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Food for Thought

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A Framework for monitoring the socio-economic impacts of offshore wind energy development on fisheries and fishing communities

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Abstract

The increasing development of offshore wind energy creates challenges due to competing ocean usage. Given that offshore wind energy development (OWED) often overlaps with traditional fishing grounds, there is a need to establish a standardized process to monitor OWED impacts on socio-economic conditions. To that end, this paper proposes a standardized two-tiered project-level socio-economic monitoring framework. The monitoring framework focuses on OWED-specific risk factors (i.e. structure presence, vessel traffic, and port utilization) that significantly affect fisheries socio-economic conditions. The two tiers separate effects into direct (Tier 1) and indirect (Tier 2) impacts of OWED on commercial and recreational fishing. For example, the presence of structures (e.g, turbines) directly affects fishing vessels' access to fishing grounds, which indirectly affects fisheries attributes such as where and how vessels conduct fishing activity. Consequently, this could affect costs and revenues. The structure employed in this paper allows for more effective prioritization of data collection since understanding the effects of the risk factors on Tier 1 elements is key for characterizing the effects of OWED on Tier 2 elements. The paper also recommends key indicators and assessment tools to evaluate changes in the fisheries socio-economic conditions throughout the lifespan of offshore wind projects. Future research should focus on operationalizing and testing this framework, taking into account specific contexts within the geographic area where monitoring occurs. Fishery socio-economic monitoring within the OWED context is needed to understand shifts in existing conditions, reduce conflict, and ensure that OWEDs respect and support fishery sustainability as well as the livelihood and dynamics within fishing communities.

Keywords offshore wind energy, fisheries, socio-economic, monitoring, fishing communities

Introduction

The current expansion of offshore wind energy development (OWED) presents challenges for fisheries with unavoidable overlap between the two sectors (Murray et al. 2024). OWED has seen rapid progress in countries like China, the United Kingdom, and Germany, which lead in installed capacity (McCoy et al. 2024). Regions like North America, South America, and Southeast Asia have nascent markets that are beginning to scale up development. As countries continue to expand their energy portfolios, offshore wind structures have become increasingly prominent (McCoy et al. 2024, Paolo et al. 2024), often overlapping with traditional fishing grounds (Schupp et al. 2021, Allen-Jacobson et al. 2023, Feist et al. 2025, Szostek et al. 2025). Overlap of differing interests across industries introduces complex socio-economic challenges, as fishing communities experience changes in access, fishing behavior, and livelihoods, in both the commercial and recreational sectors (Gray et al. 2016, Hooper et al. 2017, ten Brink and Dalton 2018, Dunkley and Solandt 2022, Chaji and Werner 2023, Song et al. 2024, Feist et al. 2025, Szostek et al. 2025). In this paper, we adopt a broad definition of *community* that includes place-, social and cultural-, and practice-based perspectives (see Kraan et al. 2025). OWED will have legal and operational impacts for commercial and recreational fishing industries that vary depending on the phase of development (e.g. construction v. operation) and the type of OWED infrastructure (fixed foundation v. floating) (Hogan et al. 2023, ICES 2025). The implications to fisheries also vary by fishery type (e.g. commercial, for-hire, private angler), gear type (e.g. static or mobile gear) and activity (e.g. fishing, transiting) (Dunkley and Solandt 2022, Bonsu et al. 2024, Feist et al. 2025). In the U.S., environmental impact statements (EIS), which are comprehensive documents required for any major federal action that could significantly affect the environment, are developed during the permitting process. EISs typically identify the potential for OWED to have moderate to major adverse impacts on commercial fisheries and cultural resources (e.g. BOEM 2023).

Despite the anticipated impacts of OWED to fisheries and fishing communities, most monitoring plans to date have focused pri-

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marily on monitoring the biological impacts, especially in the U.S. (Methratta et al. 2023). While research has highlighted the importance of monitoring socio-economic changes over time (Eolenmer Observatoire n.d, DeBacker et al. 2019, Glasson et al. 2020), comprehensive socio-economic monitoring, including elements that go beyond fishing effort changes, such as fisheries well-being or shoreside support business impacts, are notably missing. Here, we refer to monitoring as the collection of data to quantify the change over time in socio-economic responses to OWED from a predevelopment baseline through all phases of the wind project (i.e. preconstruction surveys, construction, operation, and decommissioning). Peer-reviewed studies of socio-economic impacts tend to be one-off studies led by academic or government scientists (ten Brink and Dalton 2018, Glasson et al. 2020, Chaji and Werner 2023, DePiper et al. 2023). Though informative, these are typically retrospective and focus on economic metrics and overlook broader social and cultural dimensions such as perceptions of impacts, identity, individual and community resilience, and other meaningful indicators (Willis-Norton et al. 2024). Furthermore, there is a mismatch between the duration of OWED lease area awards (e.g. 30 years in the U.S.) and many social science data collection efforts, which are short-term or static ("snapshot") in nature. While broader, long-term socio-economic data exist, they are often too spatially or temporally coarse to capture site-specific dynamics. This results in sporadic and inconsistent data across projects making it difficult to capture long-term shifts and cumulative impacts. Given the potential of OWED to have substantial impacts on fisheries and fishing communities over the entire lease period, there is a clear and urgent need to establish a framework for socio-economic monitoring. A well-designed monitoring program can provide baseline and long-term data that can also be used to validate or challenge previously predicted, observed or perceived changes. Results of monitoring programs can help to inform placement of future offshore wind projects and thus minimize observed impacts and maximize established benefits. They can also be used to differentiate fishery operational changes in response to OWED from other factors (e.g. climate change, market conditions, resource availability) to develop more targeted fisheries management measures that address the cause of such changes and help enhance fishery sustainability.

Components of the fisheries socio-economic system include individuals, fleets, and communities involved in commercial and recreational (for-hire and private angler) fisheries. Monitoring of fisheries socio-economic conditions should include economic, social, and cultural elements, such as but not limited to changes to fishing behavior, business operations, demographics, employment, human and social capital, costs and revenues, and attitudes and perceptions. This requires the participation of impacted communities to understand how shifts are perceived and experienced locally. In this context, monitoring should move away from before-after OWED monitoring approaches, which disregard temporal variability (Methratta 2024), and focus on generating longitudinal datasets that can inform decision-making, support adaptive management, and improve regulatory strategies (Bingaman et al. 2022, Ellis et al. 2023). Monitoring programs may also require the development of targeted research projects to collect and analyze data to understand relationships between offshore wind impacts and socio-economic responses. While monitoring refers to the long-term collection of socio-economic data to track trends, targeted research focuses on shorter-term studies that address specific questions or knowledge gaps about potential causal relationships, and its findings can inform and refine the design of monitoring programs.

Potential adverse impacts to fisheries from OWED include loss of access to traditional fishing grounds, increased operational costs, loss of jobs and traditional way of life, and increased actual or perceived risk (Hogan et al. 2023, Szostek et al. 2025). On land, coastal communities have historically been heavily impacted by coastal development with new industries increasing pressure and challenging the commercial fishing industry's viability in traditional working waterfronts (Claesson et al. 2006, Colburn and Jepson 2012). Careful consideration and monitoring are necessary to help ensure these issues are not exacerbated by OWED and that fishermen's way of life is preserved. OWED could provide new job opportunities within the OWED sector to fishing vessels (e.g. scout or guard vessels, biological survey work), new recreational opportunities (Smythe et al. 2020), additional scientific information (additional resource surveys, benthic mapping, atmospheric/oceanic conditions), and infrastructure improvements. The relationship between potential adverse and beneficial impacts can be complex, as Szostek et al. (2025) found that some fishermen may supplement income due to offshore wind as an adaptive approach and presents an opportunity to learn new skills, but this could have implications for wellbeing if they feel they have no choice. Recreational fishing may increase in OWED areas, however, the increase in use may affect access through crowding of commercial and recreational fishermen (Hooper et al. 2017, ten Brink and Dalton 2018, Smythe et al. 2021). These potential impacts of OWED on fisheries socio-economic conditions highlight the importance of consistent and persistent monitoring. Monitoring is crucial for a clear and precise understanding of how OWED may alter fishing communities over time, not only in economic aspects, like revenue and catch, but also in social and cultural changes, such as perceptions and attitudes (Bingaman et al. 2022), place attachment (Devine-Wright and Howes 2010), and shifts in community structure and dynamics. A well-designed monitoring framework allows for the systematic collection and analysis of data that reveal both short- and long-term changes due to OWED. This includes understanding changes in fishing behavior, community adaptation or reorganization, and unintended consequences that may emerge as OWED expands within and across regions.

Standardized data collection across individual offshore wind projects will enable comparison and integration of data from multiple projects into broader regional assessments. Adopting a regional framework allows consistency in indicators, methods, and timing, which is crucial for evaluating cumulative effects and trends over time and space. The consistency achieved from this supports more effective decision-making and adaptive management. Additionally, it further improves coordination between agencies, developers, and stakeholders by providing a common foundation of understanding fishery effects from OWED.

Uncertainty facing OWED and the dynamic natural and human systems in which projects are usually situated necessitates an adaptive and iterative monitoring approach to evaluate and improve performance as needed. Adaptive monitoring allows the incorporation of new data sources, modification of indicators, and changes in methods or focus if needed. It also allows and emphasizes stakeholder engagement, ensuring that different stakeholders are part of identifying concerns, interpreting results, and pointing out monitoring priorities. The iterative process, i.e. repeated in

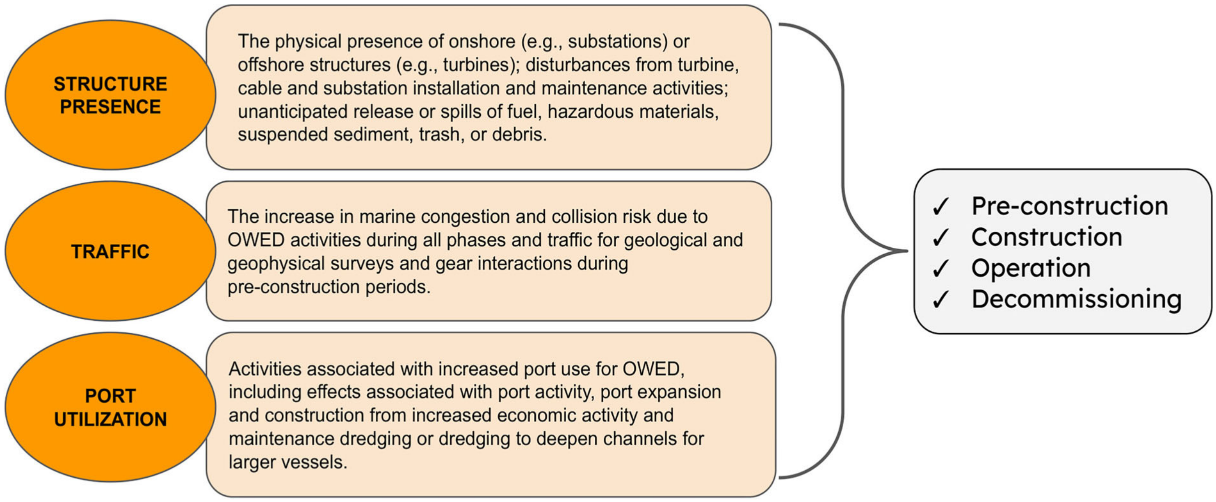

Figure 1 OWED Risk Factors identified as the most significant factors affecting the fisheries socio-economic conditions.

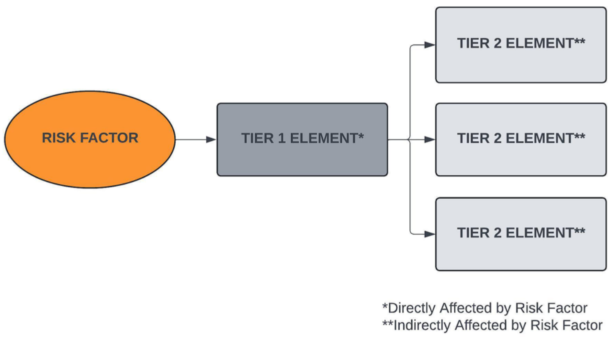

Figure 2 Schematic of conceptual model structure for each risk factor and its Tier 1 elements (direct effects) and Tier 2 elements (indirect effects).

cycles to refine approaches and solutions, builds trust, allows usage of the most relevant data, and increases "buy-in" from different stakeholders. This approach is fitting for OWED, considering technology, regulatory frameworks, and community perceptions will likely change.

In this paper, we propose a standardized project-level framework to monitor the socio-economic impacts of OWED on fisheries and fishing communities. While based on the Northeast U.S. experience, the framework is intended to aid development of socio-economic monitoring of OWEDs in other U.S. regions and overseas. The proposed framework uses a tiered approach based on identified risk factors, which are defined as an OWED induced change or stressor with the potential to significantly affect fisheries socio-economic conditions. To characterize these effects, the framework identifies direct and indirect impacts of risk factors on important socio-economic elements of the commercial and recreational fishing sectors. This approach increases the chances that cause and effect relationships between the risk factors and socio-economic elements are better understood and it provides guidance on organizing data collection efforts. The following sections of the paper elaborate on the framework's development and application. We present conceptual models for assessing direct (Tier 1) and indirect (Tier 2) OWED effects, recommend monitoring indicators (both quantitative and qualitative), and propose assessment tools to evaluate changes in access, operational dynamics, income, and community well-being over the lifespan of offshore wind projects. We conclude with specific recommendations to help ensure scientific accuracy and analytical comparability when using this framework. Developing and following through all phases of offshore wind development with a well-designed plan to monitor socio-economic conditions is critical for sustaining fisheries for future generations. Robust socio-economic monitoring, in combination with relevant bio-environmental monitoring, will provide decision makers with a powerful toolset to understand ecosystem changes throughout the lifetime of OWED projects, inform project approvals, and develop adaptive mitigation measures.

Developing and applying the socio-economic monitoring framework

The socio-economic monitoring framework presented here was developed as part of a broader effort to provide guidance for monitoring the impacts of OWED on U.S. Northeast region fisheries. During that process, we first identified three primary risk factors: Structure Presence, Traffic, and Port Utilization (Fig. 1). These risk factors were identified based on previous research and impact assessments (ICES 2021, Hogan et al. 2023, Methratta et al. 2023, Tyrell et al. 2024, BOEM 2024). For instance, in the U.S., the Bureau of Ocean Energy Management (BOEM) identified impact producing factors (IPFs) which are defined as "the cause-and-effect relationships between actions (e.g. a wind energy project) and relevant physical, biological, economic, or cultural resources" (BOEM 2024). The IPFs most relevant for the socio-economic system are those associated with structure presence, installation, maintenance, and accidental releases; changes to port utilization; and disruptions to traffic. Similarly, previous research efforts from European experience with OWED and fisheries identified key impacts of OWED on fishery operations related to the presence of struc-

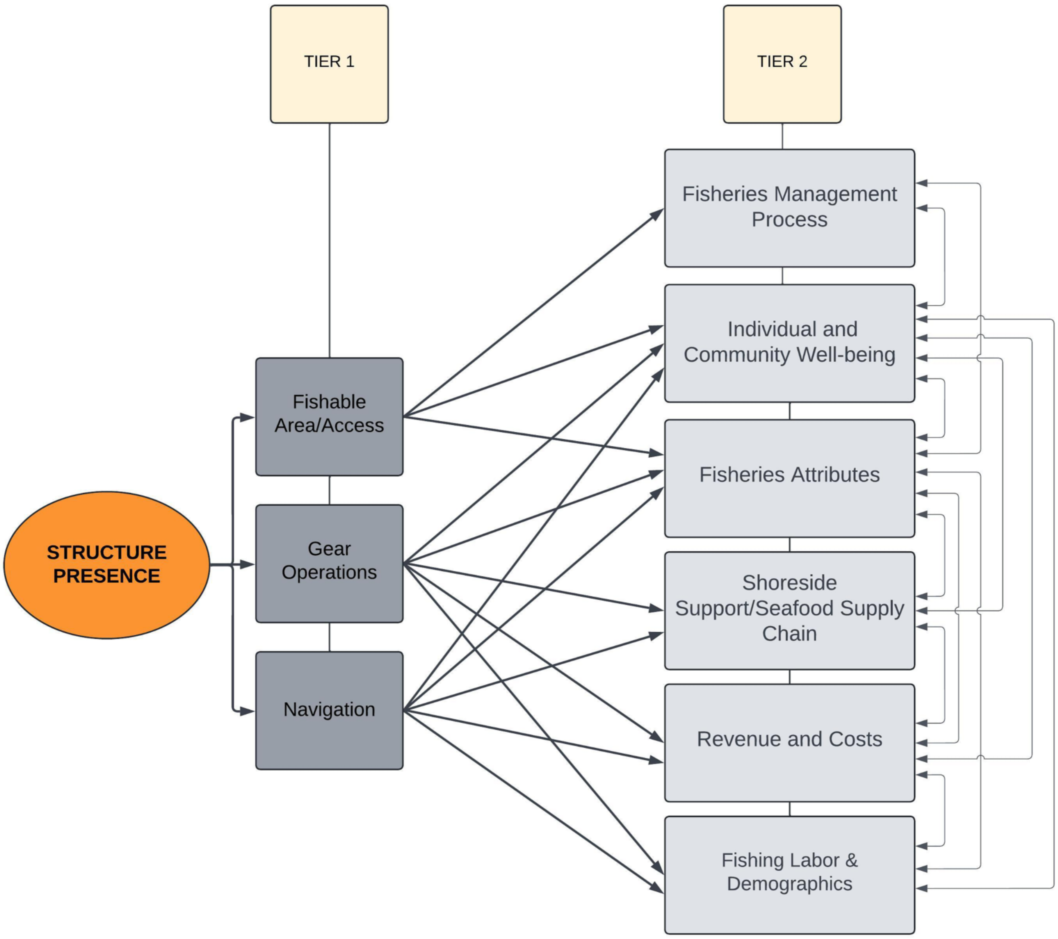

Figure 3 Conceptual model of the Tier 1 direct effects and Tier 2 indirect effects of the Structure Presence risk factor on fisheries socio-economic conditions.

tures and navigation changes (Mackinson et al. 2006, Gray et al. 2016, Szostek et al. 2025).

Individual conceptual models were then created for each risk factor. These risks were used as the starting point and relationships were established between them and elements of the fishery socio-economics. In the models, arrows represent the direction of the relationship from driver to receiver. The identification of socio-economic elements and construction of the conceptual models was based on the authors' expert knowledge in offshore wind and fisheries social science and informed by conceptual models previously constructed from fishing industry feedback sessions and public comments for the Fish FlOW integrated ecosystem assessment (IEA) (Tyrell et al. 2024). The Fish FlOW IEA collaboratively worked with ocean users to identify complex interactions between offshore wind energy, fisheries and the environment and provide tools to inform environmental analyses and reviews. Other previous research efforts, including some that collected knowledge and direct input from the fishing industry, on perceived impacts from OWED were also used (Alexander et al. 2013, ICES 2021, Hogan et al. 2023, Szostek et al. 2025). Because the risk factors identified here affect the system in ways that are direct and indirect, we developed a tiered approach for the conceptual models to distinguish between direct (Tier 1) and indirect (Tier 2) effects, allowing for clearer visualization of the relationships and action prioritization for monitoring and assessment purposes (Fig. 2).

The first versions of the conceptual models were shared and discussed with subject matter experts in the NOAA Fisheries national network of social scientists, spanning various disciplines including economics, marine policy, sociology and anthropology. Iterations of the models based on the feedback obtained resulted in the models presented in this paper. It is noteworthy to mention that these conceptual models are meant to be continuously refined with information obtained from various stakeholders and new scientific data produced to reflect as accurately as possible the experiences of those directly affected by the current and emerging relationships described.

Conceptualizing OWED effects

Figures 3, 4, and 5 show the conceptual models for the three risk factors identified in the Northeast U.S. context. These relationships may vary in different regions or countries depending upon local regulatory and environmental conditions, as well as types of OWED and fisheries. However, the tiered approach framework presented here can be adapted to reflect the local context. Elements that are directly affected by each risk factor are represented under the Tier 1 category, which are characterized in Table 1. Indirectly

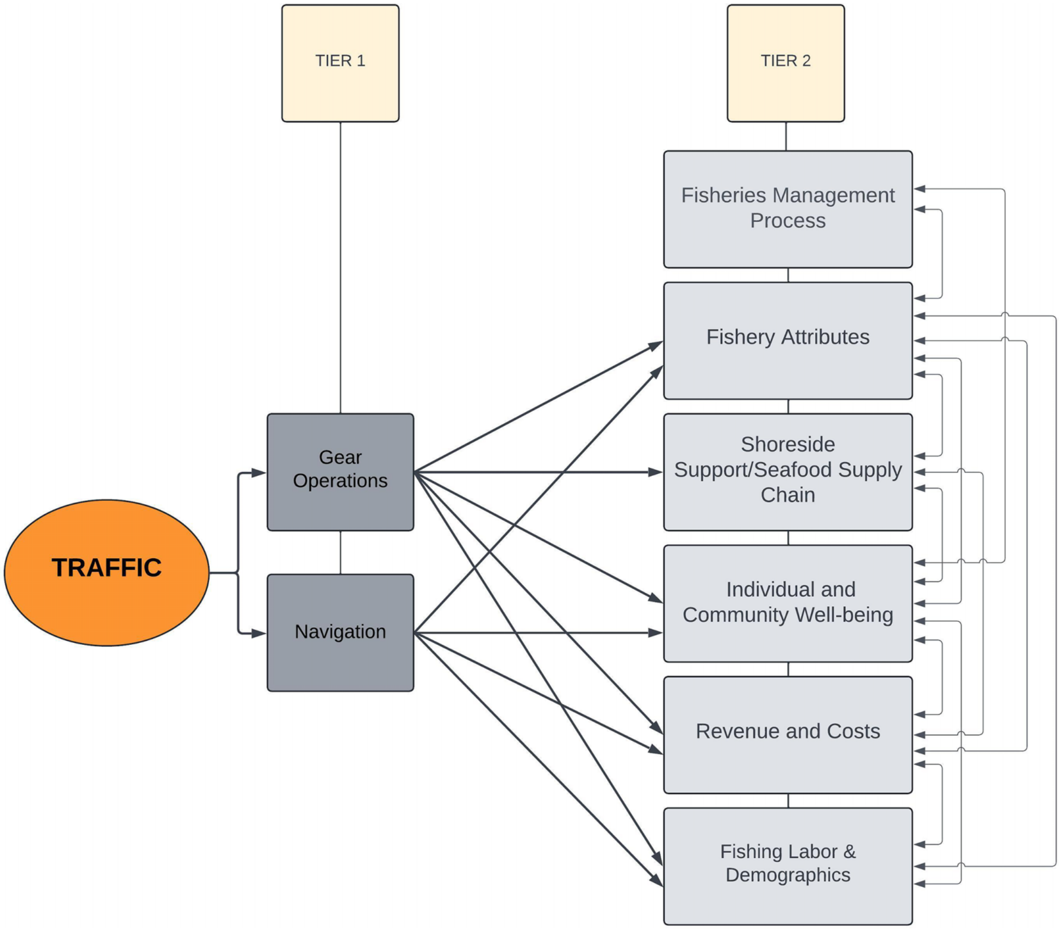

Figure 4 Conceptual model of Tier 1 direct effects and Tier 2 indirect effects of the Traffic risk factor on fisheries socio-economic conditions.

affected elements, i.e. those that are affected through changes to Tier 1 elements, are represented under the Tier 2 category (Table 1 and Supplementary Material 1). This structure allows for more effective prioritization of monitoring efforts, since understanding the effects of the risk factors on Tier 1 elements is key for characterizing the effects of OWED on Tier 2 elements. The distinction between Tier 1 and Tier 2 elements also maximizes the opportunity for controlling and distinguishing between OWED derived risk factors and other impacts (e.g. resource distribution, market conditions, fuel price), thus leading to a better understanding of cumulative and concomitant impacts.

To exemplify the relationships between Tier 1 and Tier 2 elements, in Fig. 3, allisions (when a moving vessel strikes a stationary object) with OWED structures and collisions with other vessels are examples of the direct effects of the risk factor presence of structures on the Tier 1 element navigation. The costs (Tier 2: revenue and costs) associated with vessel and gear repair as a result of damage is a potential indirect effect of the presence of structures that results from the direct effect of this risk factor on Navigation (Tier 1). Monitoring programs should include both Tier 1 and Tier 2 elements. However, it is necessary to understand the effects of risk factors on Tier 1 elements prior to or concomitantly with Tier 2 elements. This allows for the better understanding of cause and effect relationships between Tier 1 and Tier 2 elements. For example, monitoring changes to Fishable Area/Access (Tier 1) as a consequence of presence of OWED structures is critical to understanding the potential impacts this may have on Fisheries Attributes (Tier 2) (e.g. catch levels and gear usage). On the other hand, changes in fishing behavior to avoid direct impacts of risk factors would not be detected by monitoring Tier 1 alone but could be captured by monitoring Tier 2 elements. For example, Tier 1 monitoring data refers to actual interactions between gear and OWED structures. However, a vessel may change the way it operates gear due to the perceived risk of gear interactions (e.g. shorter tows due to infrastructure presence, fewer dredge tows due to risk of snagging cables on subsequent passes, and changing gear entirely from mobile to fixed gear such as from trawls to jigs). Data to understand these changes could be collected by monitoring Tier 2 elements, such as Fisheries Attributes. The conceptual models demonstrate how Tier 2 elements can also affect and compound each other. For instance, changes in Fishable Area/Access (Tier 1) will result in changes to Fisheries Attributes (Tier 2), such as a change in fishing locations, which in turn could affect fisheries Revenue and Costs (also Tier 2) by increasing steam time and fuel prices or lost revenue in seeking new fishing grounds. Changes in Revenue and Costs (Tier 2) could in turn affect Community & Individual Well-being (Tier 2). Determining whether a relationship is direct or indirect is important to maximize isolation of OWED impacts from other factors affecting the system during interpretation and application of results.

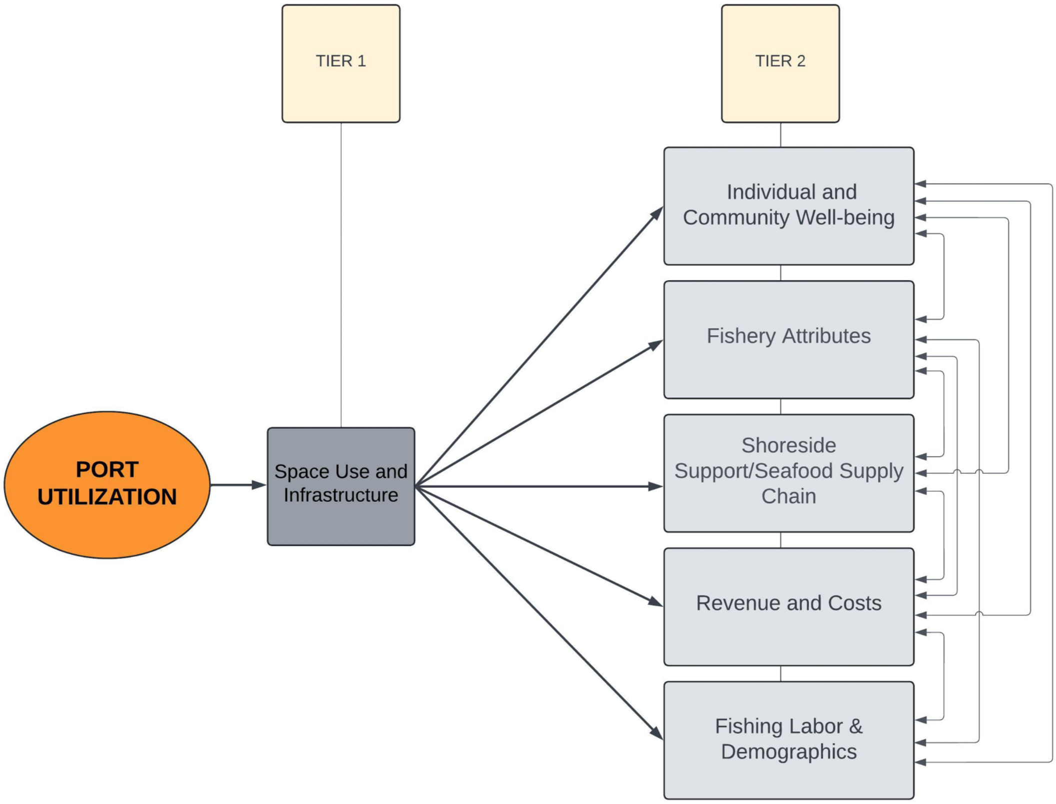

Figure 5 Conceptual model of the Tier 1 direct effects and Tier 2 indirect effects of the Port Utilization risk factor on fisheries socio-economic conditions.

Identifying indicators and methods for monitoring

Once the appropriate risk factors and elements have been selected and the conceptual models constructed, clear hypotheses and/or questions that define the purpose, goal, and context of the monitoring effort (i.e. what should be monitored) must be identified. These questions will guide the selection of indicators for monitoring Tier 1 and Tier 2 elements. The human communities that are expected to be most affected by the impacts should also be identified and considered. Differences between individual, fleet, and community level effects should be accounted for in the monitoring questions and indicators used.

Data availability and the potential initiation of data collection efforts must also be considered during this stage. Monitoring programs typically include a combination of new and existing data streams. For new data collection efforts, a minimum of 3 years of baseline data is typically recommended to understand existing interannual variability (Petruny-Parker et al. 2015, ROSA 2021, Methratta et al. 2023, 2024). Frequency of data collection should be determined at this stage and it should consider the project's development phase, e.g. every year during construction and decommissioning, and every 3–5 years during operation for the lifetime of the project. Temporal scale considerations of new and existing data collection and analyses, as well as spatial scale considerations for data collection (e.g. single turbine v. array, inside/outside project area comparisons, use of control site) should be appropriate for the question/hypothesis being addressed as well as the site-specific context (see Stokesbury et al. 2022 for a discussion on spatial and temporal considerations for interactions between OWED and fisheries). If monitoring is to involve multiple projects or the potential exists to do so, social science methodologies and indicators should be applied consistently and, whenever possible, in a standardized manner across projects to enable the evaluation of region and ecosystem scale effects (Willis-Norton et al. 2024). Ideally, a regional entity with expertise in fisheries social sciences should provide coordination of monitoring plan development to ensure comparability and effort coordination between projects. To date, such coordination in the U.S. has been limited and largely driven by the interests and priorities of lease holders with oversight entities providing guidance and recommendations for monitoring efforts.

Table 2 presents potential indicators for monitoring all Tier 1 elements associated with the three risk factors exemplified in this paper along with proposed methods and data sources for carrying out monitoring efforts. Similar recommendations for Tier 2 elements can be found in Supplementary Material 2. The indicators and methods identified in this table are representative of potential monitoring efforts in the Northeast U.S. and are meant to provide a realistic example that can be replicated and applied in other geographic locations.

Establishing metrics of performance success at the inception of the monitoring program is considered a crucial step. Assessment methods will depend on the specifics of each monitoring program, but they should involve analyses of data collected/compiled against the initial questions and hypothesis posed to evaluate whether the indicators and data selected are satisfactorily ad-

Table 1 Characterization of the direct effects of each risk factor on their respective Tier 1 elements and examples of indirect effects on Tier 2 elements. Refer to Figs. 3–5 for detailed description of the relationships between risk factors, Tier 1, and Tier 2 elements.

Direct effects Tier 1 elements	Effects on Tier 2 elements
Presence of structures	
Fishable area/access: Ability or inability of commercial and recreational fishing vessels to deploy gear and continue to actively fish within OWED areas and/or research vessels to continue long standing biological survey collections. E.g., exclusion due to navigation and gear damage risk, and user conflict; species distribution shifts; gear incompatibility and safety; and legal exclusion during construction/maintenance. **Gear operations:** gear interactions with OWED infrastructure pose risks to fishing operations, including interactions with debris from accidental releases and entanglement of fishing gear with structures and cables. **Navigation:** The presence of OWED infrastructure, including debris, poses risk of allisions and may lead to changes in vessel navigation patterns. These risks may also affect search and rescue operations.	**Individual and community well-being**: changes in dynamics affecting social networks and sense of community, and job satisfaction. **Fisheries attributes**: changes to fishing practices and research vessel operations, such as trip length, gear characteristics and gear type used, technology, and catch amount and composition. **Shoreside support/seafood supply chain:** allisions and gear incompatibility with OWED infrastructure may affect demand for different shoreside businesses (e.g. increased need for gear and vessel maintenance and replacement). **Revenue and costs:** cost of gear or vessel repair due to damage from allision and gear interaction with structures or loss of fishing revenue while gear or vessel is being repaired or replaced; Insurance increase. **Fishing labor & demographics:** potential gear entanglement and navigation hazards may affect the composition of crew and human capital (e.g. increased need for skilled labor, decreased availability of labor). **Fisheries management process:** changes in fishery management measure efficacy (spatial restrictions, catch/bycatch rate assumptions, effort controls, etc.); Loss of biological data, resulting in reduced statistical power and increased uncertainty in scientific stock assessments, advice, analysis, and, ultimately, fishery catch limits.
Traffic	
Gear operations: changes in vessel traffic patterns and congestion are expected to occur during all four phases of OWED. Increased interaction between vessels and gears can happen as a result of project activity in and around OWED areas and ports. **Navigation:** increased vessel interactions in ports as well as in and around OWED areas pose actual and perceived safety risks associated with vessel collisions and risky behavior to avoid interactions.	**Individual and community well-being**: changes in dynamics may affect social networks and sense of community, and job satisfaction. **Fisheries Attributes**: gear operation concerns and potential collisions may result in changes to fishery attributes including trip length, gear attributes, catch composition, and vessel characteristics. **Shoreside support/seafood supply chain:** timing of landings and delivery of seafood to shorebased processors and dealers; Increased risk of collision and gear interaction may also result in increased demand for repair and maintenance services for shoreside businesses. **Revenue and costs:** cost of vessel repair due to damage from collision or loss of fishing revenue while vessel is being repaired or replaced; Insurance increase. **Fishing labor & demographics:** gear operation concerns and increased risks may impact crew needs thus affecting labor characteristics and human capital.
Port Utilization	
Space use and infrastructure: the development of shore infrastructure to support OWED affects port characteristics and utilization. Changes to port infrastructure include upgrades and displacement affecting the makeup of shoreside support businesses.	**Individual and community well-being**: changes in space use and infrastructure may affect individual and community well-being through, for example, changes to community identity and sense of place as a traditional fishing port and job satisfaction. **Fisheries attributes**: changes in space use and infrastructure in ports may affect fishing operations and practices including volume of fish landed, timing of landings, port of landing and homeport location. **Shoreside support/seafood supply chain:** revenue for shoreside support businesses may increase in some ports and decrease in others if fleets shift landing and homeports based on changes to fishing grounds; Increased competition and demand for shoreside services. **Revenue and costs:** space use and infrastructure changes may impact dock access and slip costs as well as access to shoreside support services due to increased demand, affecting operational expenses for fishing vessels. **Fishing labor & Demographics:** changes in space use and infrastructure may affect fishing operations recruitment due to competition or opportunities from OWED jobs. Port upgrades are likely to change dynamics and demographics in and around ports.

Table 2 Monitoring indicators associated with each risk factor and their respective Tier 1 elements.

Risk factor	Tier 1 element	Monitoring indicators	Methods
Structure presence	**Fishable area/access**	Frequency of regulatory spatial exclusions (e.g. safety zones) from construction activity, maintenance activity or accidental releases.	Review of regulatory actions related to OWED activities, e.g. United States Coast Guard Code and Federal Regulations postings, and information on number, spatial extent, duration, and rationale of closures.
		Changes in space use and density of fishing vessels due to presence of OWED infrastructure.	Analysis of temporal and spatial trends in fisheries dependent data (e.g. Logbooks[a], Vessel Monitoring System (VMS)[b], Automatic Identification System (AIS)[c], Observer Data[d]); Analysis of OWED survey data.
	Gear operations	Frequency of gear interactions with structures or debris.	Number and characteristics of compensation claims for gear damage or losses; Social science survey data collections with fishermen and gear manufacturers.
	Navigation	Changes in navigation patterns (transiting) and trip durations.	Analysis of temporal and spatial trends in fisheries dependent data (e.g. VMS, AIS, logbook trip start/end dates)/analysis of canceled trips; Social science survey data collections with fishermen.
		Frequency of allisions with OWED infrastructure.	Number and characteristics of compensation claims for vessel damage or losses; maritime regulatory incident reports (e.g. United States Coast Guard Accident Reports) Social science survey data collections with fishermen.
Traffic	**Gear operations**	Frequency of gear interactions with OWED vessels, or other vessels as a result of increased activities.	Number and characteristics of gear compensation claims from interactions with vessels; Social science survey data collections with fishermen and gear manufacturers.
	Navigation	Frequency of collisions with OWED vessels or other vessels as a result of increased activities.	Number and characteristics of compensation claims from collisions with other vessels; maritime regulatory incident reports (e.g. United States Coast Guard Accident Reports), Social science survey data collections with fishermen and vessel repair and manufacturer businesses.
Port utilization	**Space use and infrastructure**	Changes in port use patterns and infrastructure characteristics.	Port use characteristics (e.g. # and characteristics of vessels utilizing port, area of port used, and any new development by project); Social science survey data collections with fishermen and businesses.

[a] Reports documenting trip-level data including fishing effort (e.g. hours fished), gear used, location, and all species caught and discarded.
[b] VMS is a satellite-based system used by regulatory agencies to track the real-time location and movement of commercial fishing vessels.
[c] AIS is a collision-avoidance system that uses VHF radio to automatically broadcast a vessel's identity, position, course, and speed to other nearby vessels and shore stations.
[d] Fisheries observer data is collected at sea by professionally trained, independent specialists who document catch, bycatch, and fishing effort aboard commercial fishing vessels.

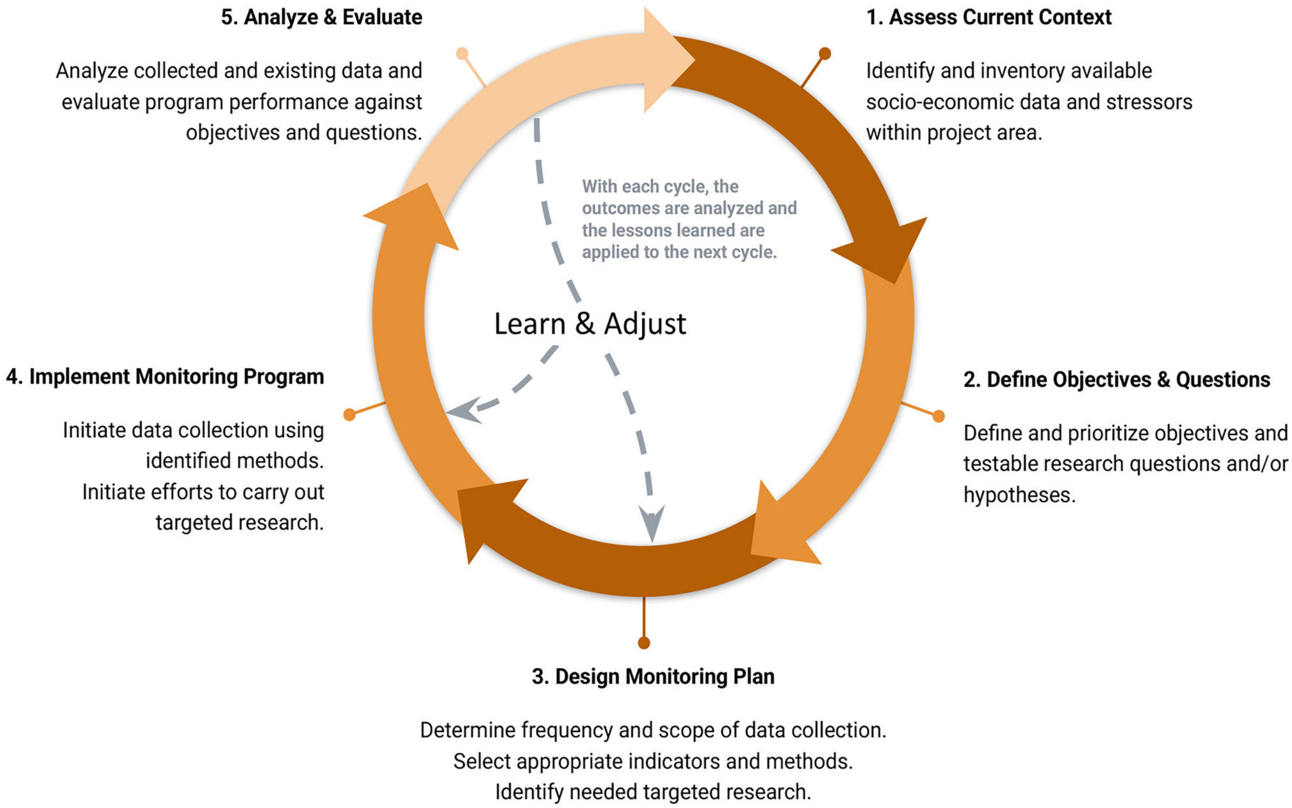

Figure 6 Adaptive approach to develop and implement a socio-economic monitoring program. The cycle begins at the top right with assessing the current context, followed by defining objectives and questions, designing the monitoring plan, implementing the monitoring plan, and finally, analyzing relevant data and evaluating program performance.

dressing the goals of the monitoring program (Bennett et al. 2021). Performance assessments of the socio-economic monitoring program benefit from using adaptive approaches to evaluate and improve performance as needed (Fig. 6). Frequency of evaluation will depend on the needs of the monitoring program, with assessments occurring more frequently during the earlier stages of implementation to make sure baseline data and immediate effects are being captured. As the program progresses, the frequency of evaluation may be adjusted to reflect monitoring needs. The feedback loop allows the incorporation of new data and developments as they emerge.

Monitoring programs may require the development of targeted research projects designed to collect and analyze data to increase knowledge and understanding of the relationships between risk factors and socio-economic elements. Targeted research does not need to be implemented with the same frequency as monitoring efforts and they may include both new studies and updating of existing tools and methodologies and involve field, desktop, and/or modeling methods. For instance, studies to investigate the perceptions of fishermen about changes to fishing activities as a consequence of OWED would increase knowledge of causal relationships and help to refine the conceptual models. Another example would be the analysis of qualitative data collected prior to the establishment of OWED areas (e.g. oral histories) to help construct a baseline to better understand changes to the fishing industry and socio-economic dynamics.

Final considerations and recommendations

This study presents a recommended framework for monitoring the potential effects of OWED on fisheries socio-economic conditions. This framework uses a two-tiered conceptual model approach that allows for the holistic understanding and visualization of the system and facilitates the prioritization of risks and elements to be monitored, as well as the identification of indicators and data to be used. The framework is adaptable to the specific needs of the monitoring program and its application requires careful consideration and assessment of the context in which monitoring will take place, including responsible entities, costs and resource allocation, and characteristics of communities affected. Additionally, while the framework was developed to address project level questions, standardization of the methods used allows for regional and national level implementation if coordination exists between monitoring (e.g. OWED lease holders) and oversight entities (e.g. state/national regulatory agencies). Specific recommendations to help ensure scientific accuracy and analytical comparability while using this framework to develop a monitoring plan include:

- Assess the effects of all relevant risk factors (e.g. structure presence, traffic, port utilization) on all Tier 1 elements identified in the appropriate context of the monitoring plan.

- Identify relevant questions for each Tier 1 element, i.e. what should be monitored to assess impacts of risk factors on each element, and the indicators, data, and information available to monitor. Any existing data, data streams, and scientific research must be identified during this process.
- Identify Tier 2 elements and the effects that can be monitored utilizing the Tier 1 assessment data.
- Consider the spatial scale and context while evaluating and identifying monitoring needs, questions, and elements to be monitored.
- Assess effects of all risk factors on all Tier 1 and selected Tier 2 elements throughout all phases of development. Timeline, spatial scale, and frequency of assessment will depend on the phase of development and elements being assessed.
- Identify any needed targeted research at the planning stage and throughout the monitoring project implementation.
- Engage often with stakeholders using best practices (see, e.g. FLOWW 2025, Fulton et al. 2015, Stephenson et al. 2016, ten Brink et al. 2021, Shrestha et al. 2025, Vetters et al. 2025) throughout all phases of the monitoring project to identify priorities and available data, including methods, data access, analyses, and research priorities.
- Implement comparable indicators and methods across wind projects within a region. A regional entity with expertise in social sciences should ideally provide coordination of monitoring plan development.
- Develop the socio-economic monitoring plan alongside and in coordination with species and habitat monitoring plans during the planning phase (e.g. in the U.S. during the drafting of each project-specific Construction and Operation Plan) and before project approval.

The global expansion of offshore wind energy development emphasizes the need for comprehensive socio-economic monitoring. The convergence of OWED and fisheries represents a complex socio-ecological challenge where environmental, technological, economic, social, and cultural elements are all acutely linked. Existing social sciences data and studies heavily veer towards economic metrics, which are insufficient to capture the full range of socio-economic impacts experienced by fishing communities. However, even within economic topics, knowledge gaps remain in need of researching such as fuel expenditures, costs of insurance, and onshore impacts (Chaji and Werner 2023). Therefore, a framework that is adaptive to changing conditions, participatory in design and implementation, and holistic in scope offers a robust approach for understanding and managing mentioned interactions. While the framework proposed here provides a foundation for integrating social, cultural, and economic data, its application will be built upon the collaboration across different stakeholders. The approach used to create this socio-economic monitoring framework may also serve as guidance for the development of strategies and indicator selection to understand the risk of fishing communities to other marine developments and competing uses, such as oil and gas, hydrokinetic, deep sea mining, and marine carbon dioxide removal. Utilizing a cohesive approach will further develop the ability of multiple stakeholders to understand and assess cumulative impacts and complex trade-offs affecting the sustainability of marine ecosystems and resources. Future research should focus on operationalizing and testing this framework, taking into account specific contexts within the regions in which monitoring is implemented. Developing and enhancing collaborative socio-economic monitoring within the OWED-fisheries context is a necessary step toward promoting co-existence, reducing conflict, and ensuring that renewable energy developments respects and supports the livelihoods, culture, and resilience of fishing communities.

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Author contribution

A.S., T.S.: Conceptualization, design and methodology, model development, drafting original document, visualizations, writing, review and revisions; K.A.M.: model development, drafting original document, visualizations, writing, review and revisions; L.M., D.C.: writing, review and revisions.

Supplementary material

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Conflicts of interest

The authors have no conflicts of interest or competing interests to declare.

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Data availability statement

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