]This questionnaire received an 8% response rate (n = 23), and responses may not be representative of the fishing industry as a whole.

TABLE 4. An overview of studies assessing fishing industry perspectives, methods, results, and knowledge gaps in relation to the economic implications of offshore wind farms on fishing support businesses.

Author	Approach	Economic implications	Primary knowledge gaps[a]
Greater Atlantic United States			
NMFS (2018a)	Input/output (I/O) modeling and Impact Analysis for Planning (IMPLAN)	In 2016, the New England commercial fishing seafood industry generated 152,217 jobs, US$13.52 billion in sales, $3.62 billion in income, and $5.51 billion in added value. The recreational sector generated 19,674 jobs, $2.06 billion in sales, $0.92 billion in income, and $1.37 billion in added value.	III, IV
NMFS (2018a)	I/O modeling and IMPLAN	In 2016, the mid-Atlantic commercial seafood industry supported 101,223 jobs and generated $13.45 billion in sales, $3.19 billion in income, and $5.06 billion in added value. The recreational sector supported 40,926 jobs and generated $4.42 billion in sales, $1.87 billion in income, and $2.94 billion in added value.	III, IV
Murray (2016)	I/O modeling and IMPLAN	The value added, combining the five main market sectors, increased total impacts from $81 million to $1.3 billion in 2014.	III, IV
Sproul and Michaud (2018)	I/O modeling	Commercial fishing vessels, charters, processors, professional services, retail dealers, fishing service and supply, tackle shops, and wholesalers generated 3,147 jobs and $538.33 million in gross sales. Generated output resulted in 4,381 jobs and $419.83 million when evaluating spillover effects across Rhode Island's economy.	III, IV
Domestic United States			
Lovell et al. (2020)	Economic survey collecting recreational fishing expenditure data	Total recreational trip expenditures across for-hire, private boats, and shore anglers totaled $10.5 billion and contributed over 167,000 employment opportunities, $24 billion in sales, $14 billion in value added to the gross domestic product, and $7.9 billion in income to the national economy from 2016 to 2017.	III, IV
Scheld (2018)	Commercial Fishing and Seafood Industry I/O Model performed using IMPLAN	All regional U.S. longfin inshore squid landings corresponded to an output multiplier of 7.64 (every dollar in landings led to $7.64 in total economic output) from 2013 to 2017.	III, IV

[a]Primary knowledge gaps are defined in Table 1.

Atlantic and mid-Atlantic Outer Continental Shelf wind planning areas (BOEM 2020a). Overall, the vast majority of studies investigating fishing industry perceptions suggest that OWF areas are expected to have a negative impact on fishing revenues and livelihoods as a direct result of overcrowding and displacement, with uncertainty surrounding the magnitude of these expected changes.

Qualitative techniques, as opposed to quantitative methods, are commonly applied when assessing the expected and realized impacts of offshore wind development on commercial and recreational fishing revenues. One example of quantitative method usage is BOEM's draft environmental impact statement on the Vineyard Wind projects (BOEM 2020b). Using guidance from the National Environmental Policy Act, nonmonetary methods were used to quantify various impacts stemming from the project proposal, defining impacts as negligible, minor, moderate, or major. Cumulative impacts of the proposed alternatives on the commercial fisheries and on for-hire recreational fishing are expected to be "moderate" to "major" according to the report. Specifically related to commercial and recreational revenues, short-term losses are expected as a result of the proposed cable placement/maintenance and construction noise (BOEM 2020b). A UK study by Gray et al. (2016) used qualitative questionnaire data paired with secondary landings and vessel movement data to identify impacts on commercial fishing before and after implementation of the eastern Irish Sea OWFs. Results from the fishing industry questionnaire suggest that wind farms have caused "negative" or "very negative" impacts on income, although no additional steps were taken to further support these results or to quantify the losses attributed to OWFs. Structured interviews with 67 harvesters and 11 wind developer industry members were conducted in a 2015 UK study investigating wind area challenges (Hooper et al. 2015). From the industry interviews, participants were asked (1) whether they expected to be impacted by future wind projects and (2) whether they had been affected by offshore wind development in the past. Results suggest that 70% of participants had been impacted by previous wind projects and 77% expected to be impacted in the future, although the degree to which these participants were affected and how they expected to be impacted in the future, were not captured in a quantitative manner. The qualitative assessment of economic impacts on fishing industry revenues is an important first step in assessing the magnitude of impacts imposed by OWFs; however, estimating monetary effects is necessary to ensure that compensation and mitigation plans are properly informed.

A number of analyses and tools have been generated to quantify the potential impacts of offshore wind areas on commercial and recreational fishing revenues. Specifically, these studies often utilize multiple data streams, such as vessel logbook information (i.e., vessel trip reports [VTRs]), vessel monitoring system (VMS) data, and landings and revenue data from commercial fishing dealer records, to quantify the total revenues obtained from a certain wind area. In the United States, VTRs, VMSs, and exvessel sales reports are often mandatory in commercial fisheries, but reporting requirements vary across regions, states, and fishery management plans (FMPs). Some works aim to link vessel logbook data, containing trip characteristics, landings, and coarse harvest area information, with VMS satellite surveillance data. The VMS data capture vessel movement, which can increase the accuracy of allocating catch to specific harvest areas. For example, the Rhode Island Division of Marine Fisheries (RI DMF; RI DMF 2017) assessed VMS data, VTRs, and dealer landings reports to identify the various gear types, species, and regional FMPs that accounted for the highest revenues earned in wind areas in the Greater North Atlantic from 2011 to 2017. The RI DMF (2017) report focused on potential impacts within the Massachusetts WEA, the Rhode Island and Massachusetts Area of Mutual Interest, and the New York WEAs. Data sources were combined and landing quantities were allocated to specific areas based on fishing density weights informed by VMS data. This method was noted in the report as an improvement from previously produced analyses, which failed to adequately apportion catch across space when assessing trip landings and revenues. Results suggested that the total exposure, in terms of total revenues earned within the areas of interest across all FMPs and years, equated to over $39 million in revenue.[12] The three highest FMPs based on revenue exposure were Atlantic sea scallop ($23.1 million); longfin inshore squid, Atlantic Mackerel, and Butterfish ($5.7 million); and Goosefish ($3.0 million) when assessed over the 6-year time period. The RI DMF (2018) study used similar data sources and weighting methods to assess exposure for three out of four New York Bight call areas (Fairways North, Fairways South, and Hudson North) over the period 2011–2016. Results suggested that over $222 million in revenues were exposed in the wind areas over the combined 6-year period, with the FMPs for Atlantic sea scallop ($211 million); Goosefish ($3.3 million); longfin inshore squid, Atlantic Mackerel, and Butterfish ($3.3 million); and Summer Flounder, Scup, and Black Sea Bass ($2.8 million) being the most exposed. The RI DMF also created a report using a combination of methods to estimate exposure over a 30-year time series for the Vineyard Wind areas given certain wind area buffers (RI DMF 2019). The RI DMF Vineyard Wind study used autoregressive integrated moving average methods to project exposures for the 30-year

[12]There is no description of deflating dollar values in the report such that values are assumed to be presented in nominal dollars.

time series, which equated to about $30–35 million in cumulative exposed revenues depending on the buffer assumed. The model parameters, model performance, and peer review status of the model and methods were not disclosed in the report. In 2018, NOAA submitted an analysis in response to the 2018 BOEM call for information and nominations for the commerical leasing for wind power on the Outer Continental Shelf in the New York Bight (NMFS 2018b). The submission assessed the exposure of various ports and species, as well as vessel-level exposure, in terms of revenues and earnings acquired from proposed New York Bight wind areas (~688,000 ha) from 2012 to 2016. The analysis employed modeled VTR data using the statistical approaches described by DePiper (2014). DePiper (2014) used statistical modeling techniques to compare VTR self-reported information to more precise observed haul-level data. This technique ultimately allows revenues to be distributed more accurately within self-reported VTR harvest areas. The study suggests a total exposure of $334.8 million[13] in revenues from all of the New York Bight wind areas from 2012 to 2016 (NMFS 2018b). The findings indicate that the most exposed FMPs were those for Atlantic sea scallop ($268 million) and Atlantic surfclam and ocean quahog ($48 million).

In the BOEM-funded study by Kirkpatrick et al. (2017), revenues resulting from catch landed in Northeast and mid-Atlantic U.S. WEAs were calculated using data from three main sources: VMSs, VTRs, and spatial data from the Northeast Fisheries Observer Program database. The statistical method described by DePiper (2014) was also used in this analysis. Revenues were estimated using a multiway fixed-effects model, and results were summarized using exposure measures. In the report, exposure was defined as the revenues from catch harvested within a wind area and exposure measures should not be regarded as directly estimating actual economic impacts. Instead, exposure measures can be used to inform the extent to which revenues might be negatively impacted by WEA development, depending upon how harvesters ultimately respond to closures or restrictions. The exposure measures were estimated using data from the years 2007–2012. The Kirkpatrick et al. (2017) analysis accounted for 82.5% of all exposed wind area revenues, whereas the other approximately 17.5% of exposed revenues in wind areas were not accounted for due to data reporting limitations. Results suggest that the eight proposed WEAs generated an average of $14 million[14] in commercial revenue annually over the time period assessed (i.e., 1.5% of the total commercial fishing revenue generated in the New England and mid-Atlantic region). Total exposure based on revenues was further summarized by port, vessel size-class/gear type, and commercial species. The ports with the highest exposure from offshore wind were New Bedford, Massachusetts; Atlantic City, New Jersey; Cape May, New Jersey; and Narragansett, Rhode Island. The vessel types and gear types most exposed varied by port. In New York and New Jersey, large scallop/clam dredges had the highest potential exposure resulting from wind development, but in Rhode Island and southern Massachusetts, small pot and gill-net vessels had the highest exposure. Lastly, the Atlantic sea scallop was the species with the highest exposure, with an annual average of $4.3 million in revenue generated from WEAs. The relative exposure of recreational for-hire vessels and private and for-hire trips to WEAs was also investigated by Kirkpatrick et al. (2017), with exposure calculated using recreational expenditure data rather than revenues. About 6.3% of average annual for-hire gross revenues ($23 million) and 3.8% of for-hire and private boat fisher trips were exposed to the WEAs. Lastly, cumulative impacts were estimated to describe the degree to which exposed vessels are expected to be impacted by wind areas. For this analysis, a fishing location discrete choice model was used to identify the likelihood that fishing would occur in each WEA. A random utility model was used to estimate the utility of fishing in a particular zone given expected revenue, costs, revenues net variable costs (RNVC), wind speed, exvessel prices of key species, season, and vessel characteristics. From this model, the changes in RNVC were assessed and reported in 2012 dollars. To keep the analysis tractable, permits were grouped into various clusters based on fishing area and gear type. Assuming that all WEAs were closed, the cumulative commercial fishery impact summary reported changes in RNVC ranging from $6,588 to $516,984 across the permit clusters. Smaller vessels, grouped in cluster 1, showed higher changes in RNVC and were more heavily impacted by the loss of fishing grounds.

The Socioeconomic Impacts of Atlantic Offshore Wind Development website (NMFS [NOAA Fisheries])[15] relies on commercial fisheries landings data and VTRs to highlight how various gear types, FMPs, species, ports, and vessels are most likely to be affected by offshore wind areas. The site offers reports that include summaries for commercial fisheries as well as limited information on recreational party and charter trips. The wind areas and vessel locations were generated, again, using techniques outlined by DePiper (2014) as well as methods described

[13]Values from NMFS (2018b) are presented in 2014 constant U.S. dollars.

[14]Values from Kirkpatrick et al. (2017) are presented in 2012 constant U.S. dollars.

[15]This site was released in 2020 and is available at https://www.fisheries.noaa.gov/resource/data/socioeconomic-impacts-atlantic-offshore-wind-development.

by Benjamin et al. (2018). The reports summarize the fisheries that were most "impacted" based on the landings and revenues earned within wind areas from 2008 to 2019. Note that this definition of impacted is the same as that of the term "exposed" in the Kirkpatrick et al. (2017) report. Preliminary results suggest that, for all WEAs in the Greater Atlantic region, there were an estimated $110 million in revenues from the top-five most impacted species over the period 2008–2019 (2019 dollars). When the data were summarized by FMP across all years and all proposed northeast WEAs, the FMPs most impacted were Atlantic sea scallop; Atlantic surfclam and ocean quahog; and Atlantic Mackerel, longfin inshore squid, and Butterfish, with cumulative revenues of $42.5, $31.6, and $14.2 million, respectively (2019 dollars).

A suite of NOAA wind area maps and Web tools has been generated by the Northeast Fisheries Science Center (NEFSC) and the Greater Atlantic Regional Office, which again incorporates the methods described by DePiper (2014).[16] Another mapping initiative includes the Island Institute's Mapping Working Waters project, which generated maps of heavily fished areas off the coast of Maine through data collected from fisher interviews (Klain et al. 2017; Snyder 2020). Similar mapping efforts and engagement strategies have been implemented in the Rhode Island Ocean Special Area Management Plan (University of Rhode Island Coastal Resources Center/Rhode Island Sea Grant) and in the RODA partnership's Ocean Data Portals project, mapping the northeastern coast of the United States (McCann et al. 2013).

Potential mitigation strategies to offset losses and costs have been presented in multiple reports, most of which include compensation packages and funds (IE and MOP 2009; EEI 2014; BOEM 2020a). One example is the 2014 report to BOEM (EEI 2014), which draws upon offshore oil and gas mitigation techniques such as retraining programs for displaced fishermen along with established funds to offset property losses and damages. Proposed mitigation strategies, including funds for compensating fishermen, often lack guidance on the amount of funds necessary to adequately meet the needs of the fishing industry. This task would ultimately require additional economic analyses capturing net changes in fishing revenue, income, and livelihoods.

The Fishing Liaison with Offshore Wind and Wet Renewables Group (FLOWW; FLOWW 2014) offered a guide to best practices for offshore wind development in the UK, which references Seafish's (2012) best practice guidance document. Seafish (2012) provides generalized methods for identifying and calculating revenues from impacted areas. The FLOWW (2014) report nicely summarizes data sources and compares their relative quality and robustness. The report also provides an overview of methods for estimating the value derived from specific fishing locations, which can be used to assess impacts of displacement or area closures. Unfortunately, the suggested methods for quantifying impacts on revenue lacked consensus from the peer review process and does not supply references to published works, which makes replication difficult. Lastly, the FLOWW (2014) report does not mention or compare recently developed statistical and econometric modeling techniques. With additional research references and specific analysis recommendations, this type of guidance report is needed to formalize the process by which OWF economic impacts, including impacts to fishing revenues, are quantified in the Greater Atlantic region.

Overall, more is known about federal commercial fishing revenues than other economic data components in the Greater Atlantic region due to federal seafood dealer reporting requirements. Despite these requirements, there are still many informational gaps in determining the degree to which OWFs affect fishery revenues, income, and earnings. Additional work is needed to highlight and identify the best available science in estimating revenues acquired from wind area-sourced landings. This effort would be best served if methods were peer reviewed prior to their use in technical reports, especially when reports are used to inform decision-making processes concerning OWFs. Moreover, consensus among researchers on a standard set of metrics and methods, including time periods to consider and statistical models, should be discussed to ensure that comparisons across works can be reasonably made and to streamline future analyses. For example, exposure estimates in terms of revenues harvested from wind areas are now becoming the status quo, without considering a harvester's potential to recoup revenues from alternative fishing sites. Therefore, it is unclear whether exposure is a suitable substitute for total net revenue losses when reporting impacts to harvesters' incomes, livelihoods, and revenues. Standardization of metrics and methods can also assist in achieving the larger goal of creating a comprehensive accounting of the cumulative costs and benefits stemming from OWF and fishing industry interactions. Given the numerous sources of data, analyses, and tools available for estimating revenues that are exposed to OWFs, an economic guidance document outlining best practices, similar to that from FLOWW (2014), combined with pointed technical guidance, similar to that from Seafish (2012), would be highly useful in creating a standardized set of methods to assess the costs and benefits stemming from OWFs in the Greater Atlantic region. In addition, understanding recreational demand in response to expected catch is another knowledge gap that requires further research. The indirect impacts of WEAs

[16]These tools include, but are not limited to, the Fishing Footprints website and the Socioeconomic Impacts of Atlantic Offshore Wind Development Web page.

on revenues, such as the impact of crowding due to fishing displacement, is another area of uncertainty for which little research has been published. Additionally, change in revenues is a useful measure for economic performance, but it is not a substitute for profitability. Calculating the profitability of commercial fishing businesses requires detailed information on total variable, fixed, and quasi-fixed costs. A large portion of these types of costs are collected in the Commercial Fishing Business Cost Survey for the Greater Atlantic region, which is conducted by the NEFSC Social Sciences Branch; however, low response rates have caused complications in summarizing and modeling the data collected (Ardini et al. 2022). Lastly, additional research must be conducted to link the primary impacts on fishing revenues and earnings to secondary impacts on support businesses, which is further explored in a later section.

Cost of Insurance

The cost of fishing vessel insurance has been discussed in a handful of stakeholder engagement sessions and best practices/mitigation reports, with insurance rates often being speculated to increase due to the navigational hazards posed by OWF turbines (Perry et al. 2012; Schultz-Zehden et al. 2018). A report (Hall and Lazarus 2015) summarizing themes from stakeholder meetings that focused on floating turbines off the coast of Maine identified insurance costs as a concern of local fishermen in response to turbine development. The participating fishermen also expressed concern and confusion from uncertainty over insurance companies potentially creating exclusionary distances from the turbines (Hall and Lazarus 2015). Through a mixed-approach study focusing on OWF spatial planning in the North Sea, Gusatu et al. (2020) conducted semi-structured interviews with fishing industry experts to identify potential pathways and challenges in offshore space management. In the study, insurance was one of the main barriers identified by Scottish fishing organization representatives when questioned about the co-location of OWFs and fishing activities. Additionally, Hooper et al. (2015) found that one-third of the 67 UK crab and lobster fishermen interviewed for their study were concerned about the validity of their insurance while fishing in wind areas. Results from interviews held with fishing industry stakeholders off the coast of Scotland indicated that insurance premiums may financially bar commercial fishermen from operating in wind areas, even if the areas remain open to fishing (Moura et al. 2015). There are also concerns about the liability of fishermen if underwater cables are damaged—an issue that has surfaced in other, non-wind-related infrastructure sites. Even without explicit regulations or rules prohibiting fishing activity in a given wind development area, fishermen may still exclude otherwise viable fishing locations for fear of safety- and insurance-related repercussions (Kirkpatrick et al. 2017).

Despite the numerous studies citing insurance as a major economic concern of the fishing industry, minimal works have aimed to quantify changes in insurance premiums and claims. Rather than directly estimating the potential increase in insurance expenditures, developers such as Vineyard Wind have created a trust fund for the fishing industry to offset multiple costs, including insurance. The generation of the $25.4 million trust is based on revenue exposure estimates and multipliers using VTRs, commercial fishing dealer reports, and VMS data rather than estimating the increases in insurance costs to the suite of vessels potentially impacted by OWFs (BOEM 2020a).

Although there are limited works aiming to quantify insurance cost shifts, there are multiple cases in which best practices related to insurance cost mitigation strategies have been generated. The review by Moura et al. (2015) suggests insurance support, provided by the government and/or wind developers, to be a best practice strategy for offsetting potential increases in insurance premiums. The review, however, failed to provide guidance on how to estimate increases in insurance premiums for fishing vessels operating within OWFs to adequately inform compensation plans. In addition, FLOWW (2014) offers guidance to UK fishermen for situations in which they come in contact with cables and describes how to file claims in the event of lost or damaged fishing equipment. It should be noted that the report does not provide methods or guidance on how compensation for displacement or disruption of fishing activities should be calculated. The underlying theme of these works suggests that there are major uncertainties concerning how insurance rates will be impacted by OWFs in the early stages of offshore development, operation, and decommissioning. There are also clear knowledge gaps in how liability or compensation will be allocated to the fishing industry in the case of accidents or loss of gear due to interactions with OWFs.

To better understand how insurance rates might be impacted by offshore wind at all stages, time series data are necessary to fill the existing knowledge gaps. Some vessel insurance providers disclose a nonexhaustive list of determining factors used in calculating premiums, which includes loss of gear or loss exposure, a single vessel's claims history, and area(s) of operation. Other insurance providers request or consider claims history information but do not explicitly mention this to be a determining factor in generating premium rates. Collection of data related to these variables may help to estimate changes in insurance premiums with the introduction of offshore wind and its associated structures. There is little transparency in how rates are calculated, thus making it problematic to predict insurance premiums and expenses. Furthermore, there is also uncertainty around how future claims could potentially affect the cost of the larger insured group over time. Despite these limitations, there are methods for collecting insurance information that can inform models or baseline estimates within the Greater Atlantic region. The Commercial Fishing Business Cost Survey (NEFSC Social Sciences Branch) collects annual vessel- and business-level cost information from commercial fishermen in the Northeast and mid-Atlantic, including data on insurance premiums (Ardini et al. 2022). However, given that this survey effort is voluntary, response rates have suffered and insurance data analyses (e.g., annual increases or econometric models of insurance premiums) have yet to be generated. Mandatory collection of insurance cost data would enhance the opportunity to assess the direct impacts of wind areas on insurance rates and to fill the data gaps related to this topic. Lastly, additional research and recommendations on establishing liability agreements between wind companies and local fisher groups should be explored. Without a clear understanding of how developers and fishermen will be covered, the burden of insurance costs cannot be accurately estimated. Overall, insurance costs are an area of concern for the fishing industry, yet there are limited data, analyses, and proposed solutions on how to best quantify and adequately mitigate this externality.

Support Businesses

To fully assess economic impacts resulting from offshore wind and interactions with fishing industries, economic impacts to fisheries supply chains and associated support businesses must also be considered. To consider supporting businesses, additional evaluations across the five main market sectors of the seafood industry would be necessary. This includes the harvesting/commercial fishing sector, processors and dealers (primary wholesaling), import/export operations, secondary wholesaling/distributing, and seafood retailers (Murray 2016; NMFS 2018a). Multilevel market impacts are often omitted in efforts to capture the cumulative costs stemming from OWFs (Snyder and Kaiser 2009). Recreational fisheries also support a wide array of market sectors by providing products and services to anglers. Specifically, when anglers participate in fishing activities, they support sales and employment in recreational fishing and other businesses. Anglers purchase fishing equipment from bait-and-tackle shops, rent and buy vessels, and pay to participate in charter or party fishing trips. In addition, both commercial and recreational activity leads to food and drink purchases at local restaurants, the purchase of fuel for vessels, and expenditures on hotel accommodations for overnight fishing trips, thereby further stimulating economic activity in shoreside communities (NMFS 2018a). Despite these relationships, many support businesses that are dependent upon fishing industry activities are often understudied, especially in the Greater Atlantic region.

Though there are limited peer-reviewed studies capturing the cost implications driven by OWFs on fishing support businesses, regulating agencies such as BOEM have produced guidance documents describing suggested methods for assessing the economic impacts that stem from OWFs (AECOM 2017). The AECOM (2017) report suggested identifying cumulative impacts by using a socioeconomic cost–benefit analysis. This involves first constructing a socioeconomic profile of the community that is expected to be impacted; then identifying and assessing the scope and magnitude of socioeconomic impacts; and, lastly, evaluating the cumulative impacts derived from the project. In terms of how to quantify the economic impacts, the report suggests identifying the expected economic changes by using three metrics: job creation, output, and tax revenue. Moreover, changes to the economy are often measured at three levels of impact: direct, indirect, and induced. Here, total direct impacts often pertain to sales, income, and employment generated from initial purchases. Indirect impacts capture sales, income, and employment of industries that supply to the industry or project of focus. Induced impacts are sales, income, and employment resulting from expenditures by employees of the direct and indirect sectors of focus. A variety of tools and programs have been developed to estimate total economic impacts, including employment factors, the Regional Input/Output (I/O) Modeling System (RIMS II), the Jobs and Economic Development Impact (JEDI) model, and Impact Analysis for Planning (IMPLAN[17]; AECOM 2017). A common element of these tools and models is the use of multipliers that express intersectoral economic relationships and can be used to estimate total economic impacts resulting from expenditures in a particular sector. Overall, the total economic impacts are only a small component of the entire socioeconomic cost–benefit analysis, yet they are necessary for creating more complex cumulative analyses. Despite the lack of research capturing the full socioeconomic costs and benefits of OWFs, as suggested by the BOEM guidance document (AECOM 2017), there have been multiple efforts to estimate the total economic impact of various sectors of commercial and recreational fisheries. Scheld (2018) used the NOAA/NMFS Commercial Fishing and Seafood Industry I/O Model via IMPLAN software to identify the total amount of economic activity derived from total longfin inshore squid landings in the northeastern United States between 2013 and 2017. Scheld (2018) concluded that the examined fishing activity corresponded to an output multiplier of 7.64, meaning that every dollar received from

[17]These tools and Web programs have been ordered from simplest to most complex.

exvessel landings led to $7.64 in total economic output.[18] Another study (Murray 2016), based on I/O modeling and IMPLAN, analyzed the scope and extent of economic contributions of the Atlantic surfclam and ocean quahog fisheries combined at each level along the market chain in the mid-Atlantic region, starting from the fishermen in the harvest sector through to the final sale to direct consumers (generally by retail markets and restaurants). The study results suggest that the value added by combining the five main market sectors increased total economic contributions from $81 million to $1.3 billion in 2014 (Murray 2016).

Lovell et al. (2020) estimated recreational fishing trip expenditures from 2016 to 2017 using a nationwide economic survey. Expenditure data from the survey were then incorporated into an IMPLAN I/O model to estimate the total contributions or impact of the recreational sector to the entire U.S. economy. Results suggest that the total recreational trip expenditures across for-hire, private boats, and shore anglers totaled $10.5 billion and contributed over 167,000 opportunities in employment, $24 billion in sales, $14 billion in value added to the GDP, and $7.9 billion in income to the national economy.[19]

Although multipliers and I/O tools are common in assessing economic impacts, there are limitations to their use. Specifically, the usage of particular I/O models or tools is contingent on the data available and the quality of those data when generating outputs. In addition, these models often contain rigid assumptions (i.e., linear production functions, constant relative prices, and homogeneous sector output) that also need to be considered when determining the appropriateness of modeling and when interpreting the results (Steinback 1999). Given the ease of generating estimates from these models, modeling conducted by trained experts and peer review of findings and methods are critical for validating that these models are being used and interpreted properly.

The National Marine Fisheries Service produces the "Fisheries Economics of the United States" report on an annual basis, describing how U.S. commercial and recreational fishing affects the economy in terms of employment, sales, and value-added impacts. The generation of these reports relies on two unique IMPLAN models from the NOAA Economics and Sociocultural Analysis Division and the NMFS Office of Science and Technology (NMFS 2018a). Report results suggest that in 2016, the New England commercial seafood industry supported 152,217 jobs and generated $13.52 billion in sales, $3.62 billion in income, and $5.51 billion in added value. The New England recreational sector generated 19,674 jobs, $2.06 billion in sales, $0.92 billion in income, and $1.37 billion in added value. In the mid-Atlantic region,[20] the commercial seafood industry supported 101,223 jobs and generated $13.45 billion in sales, $3.19 billion in income, and $5.06 billion in added value. The mid-Atlantic recreational sector supported 40,926 jobs and generated $4.42 billion in sales, $1.87 billion in income, and $2.94 billion in added value.[21] A joint project between the Commercial Fisheries Research Foundation and the University of Rhode Island used I/O modeling to estimate annual gross sales and jobs for the Rhode Island fisheries and seafood sector in 2016 (Sproul and Michaud 2018). The study used business listings from the Rhode Island Secretary of State Corporate Database and marketing databases to inform the I/O models. The study found that in 2016, the commercial fishing vessels, charters, processors, professional services, retail dealers, fishing service and supply, tackle shops, and wholesalers generated 3,147 jobs and $538.33 million in gross sales. In addition, there were 4,381 jobs and $419.83 million in output generated when considering spillover effects across the entire Rhode Island economy (Sproul and Michaud 2018).

Another tool to capture direct, indirect, and induced economic impacts stemming from OWFs is the JEDI offshore wind model. The JEDI tool is specifically designed to allow users to estimate economic development impacts from wind power generation projects, such as outputs on jobs, earnings, and other elements during the construction period (NREL 2015). Unfortunately, no user guide is available to help identify which multipliers are used, unlike the land-based JEDI wind model that is also offered by the National Renewable Energy Laboratory. Although the JEDI model is available for download and public use, it was not operable during author trials. Despite these setbacks, tools such as the JEDI model could be valuable in comprehensively evaluating the net costs and benefits from OWFs on the fishing industry.

Understanding the cumulative economic contributions of OWFs and the fishing industry by identifying and evaluating costs and benefits is the first step to better understanding OWF impacts on fishing support businesses. Despite this major knowledge gap, creating analyses that identify the total economy of each industry (fishing and OWFs) can serve as an initial step toward a better understanding of total contributions to regional economies. Further work is also needed to emphasize the importance of properly using the various economic tools and models available to end users and to preserve the integrity of

[18]Reported in 2017 dollars.

[19]Assumed to be reported in nominal dollars, given that there was no discussion of dollar value conversions in the report.

[20]In the NMFS (2018a) report, mid-Atlantic states included Delaware, Maryland, New York, New Jersey, and Virginia.

[21]Impacts from OWFs on shoreside support industries are more likely to occur at a finer spatial scale than those evaluated in the "Fisheries Economics of the United States" report.

these types of analyses. When conducting any support business analysis, it is also advised to consider the unique attributes of the commercial fishing industry. For example, fishery product landings undergo product development, processing, and distribution changes, creating additional economic value beyond the initial landed value. These impacts further complicate which methods, processes, and tools should be selected for impact evaluations. Furthermore, the lack of data on secondary and tertiary effects of the fisheries supply chain in relation to OWFs creates a gap in understanding and evaluating the potential and realized economic impacts. Economic effects should be evaluated at each level along the entire market chain of distribution—from the fishermen in the harvest sector through the final sale to consumers (generally by retail markets and restaurants)—to fully assess the related costs and benefits. Economic impacts can be researched by using new methods or by improving existing processes to more closely align with offshore wind development, operation, and decommissioning. Collection of high-resolution economic data at the community level, paired with expert use of the available tools, is the first step in capturing the effects of OWFs on fishing support businesses.

DISCUSSION

In this article, we provide an overview of fishing industry perspectives as well as methods and results from studies quantifying economic impacts imposed by OWFs on the fishing industry in the Greater Atlantic region. In doing so, we hope to create a deeper understanding of how current and future offshore wind development impacts can be effectively quantified and mitigated in the Greater Atlantic and in other regions. We also offer research opportunities and areas of improvement by identifying common pitfalls that persist across all economic areas of focus. Specifically, after reviewing each section, there are four main knowledge gap themes that have been identified across the four economic areas of focus: (1) a lack of economic data or economically centered data collection efforts; (2) minimal works aiming to quantify the economic impacts in key areas of concern, especially pertaining to industry costs and support businesses; (3) a lack of peer-reviewed models and methods when quantifying economic impacts; and (4) limited syntheses containing best practices or lessons learned associated with quantifying the economic impacts posed by OWFs on fisheries. A visual interpretation of the relative need for improvement in each of these areas across each economic section is displayed in Figure 4. These common themes are the primary barriers to improving the quantification of costs and benefits.

The need for economic data is prevalent in almost every area of focus discussed in this article; this is particularly true for fuel, insurance, and support business analyses. Primary insurance and support business data in the Greater Atlantic region are often hindered by low industry member participation, and in some cases, data collection efforts are nonexistent in the region. Specifically, fuel and other operating costs are collected but only for a small proportion of trips. In addition, this data collection is stratified on biological data needs rather than economic data needs, creating additional challenges in generating unbiased, reliable cost estimates. It would be advantageous to increase the collection of economic data to assess the economic impacts of OWFs. Lastly, enhancing the quality of the economic data currently collected can be initiated by incorporating reporting requirements comparable to those of biological data efforts.

More focused economic data collection efforts may also be required in supporting theories on harvester behavior. For example, Kirkpatrick et al. (2017) used choice modeling techniques to determine a harvester's next-best choice based on expected earnings in the event that a wind area is closed; however, a body of literature suggests that this may not fully capture how fishermen operate (Haggett et al. 2020). A discrete choice survey effort investigating harvesters' or recreational anglers' willingness to operate in various fishing areas based on a bundle of trip characteristics could verify the assumptions made by Kirkpatrick et al. (2017). Increasing the emphasis on economic data and data collection efforts is the crucial first step in closing knowledge gaps related to the cost implications that are imposed by OWFs but also in building a more holistic and multidisciplinary perspective, which is necessary for understanding and managing fisheries.

Given the lack of basic economic data, it is not surprising that there are minimal studies quantifying the impacts of offshore wind on the fishing industry across the majority of economic topics examined in this article. However, even where regional data do exist, such as fuel or economic contributions data, there is still little to no research specifically related to estimating the costs imposed by OWFs on the industry. For example, despite the abundance of industry commentary on fuel costs along with the large role of fuel expenditures in fishing business operations, changes to fuel costs have yet to be quantified in the region. From our research, we suggest that increases in fuel expenditures can be assessed in the region by using models or works presented by Samoteskul et al. (2014) or Kirkpatrick et al. (2017). Methods from Samoteskul et al. (2014) can be used to produce increases in expenditures focused on transit or steam times to fishing areas, and methods from Kirkpatrick et al. (2017) can be used to estimate changes in fuel expenditures resulting from harvesting in alternative fishing locations due to wind area closures. In addition, although studies have quantified the total economic contribution of recreational and

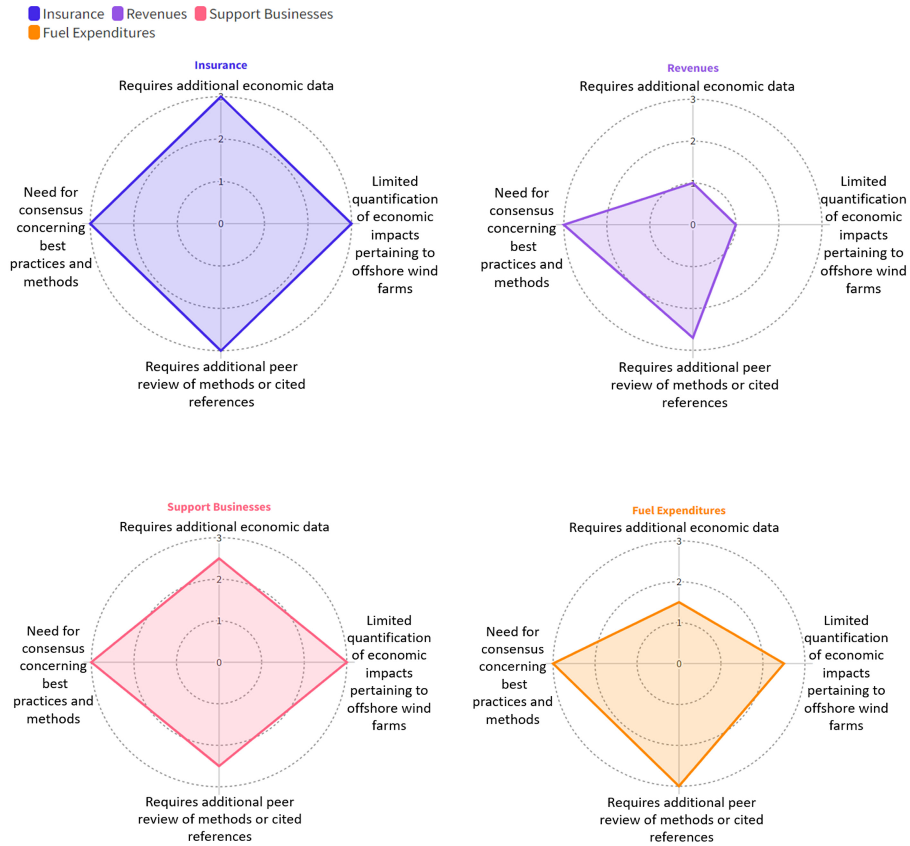

FIGURE 4. Radar charts depicting the prevalence of choice knowledge gaps across four key economic areas of concern (fishing industry) in relation to offshore wind. An increased distance from the origin represents a larger knowledge gap relative to others when assessing the economic topic.

commercial fishing to the economy, additional steps must be taken to quantify the negative and positive impacts on local economies imposed on the fishing industry, which are driven by the operation and development of OWFs. Identification of net impacts on employment and income is especially important in the assessment of fishing support businesses. Overall, additional steps are needed to quantify OWF-sourced impacts. In creating these assessments, a full profile of quantified contributions and costs imposed by OWFs will add to generating a comprehensive assessment of the net impacts on the fishing industry.

The need for (1) peer review methods and (2) a consensus on best practices is a recommendation for all economic areas of focus; however, addressing this need requires additional progress on closing the first two knowledge gaps—economic data and quantification studies—as a preliminary step. The use of peer-reviewed methods can increase confidence in results, while consensus on best practices facilitates the interpretation and comparison of results over various temporal and spatial scales.

Currently, there is a suite of tools and analyses that rely on a variety of methods and techniques to capture revenues in the Greater Atlantic region. Although there has been an evolution in the sophistication of methods used in this area of work, it is unclear which methods are preferred and whether those methods have been appropriately vetted within the scientific community. This is also true for fishing support business analyses, where guidance on current methodologies and studies evaluating the economic contributions from each sector exist. However, there is no discussion on how to quantify the net costs and benefits from the resulting interactions between the two sectors. We suggest that assessments by nongovernmental organizations should take steps to identify and review the suggested methods as well as rank the relative quality of existing studies in producing guidance pertaining to economic assessments of OWFs and the fishing industry.

Refining and building consensus around preferred methods are imperative for understanding trends over time and are a vital component to quantifying and mitigating impacts on fishing industries. The United States would benefit from a comprehensive guidance document on assessing offshore wind's economic impacts, which specifically outlines recommended methods that are supported by peer-reviewed literature, and available data streams for conducting offshore wind impact assessments. This guidance document should be developed to best inform mitigation and compensation plans and strategies, including draft works, such as the document developed by BOEM (2022).

One final overarching knowledge gap that, if addressed, can assist in improving economic analyses is the need for interdisciplinary research. Multidisciplinary biosocioeconomic models are necessary for generating a holistic view of fisheries to capture the full extent of positive and negative externalities when assessing the impacts of OWFs. Concepts such as wind-related job creation and potential increases in ecological biodiversity and productivity need to be evaluated simultaneously when capturing net costs and benefits of the interactions among OWFs, the fishing industry, and biological systems. Piecemeal approaches to capture the impacts of offshore wind not only miss key components in understanding the entire system, but are also inefficient given the overlap in areas of study. Assessment of wind areas comprehensively across disciplines offers an opportunity to create multipurposed data collection efforts that maximize utility and increase the streamlining of data sources. The NMFS Ecosystem and Socioeconomic Profiles and similar efforts, which aim to incorporate multidisciplinary input into stock assessment models, continue to be developed across the United States and may serve as a framework for generating holistic perspectives of natural systems and their intersection with anthropogenic activity (Shotwell 2018). Cross-collaboration efforts can help to erode the data gaps identified in this article and to improve the potential for assessing future changes to offshore ecosystems and the services that they provide.

Although this work focuses on the unique economic challenges faced in the Greater Atlantic region, our methods and results, as well as the four underlying knowledge gaps identified, can be applied more generally to guide economic impact assessments for any region. The rapid development of offshore wind areas in the Greater Atlantic region has enabled multiple research questions, methods, and gaps to emerge. The present paper capitalizes on this rapid emergence by synthesizing these works to establish a baseline of existing economic challenges and how they are currently being assessed or how they can be assessed in the future. This baseline can be best utilized by regions initiating the offshore wind exploration process but can also be adopted into existing offshore wind development plans. From a regional perspective, researchers can compare methods to determine the most appropriate technique and build toward a consensus of practices to generate guidance on calculating economic impacts. The consensus on appropriate methodologies and the data to support them can be extended to other regions and could inform the process at a potentially earlier stage of OWF development. Specifically, emerging and existing research plans, mitigation documents, and best practices guides should consider our four primary knowledge gaps to ensure that the economic impacts stemming from OWFs are more fully considered.

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