Title

Evaluating the Impacts of Offshore Wind Development on Marine Ecosystems

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Contents

Executive Summary

To inform the sustainable development of offshore wind (OSW) in California, the California Marine Sanctuary Foundation (CMSF), a non-profit with 30 years of experience improving the resilience and stewardship of California's coastal resources, is developing the Offshore Wind Environmental Monitoring Guidance (EMG) for the California Ocean Protection Council.[1] In support of the EMG, this study reviewed scientific and gray literature and synthesized existing knowledge on fixed bottom and floating OSW's impacts on marine ecosystems. The primary impacts on marine ecosystems include noise effects, displacement, entanglement and collision with, attraction to, or avoidance of OSW infrastructure, habitat alterations, anthropogenic emissions and pollution, and electromagnetic field (EMF) effects. Identifying knowledge gaps and monitoring priorities is critical for initial OSW development in California. This synthesis reveals that while we have a more developed understanding of OSW's acoustic and EMF impacts on marine megafauna, we lack a similarly complete understanding of OSW's ecosystem-wide impacts on most taxa.

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[1] California Ocean Protection Council, (2023).

Definitions

Birds and Bats: Avian (birds) and chiropteran (bats) species.

Ecosystems: Interaction of abiotic and biotic components, linked through nutrient cycles and energy flows.

Fish: Gill-bearing vertebrates.

Fishery Ecology: The interactions between fish populations, their habitats, nutrient cycles, and energy flow (non-commercial/recreational).

Habitats: The manifestation of a species' ecological niche.

Impact: The changes, consequences, or results of the presence of floating offshore wind turbines or the activities associated with their presence on marine ecosystems.

Knowledge base: The underlying accepted facts, accepted assumptions, or scientific consensus about a particular topic.

Marine ecosystems: The network of biotic and abiotic components in the ocean, including pelagic, benthic, and intertidal zones.

Marine Mammals: Mammals (warm-blooded animals with lungs, produce milk, and have hair) that spend most of their lives in marine environments or that depend on marine environments for survival. Marine Mammals include cetaceans (whales, dolphins, and porpoises), pinnipeds (seals, sea lions), sirenians, and fissipeds.

Mitigation: Any action taken to reduce an impact created by the presence of floating offshore wind turbines or the activities associated with turbine presence, offshore wind farm site characterization, park construction, operation, and decommissioning.

Monitoring: Repeated, systematic observation, measurement, data collection, proxies, and indicators. Monitoring can be conducted to inform management, as part of scientific research, and to inform mitigation.

Turtles: Reptiles from the order Testudines and the suborder Cryptodira (sea turtles only).

List of Figures

1. Introduction

California aims to develop the world's largest floating OSW energy project, with targets of 2-5 gigawatts (GW) installed capacity by 2030 and 25 GW by 2045[2]. Up to 400 wind turbines that could each stand nearly 853 feet tall, within approximately 580 total square miles, could be installed along the California coast by 2030.[3] [4] However, as an emerging technology, little is known about the environmental impacts of floating turbines. In 2022, the global floating installed capacity totaled only 124.4 megawatts (MW).[5] The global fixed-bottom (non-floating) installed capacity in 2022 totaled 59,009 MW.[6] California's turbines will float deeper, farther from shore, and at a greater scale than existing floating projects. This scale presents new challenges for understanding, monitoring, and mitigating potential impacts of OSW on California's marine ecosystems.

In December 2022, the Bureau of Ocean Energy Management (BOEM) facilitated the auction of sea space for California OSW in the Humboldt and Morro Bay Wind Energy Areas (WEA) (Figure 2, p. 8).[7] Five separate entities successfully bid on the two WEAs, which cover 373,268 acres (1503 km^2) (Figure 1 & 2 p. 8).[8]The two WEAs have the potential to produce at least 4.5 GW of renewable electricity and power more than 1.5 million homes.[9]

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[2] California Energy Commission (19 Jan. 2024). www.energy.ca.gov/data-reports/reports/ab-525-reports-offshore-renewable-energy.

[3] Ibid, 9.

[4] General Electric (GE) Vernova (7 November 2019).

[5] Musial et al., W. (31 May 2023).

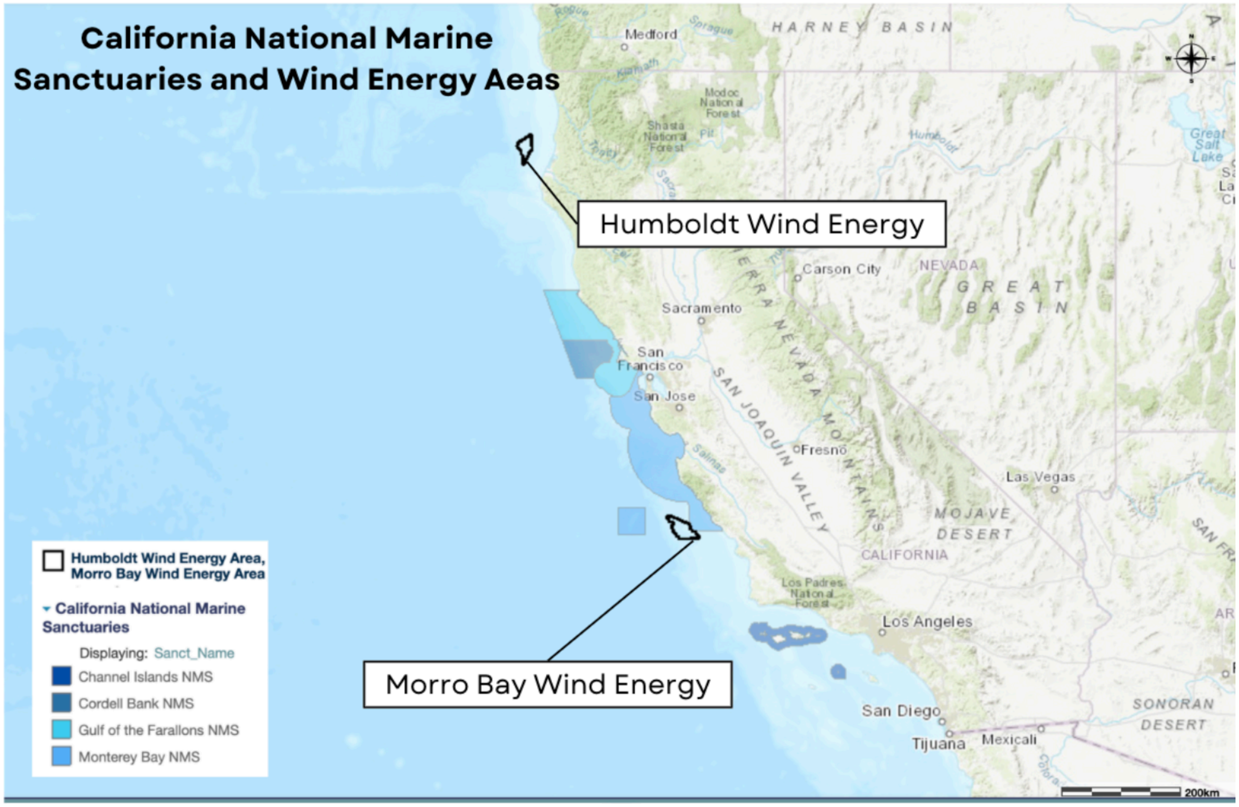
[6] Ibid, xii.

[7] Bureau of Ocean Energy Management (BOEM), California Activities. www.boem.gov/renewable-energy/state-activities/california.

[8] BOEM, California Activities.

[9] Ibid.

Figure 1. California Wind Energy Areas (WEA)



Data Source: Data Basin

Figure 2. California OSW Lease Information[10]

Wind Energy Area (WEA)	**Dimensions & Capacity**	**Developer**
Humboldt (OCS-P 0561)	● 256 km^2 ● 1,025 MW	RWE Offshore Holdings LLC
Humboldt (OCS-P 0562)	● 279 km^2 ● 1,117 MW	California North Floating LLC
Morro Bay (OCS-P 0563)	● 324 km^2 ● 1,296 MW	Equinor Wind US LLC
Morro Bay (OCS-P 0564)	● 325 km^2 ● 1,302 MW	Golden State Wind LLC
Morro Bay (OCS-P 0565)	● 325 km^2 ● 1,302 MW	Invenergy California Offshore LLC

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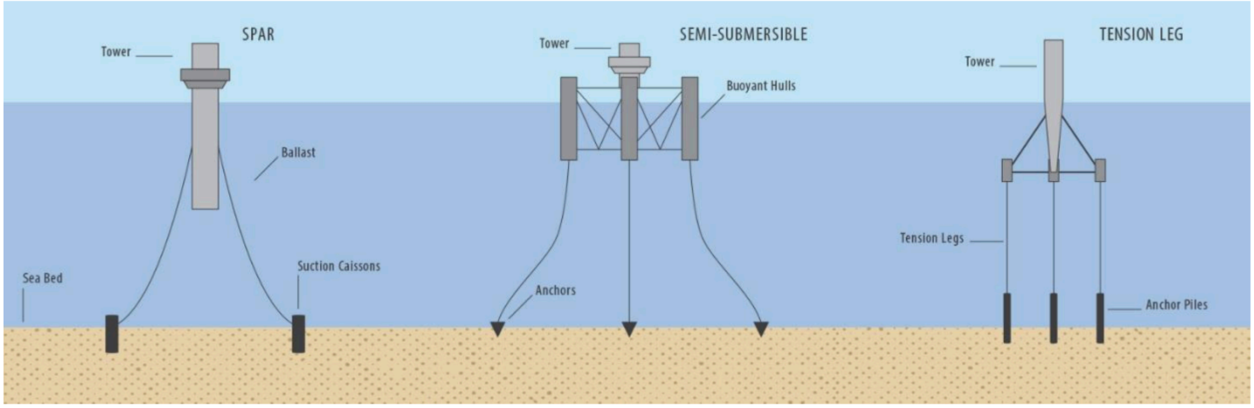
[10] Ibid.

Achieving commercial-scale OSW in California requires addressing substantial infrastructure and environmental challenges. The water depth of the Pacific Outer Continental Shelf requires California to develop floating turbines exclusively instead of traditional, fixed-bottom turbines.[11] Fixed-bottom OSW turbines cause greater seafloor disturbance to secure the turbine. Fixed-bottom OSW turbines also have an increased presence throughout the water column. Both fixed-bottom and floating turbines have the potential to create artificial reefs. Floating turbines can be deployed further from shore, decreasing their visual impacts. Multiple configurations of platforms/foundation types and mooring systems exist for floating turbines (Figure 1 below).[12] The California Energy Commission (CEC) reports semi-submersible (made of concrete, steel, or a hybrid) platforms are likely to be adopted in the California industry (Figure 3).[13]

Figure 3. Types of Floating Turbine Platforms



Source: ICF (2020)

BOEM and the industry lessees are developing critical site assessment plans, initial environmental reviews, and surveys of lease areas in California. BOEM's Programmatic

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[11] California Energy Commission (19 Jan. 2024).

[12] ICF (2020).

[13] Jones et al 2024. Assembly Bill 525 Offshore Wind Strategic Plan. California Energy Commission. Publication Number: CEC-700-2023-009- V1-D.

Environmental Impact Statement (EIS) will analyze the potential impacts and identify mitigation measures of Federal OSW energy development activities off California's central and north coasts. The Programmatic EIS will be a holistic framework for BOEM's future project-specific EIS for the individual lease areas that assess the impacts of OSW operation and maintenance and decommissioning activities.[14]

After completing the Programmatic EIS, BOEM must approve each lessee's site assessment and construction and operation plans incorporating an EIS. The site assessment process is expected to be completed in late 2025.[15] Establishing standardized monitoring guidelines and conducting baseline research is crucial. Additionally, assembling a diverse group of stakeholders presents challenges, yet ensuring a holistic and informed approach to monitoring and mitigation efforts is necessary.

As BOEM and industry begin their initial environmental review process, CMSF's EMG can help facilitate knowledge-sharing and best practices for monitoring the impacts of OSW on California's marine ecosystems. In support of the EMG, this study reviewed scientific and gray literature on the impacts of floating and fixed-bottom OSW energy on marine ecosystems. This report, literature database, and information hub seek to provide lessons learned from previous OSW experience applicable to California to ensure that potential impacts on marine ecosystems are monitored and mitigated with due diligence and to develop an online database of key references and information relevant to California OSW.[16]

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[14] Ibid.

[15] Ibid.

[16] King, Connor (2024). *OSWIM: Offshore Wind Impacts and Monitoring Hub.*https://coda.io/@connor-king/oswimhub.

2. Methodology

This study developed a taxonomy based on metadata to categorize identified literature systematically. Metadata included author information, literature type, research question(s), monitoring methods, technology, impact source/stressor, development phase, receptor, geographic area (study location), spatial and temporal scales of the studies, and main findings (further described in Appendix A).

The findings were separated into four focus areas: Marine Mammals and Turtles (MMST), Birds and Bats (BB), Fish and Fishery Ecology (FFE), and Habitats and Ecosystems (HE). The results are thematically organized by the types of impacts (e.g., collision).

Existing literature databases for OSW resources, scientific and academic publications, and government and industry gray literature reports published through May 2024 were reviewed. Existing databases include the U.S. Offshore Wind: Synthesis of Environmental Effects Research Database (SEER) or Tethy's, the Regional Wildlife Science Collaborative (RWSC) Offshore Wind & Wildlife Research Database, and the United Kingdom Energy Resource Center Energy Data Center (UKERC EDC) Database of Evidence for the Impact of Offshore Wind Farms on Marine Ecosystem Services.[17] [18] [19]

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[17] "U.S. Offshore Wind: Synthesis of Environmental Effects Research (SEER)." *Tethys: Environmental Effects of Wind and Marine Renewable Energy*, Pacific Northwest National Laboratory, tethys.pnnl.gov/pacific-offshore-wind-environmental-research-recommendations.

[18] "Offshore Wind & Wildlife Research Database." *RWSC*, Regional Wildlife Science Collaborative for Offshore Wind (RWSC), https://database.rwsc.org/.

[19] Energy Data Centre (EDC) . (n.d.). *Database of evidence for the impact of offshore wind farms on Marine Ecosystem Services*. UKERC EDC: Data. https://ukerc.rl.ac.uk/cgi-bin/dataDiscover.pl?Action=detail&dataid=554a8785-3f6f-4202-a742-d55708391a0a

3. Results

Relevant primary impacts studied on marine ecosystems include noise effects, displacement from, entanglement and collision with, attraction to, or avoidance of OSW infrastructure and vessels, habitat alterations, anthropogenic emissions and pollution, and electromagnetic field (EMF) effects. In total, 61 references were identified. All reviewed literature was published between 2009 and 2024, with 76.3% published after 2020. Furthermore, 27 (44%) sources deemed most relevant to California marine ecosystems are discussed.

Most (75%) examine impacts on whales, birds, and pelagic communities, with few studies providing insights into sea turtles, bats, benthic communities, or atmospheric and oceanographic processes. Geographically, most research has been conducted in Europe, specifically the North Sea (30%). At a finer spatial scale, 100% of the studies were conducted in depths less than 150 m of water. Notably, 83% of those studies were conducted in depths less than or equal to 100 m. California's turbines could occur at depths between 800 and 2,000 m.[20]

Figure 4 (p. 15) shows the chronology of the reviewed literature, grouping the publishing years from 2005-2009, 2010-2014, 2015-2019, and 2020-2024. Figure 5 (p 15) shows the taxonomic groups of the receptors (four focus areas). Most studies focused on MMST (27.4%) and FFE (32.1%). The least studied receptor is BB (17.9%). Figure (p. 16) shows the share of impacts discussed within the reviewed literature. The most studied impacts were habitat alterations (21.1%) and noise effects (14.5%). The least studied impacts were physical processes (5.3%) and nutrient cycling (2.6%). Two previous studies with similar research questions or objectives were identified. Gray literature reports discussing OSW impacts on marine

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[20] Raghukumar, Kaus, Tim Nelson, Grace Chang, Chris Chartrand, Lawrence Cheung, Jesse Roberts, Michael Jacox, and Jerome Fiechter. 2020. A Numerical Modeling Framework to Evaluate Effects of Offshore Wind Farms on California's Coastal Upwelling Ecosystem. Publication Number: CEC-500-2024-006.

ecosystems by the California government, as well as BOEM, were also identified. Figure 7 (p. 16) shows the impacts on marine ecosystems identified within these related studies and relevant gray literature.

Figure 4. Chronological Share of Literature

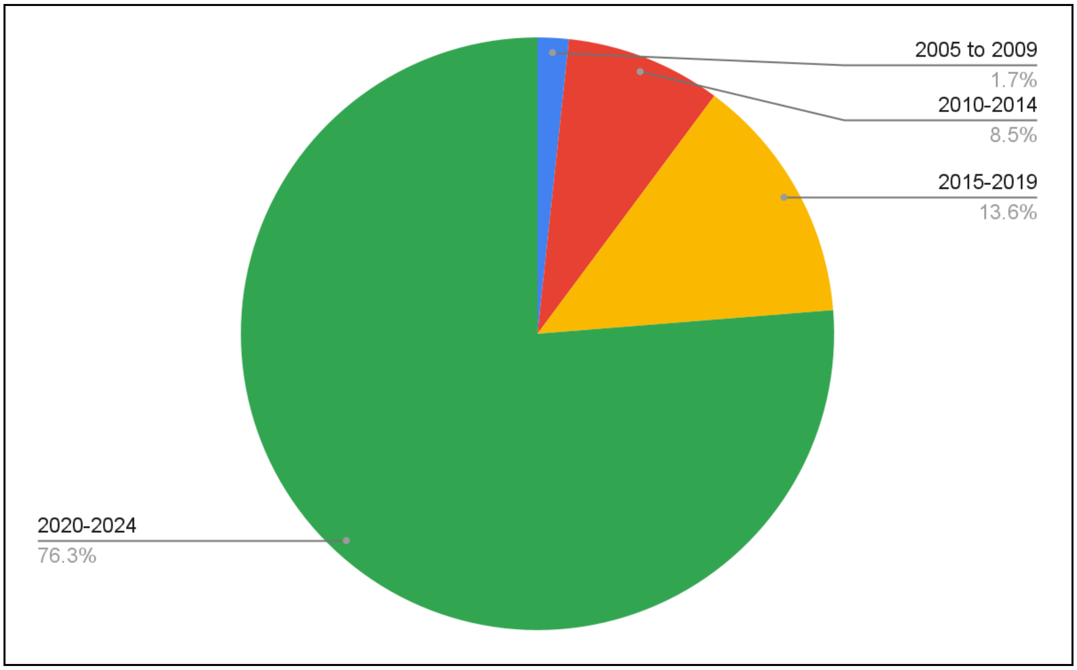


Figure 5. Taxonomic Share of Literature

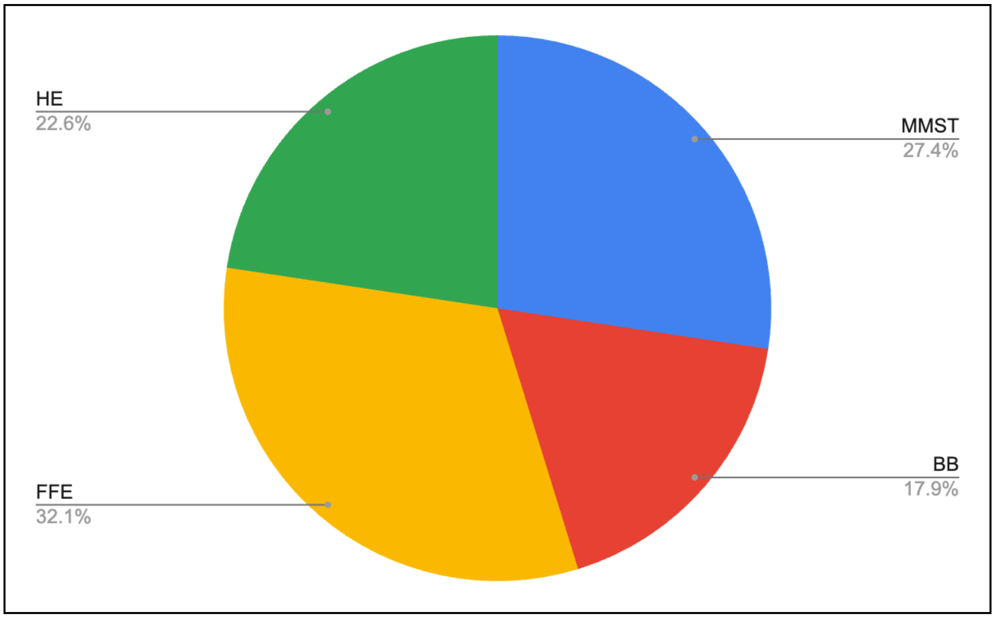
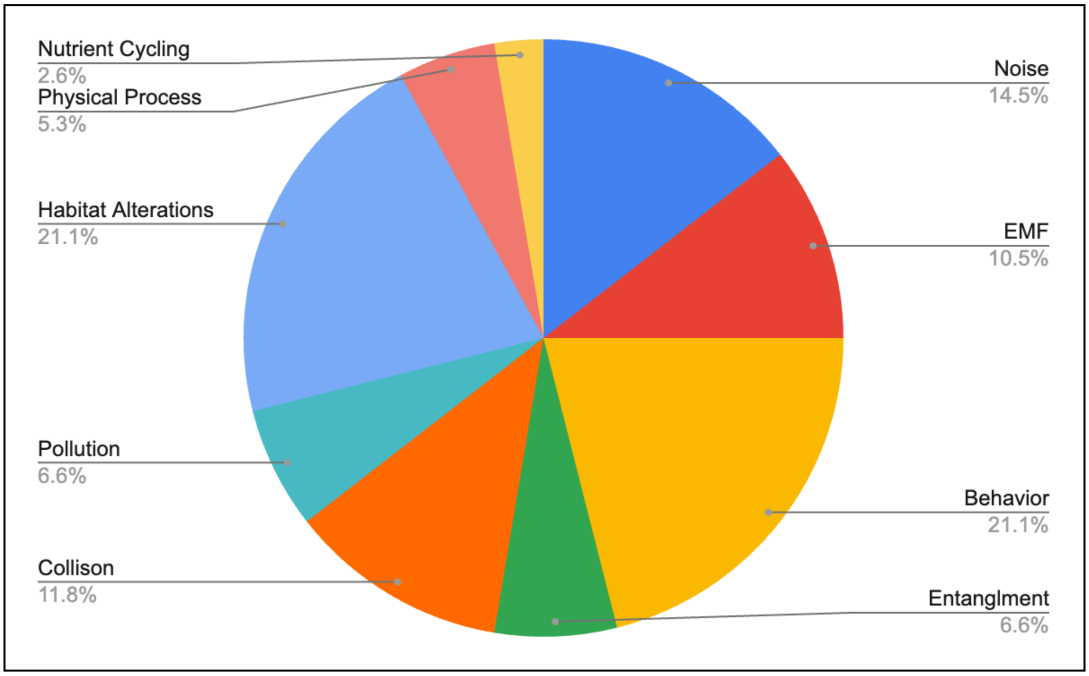


Figure 6. Impacts/Stressors Share of Literature



BOEM recently conducted a Biological Assessment (BA) to assess the impacts of site assessment activities in California WEAs on whales, sea turtles, fish, and their habitats listed in the Endangered Species Act (ESA).[21] The BA identified the following impacts for Endangered Species Act (ESA) listed species associated with geophysical and geotechnical surveys and deployment and decommissioning of meta ocean buoys in the California WEAs[22] :

- Noise from geophysical and geotechnical surveys and vessel noise
- Vessel collisions
- Entanglement
- Chemical and toxic pollution
- Marine debris

Figure 7. Impacts Identified in Related Studies and Gray Literature

		Impact				
		Noise	**EMF**	**Entanglement**	**Collision**	**Habitat Alterations**
Author	Farr et al. (2021)	X	X	X	X	X
	Watson et al. (2024)				X	X
	California Energy Commission, *CEC-800-2022-001* (2022)	X	X	X	X	X
	U.S. DOI, BOEM (2022)	X	X	X	X	X

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[21] Reeb et al. (2022), 2.

[22] Ibid, 1

Figure 8 below lists the ESA-listed species BOEM defined as "likely to occur" in California's WEA during geophysical and geotechnical surveys and deployment and decommissioning of meta ocean buoys. The report found "that the impacts to protected species and critical habitat from site characterization surveys and site assessment activities will be negligible and not likely to adversely affect ESA-listed protected species or associated critical habitat adversely" (BOEM 2022, p. 60).

Figure 8. Endangered and Protected Species Likely to Occur in California WEA (BOEM July 2022)

Focus Area (Taxa Group)	**Species**
MMST	Blue whale *(Balaenoptera musculus)*
MSST	Fin whale *(Balaenoptera physalus)*
MSST	Humpback whale *(Megaptera novaeangliae)*
MMST	Gray whale *(Eschrichtius robustus)*
MSST	Sperm whale *(Physeter macrocephalus)*
MSST	Steller sea lion *(Eumetopias jubatus)*
MSST	Guadalupe fur seal *(Arctocephalus townsendii)*
MSST	Leatherback sea turtle *(Dermochelys coriacea)*
MSST	Loggerhead sea turtle *(Caretta caretta)*
FFE	Chinook salmon *(Oncorhynchus tshawytscha)*
FFE	Coho salmon *(Oncorhynchus kisutch)*
FFE	Steelhead *(Oncorhynchus mykiss irideus)*
FFE	Eulachon *(Thaleichthys pacificus) Southern DPS*
FFE	Green sturgeon *(Acipenser medirostris), Southern DPS*

3.1 Marine Mammals and Sea Turtles (MMST)

Figure 9. Impacts on Marine Mammals and Sea Turtles

		Impact			
		Noise	**Entanglement/ Collison**	**Displacement**	**Habitat Alterations**
Author	Harnois et al. (2015)		X		X
	Rockwood etal (2020)		X		
	Risch et al. (2023)	X		X	
	Thomsen et al. (2023)	X		X	X
	Gall et al. (2021)	X		X	
	Vallejo et al. (2017)			X	

While we have limited data on taxa specific to CA, our conditions are unique and yet to be tested. Impacts to anticipate include entanglement, noise pollution, and behavior changes. The least studied impact on MMST was entanglement (8.3%). Taut mooring configurations present the lowest risk of entanglement.[23] The lowest noise-emitting activities occur during the installation of suction bucket foundations and floating foundations that use suction caissons,

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[23] Harnois et al. (2015).

drag, dead-weight, or embedded anchors.[24] Additionally, 6.5 and 9.5 MW floating and fixed-bottom turbines produce similar operational noise levels.[25] Significantly, the operational noise of larger turbines (20 MW) could lead to greater cumulative noise pollution than 10 MW turbines.[26] Modeling on vessel speed reductions has been shown to decrease blue and humpback whale vessel collisions in California by 5.8% and 5.4%, respectively.[27]

The operational noise levels for California's projects are unknown as the industry has not decided on the exact platform/foundation type and mooring system configuration. Displacement of MSST due to OSW is primarily short-term and concentrated during the construction phase.[28] No literature discussed the impacts of decommissioning activities on MMST; however, the risks and impacts are likely similar to those of preconstruction activities.

Entanglement

Harnois et al. (2015) examined the risk of entanglement for marine megafauna (cetaceans, pinnipeds, sea turtles) caused by different offshore renewable energy mooring system configurations. They determined risk based on three parameters: tension characteristics, swept volume, and curvature.[29] They investigated six different mooring configurations. These included[30]:

- Catenary with chains only
- Catenary with chains and nylon ropes
- Catenary with chains and polyester ropes

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[24] ICF (2020), ES-4.
[25] Risch et al. (2023).
[26] Thomsen et al. (2023).
[27] Rockwood et al. (2020),146.
[28] Vallejo et al. (2017) , 8698-8708.
[29] Harnois et al. (2015).
[30] Ibid, 36-42.

- Catenary with accessory buoy
- Taut
- Taut with accessory buoy

They found that the taut configuration has the lowest relative risk of entanglement. The highest relative risk occurs with catenary moorings with chains and nylon ropes or catenary moorings with accessory buoys. Additionally, catenary mooring with chains only or with chains and polyester ropes, as well as taut moorings with accessory buoys, also have higher relative entanglement risks.[31]

Noise Pollution

Behavior changes such as attraction or avoidance of OSW farms can be caused by noise pollution from the OSW turbines' construction, operation, and maintenance. Risch et al. (2023) investigated and characterized the operational noise of floating turbines at the Kincardine and Hywind Scotland OSW farms.[32] The Kincardine farm (60-80 meter water depth range) comprises five 9.5 MW semi-submersible turbines. Hywind Scotland (95-120 meter water depth range) contains five 6 MW spar-buoy (Figure 1, p. 7) turbines. In both farms, the turbines are anchored via three mooring cables[33]. They found similar operational noise between fixed-bottom and floating turbines at the Kincardine and Hywind Scotland OSW farms[34]. With similar operational noise of both fixed-bottom and floating turbines, results of studies discussing the response of MMST to the noise pollution of fixed-bottom turbines are thus much more relevant to baseline knowledge of floating turbine acoustic impacts.

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[31] Ibid, 47.
[32] Risch et al. (2023).
[33] Ibid, 10.
[34] Ibid, 35.

Thomsen et al. (2023) modeled the operational noise of a 10 MW and 20 MW direct drive, fixed-bottom monopile turbine.[35] They found operational noise from a 10 MW turbine would not likely lead to any significant temporary auditory injury in marine mammals.[36]

Additionally, they found that impact ranges for permanent hearing threshold shifts were small (i.e., up to 50 m from the sound source) and likely negligible. The same was found for temporary hearing threshold shift impact ranges for the 10 MW turbine.[37] However, the impact ranges for temporary hearing threshold shifts from the 20 MW turbine could reach approximately 700 m for low-frequency cetaceans, potentially more significant than the distances between turbines. Thus, multiple 20 MW turbines could lead to cumulative noise pollution.[38] They also theorize that marine mammals may ignore the impacts of operation noise for the opportunity to feed, provided by the artificial reef effect within OSW farms.[39]

Vessel Collision

On the US West Coast, vessel collision whale mortalities (confirmed by carcasses) are the highest source of human-caused mortality for blue whales (*Balaenoptera musculus*) and the second highest for humpback whales (*Megaptera novaeangliae*).[40] Modeling by Rockwood et al. (2017) estimated that between 18 blue whales and 22 humpback whales are killed yearly within the Exclusive Economic Zone waters off of California, Oregon, and Washington between July and December, during their peak abundance.[41] Rockwood et al. (2020) modeled and estimated the effectiveness of vessel speed reductions in decreasing whale mortality. They applied the

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[35] Thomsen et al. (2023).
[36] Ibid.
[37] Ibid, 4.
[38] Ibid, 5,
[39] Ibid.
[40] Rockwood et al. (2020), 146.
[41] Ibid.

model in a 12,640 km^2 study area extending past the 200-meter isobath off the coast of San Francisco.[42] In a five-year period, their model estimated approximately a 5.8% blue and 5.4% humpback whale mortality decrease.[43] Vessel speed reductions, informed maritime spatial planning, and ample monitoring of populations could all reduce the risk of mortality for MMST in and around OSW farms.

Behavior Changes

Additional behavioral changes among MMST due to the presence of OSW farms include displacement from and avoidance of OSW farm areas. Gall et al. (2021) examined the response of harbor porpoises (*Phocoena phocoena*) to pile-driving and vessel activities during the construction of a U.K. OSW project between 2017 and 2019.[44] This project contains 84 fixed-bottom turbines up to 45 m deep. Their study area encompassed 50 km^2. They found that compared to their baseline, an 8–17% decline in porpoise presence was observed in their study area during pile-driving and other construction activities. The probability of detecting porpoises was positively related to the distance from vessel and construction activities and negatively related to vessel intensity and background noise. The displacement of harbor porpoises was observed up to 12 km from pile-driving locations and 4 km from construction vessels[45]. Although the construction of OSW in California will not require pile-driving to install turbines, mooring systems will interact with the benthic environment, and construction and maintenance vessels will be present.

Comparably, Vallejo et al. (2017) investigated the behavioral response of harbor porpoise (*Phocoena phocoena*) to an OSW project in the U.K. The project comprises 60 30-40 m deep

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[42] Ibid, 148.
[43] Ibid, 163.
[44] Gall et al. (2021).
[45] Ibid.

fixed-bottom turbines, over 13 km^2. They found no long-term displacement of harbor porpoises but instead short-term displacement during construction.[46] During construction, harbor porpoises were not observed in the study area. Approximately twice as many individuals were observed per km^2 surveyed during the preconstruction and operation phases.[47]

Further research is needed to understand how floating turbine size, mooring configurations, and platform types influence primary and secondary entanglement risk, noise pollution levels, and behavior changes such as attraction or avoidance. Vessel speed reductions are a possible immediately implementable mitigation measure to reduce risk to protected and non-protected marine megafauna. Previous OSW experience may suggest MMST displacement is more significant during construction.[48] [49]

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[46] Vallejo et al. (2017).

[47] Ibid, 8703.

[48] Vallejo et al. (2017).

[49] Gall et al. (2021).

3.2 Birds and Bats (BB)

Figure 10. Impacts on Birds and Bats

		Impact			
		Collison	**Avoidance**	**Attraction**	**Habitat Alterations**
Author	Weiser et al. (2024)	X	X		
	Peschko et al. (2020)		X		X
	Preschko et al. (2020b)		X	X	
	Ahlen et al. (2009)	X		X	X

Attraction and Avoidance

Sustaining research into the spatial and temporal distribution of California's migrating Birds and Bats (BB) is crucial to determining the most at-risk species. Climate change will alter species distribution and the impacts from the presence of OSW at this scale are unknown. Studies have demonstrated that OSW turbines may provide increased foraging opportunities for Birds and Bats (BB), thus increasing the risk of collision with turbines.[50]

Weiser et al. (2024) evaluated the altitude of migrating Pacific Flyway geese off the coast of southeastern Alaska, British Columbia, Oregon, Washington, and California to estimate the potential for interactions with future OSW infrastructure in these regions. The species included:

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[50] Ahlen et al. (2009), 1322.

- The Pacific greater white-fronted goose (*Anser albifrons sponsa*),
- The tule greater white-fronted goose (*Anser albifrons elgasi*),
- The lesser snow goose (*A. caerulescens caerulescens*).[51]

They found under normal conditions that 56% of goose migrations in offshore areas (>1 km) were expected within the rotor-swept zone (20-200 meters) of a wind turbine during the day and 28% at night.[52]

Peschko et al. (2020) investigated the behavior and habitat use changes of seven breeding common guillemots (Uria algae) across an area that contains 208 turbines, covering 105 km^2.[53] Their analysis showed a 63% reduction in resource selection in the OSW farm areas compared with the surrounding area. The avoidance of OSW turbines increased to 75% when the blades were rotating.[54]

Peschko et-al. (2020b) conducted a before-after control impact analysis of guillemot and kittiwake (*Rissa tridactyla*) behavior changes in the same OSW farm area as Pescheko et al. (2020).[55] Guillemot's relative density in the OSW farm decreased by 63% in spring and 44% in the breeding season.[56] Kittiwake's relative density in the OSW farm decreased by 45% in the breeding season and 10% in spring.[57] Guillemots showed a response radius of ~9 km in spring, and kittiwakes a radius of ~20 km in the breeding season.[58] Similar behavior is possible by the species interacting with OSW in California, and adequate monitoring of these species is therefore necessary.

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[51] Weiser et al. (2024).
[52] Ibid, 8.
[53] Ibid, 2-4.
[54] Ibid, 9.
[55] Peschko et al. (2020b), 3.
[56] Ibid, 7.
[57] Ibid, 7.
[58] Ibid.

Ahlen et al. (2009) investigated the behavior of 11 species of Scandinavian bats during migration and foraging at sea in response to OSW farms.[59] Individuals were observed flying between the surface and 40 meters high, often changing altitude rapidly.[60] They observed individual bats (*Pipistrellus pygmaeus, P. nathusii,* and *Nyctalus leisleri*) nesting in and foraging near a group of turbines 5.8 km offshore[61]. They found insects were attracted to turbines during certain weather conditions. More significant numbers of insects likely mean foraging bats near OSW wind turbines at low altitudes may be prone to collision.[62]

Potential sources of impacts from OSW to BB include collision with, avoidance of, or attraction to OSW infrastructure and habitat alterations. Significant research has evaluated general risks, such as increased mortality rates and disrupted migration patterns associated with current onshore and OSW projects. Understanding the specific impacts on California's unique avian and chiropteran species will require rigorous surveying and investigations of species distribution. Additionally, the commercialization of this novel technology demands collaboration and communication among all stakeholders. Addressing these research gaps will facilitate the environmentally responsible advancement of OSW initiatives in California, ensuring the protection of critical wildlife populations.

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[59] Ahlen et al. (2009), 1318.
[60] Ibid, 1321.
[61] Ibid, 1321.
[62] Ibid, 1322.

3.3 Fish and Fishery Ecology

Figure 11. Impacts on Fish and Fishery Ecology

		Impact		
		Noise	**EMF**	**Habitat Alterations**
Author	Harsanyi et al. (2022)		X	X
	Hutchinson et al. (2023)		X	X
	Wyman et al. (2018)		X	X
	Duffy et al. (2023)	X		X
	Reubens et al. (2013)			X
	Mooney et al. (2020)	X		X
	Wilber et al (2017)	X		X
	Karama et al. (2021)			X

The least studied impacts on FFE included noise pollution (14.28%) and EMFs (17.86%). Anthropogenic EMFs produced by subsea transmission cables can have detrimental and negligible impacts on the behavior and development of fish species. This spectrum includes decreased sperm mobility of Mediterranean mussels (*Mytilus galloprovincialis)* or increased foraging behavior of Little skates (*Leucoraja erinacea*). A species-specific understanding of EMF's impacts on FFE mainly exists; thus, continued research into the impact of EMF on California's FFE is necessary. EMFs from a subsea cable in the San Francisco Bay Area produced no negative impact on salmon migrations.[63] Floating wind turbines have a decreased presence in the water column compared to fixed-bottom turbines and may create less of an artificial reef. Artificial habitats become stable after 1.5–2 years in coastal areas of Japan and may take similarly as long to manifest in California.[64]

Electromagnetic Fields (EMFs)

Harsanyi et al. (2022), Hutchinson et al. (2023), and Wyman et al. (2018) all detail the effects of EMF on various fish species. Limited species-specific scientific data are available on known EMF thresholds and tolerance.[65] Harsanyi et al. (2022) cite the following known effects of EMF on various species:[66]

- Significantly decreased sperm motility of Mediterranean mussel (*Mytilus galloprovincialis)*
- Delay onset of mitosis and cause developmental abnormalities in sea urchins *Lytechninus pictus* (V.) and *Strongylocentrotus purpurattus* (S.)
- Alter *Xenopus laevis* (D.) embryos' cleavage planes
- Increased egg-shell permeability of Atlantic salmon (*Salmo salar)* (L.), Sea trout (*Salmo trutta)* (L.), and Rainbow trout (*Oncorhynchus mykiss)* (W.)
- Accelerated rates of embryonic development of *Daphnia magna*
- Delays the hatching period of zebrafish *(Danio rerio*)
- Affect the internal compass of Caribbean spiny lobster (*Panulirus argus*)
- Alter sheltering behavior of Spiny-cheek crayfish (*Orconectes limosus*)

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[63] Wyman et al. (2018).
[64] Karama et al. (2021), 302.
[65] Harsanyi et al. (2022).
[66] Ibid, 2.

Harsanyi et al. (2022) then explored the impacts of EMF on the early development of the European Lobster (*Homarus gammarus)* and Edible crab (*Cancer pagurus*). They found that chronic exposure to artificial EMFs at 2.8 mT resulted in smaller larvae, lower mortality rate, increased deformities, and decreased lobster larvae' swimming performance.[67] Current subsea power cables typically produce artificial EMFs up to 3.2 mT. However, congesting cables into a single area could increase EMF effects.[68]

Hutchinson et al. (2023) investigated the influence of anthropogenic EMF on the behavior of the American Lobster (*Homarus americanus*) and Little Skate (*Leucoraja erinacea*). They found increased exploratory and foraging behavior in skates in response to EMF and a more subtle exploratory response in lobsters.[69] Skates exposed to the treatment enclosure first traveled almost twice as far (93% increase). Lobsters exposed to EMF spent more time exploring the seabed than climbing the enclosure.[70]

Wyman et al. (2018) examined the behavioral response of migrating juvenile salmonids caused by a subsea high-voltage DC power cable in the San Francisco Bay.[71] They found that cable activity was not associated with the probability of a successful migration, and fish migration times also increased with cable activity.[72] Overall, the presence of the cable produced mixed effects within their study, leading salmonids to be both attracted to and avoidant of the cable.[73]

Anthropogenic EMFs produce a range of impacts on FFE. The uncertainty and lack of holistic understanding of all known species' responses warrant research on the responses of

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[67] Ibid, 11.
[68] Ibid, 2.
[69] Hutchison et al. (2020).
[70] Ibid, 8-9.
[71] Wyman et al.. (2018).
[72] Ibid, 12.
[73] Ibid, 13.

California’s species likely to occur in WEA. It should be anticipated that EMFs can lead to both detrimental and negligible impacts on FFE.

Noise Pollution

Duffy et al. (2023), Wilber et al. (2017), and Mooney et al. (2020) all examined the acoustic impacts of OSW. Duffy et al. (2023) conducted a desktop study of the impacts of geophysical and geotechnical site assessment surveys on 37 of Ireland's most commercially important fish and shellfish.[74] Figure 12 (p. 31) shows the impacts they identified from noise caused by site survey activities on fish and shellfish.[75] Single-use air guns and airgun arrays are the most impactful instruments used in site surveys. It is important to note they found impacts on the behavior of these groups are likely but temporary.[76]

Wilber et al. (2017) studied Flatfish abundance, size, and condition surrounding the Block Island Wind Farm (BIWF) in Rhode Island. This wind farm consists of five 6-MW fixed-bottom turbines in ~30 m of water.[77] Notably, they found fall flounder abundance decreased during the pile-driving period. In spring, flounder abundance increased during the cable laying period.[78] However, these observations could result from temporal habitat preference unrelated to OSW activities. Overall, their study found no indication that OSW attracted the flatfish sampled, nor did construction activities negatively impact the flatfish sampled.[79]

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[74] Duffy et al. (2023).
[75] Ibid, 45-55.
[76] Ibid, 69.
[77] Wilber et al. (2018).
[78] Ibid, 27-8.
[79] Ibid, 30.

Mooney et al. (2020) reviewed and identified research gaps as of 2020, on the acoustic impacts of OSW on fish and invertebrates. Figure 13 (p. 32) summaries the gaps they identified.[80]

Figure 12. Potential Noise Impacts on Fish and Shellfish

Impacts	
Fish	**Shellfish**
Air Bladder Damage	Otolith/Statocyst Damage
Otolith/Statocyst Damage	Organ/Tissue Damage
Organ/Tissue Damage	Mortality/Abnormality
Mortality/Abnormality	Startle response
Startle response	Sound avoidance
Sound avoidance	Foraging
Foraging	Bioturbitaton
Reproduction	Metabolic Rates
Auditory Masking	Stress-bio indicators
Metabolic rates	Metamorphosis/Settlement
Stress bioindicators	Catch rates/abundance
Metamorphosis/Settlement	
Catch rates/abundance	

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[80] Mooney et al. (2020).

Figure 13. Research Gaps on Acoustic Impacts to FFE

Research Gap	**Description**
Temporal Variation	Impacts during critical life stages (e.g., breeding, foraging)
Early Life Studies	Larval stages and recruitment processes
Site Surveys and Decommissioning	Impacts of underwater site surveys and decommissioning activities
Current-Use Seismic Sources	Impact of seismic sources commonly used in underwater exploration.
Species and Population Differences	Variations in response among different species and populations.
Free-Swimming Animals	Impacts on the behavior of free-swimming invertebrates.
Larger, Current-Use Turbines	Impacts of larger turbine structures on underwater ecosystems.
Scales of Impact	Analyze the varying degrees of disturbance caused by different noise levels.
Operational Communities	Impacts on communities that develop during operation (due to the artificial reef effect)
Null Data	Instances where no significant impacts of noise pollution are detected.

Habitat Alterations

Reubens et al. (2013) and Karama et al. (2021) discuss the impacts of habitat alterations on fish species congregating around two different OSW farms. Reubens et al. (2013) compared the growth rate, size, and diet of Atlantic cod (*Gadus morhua*) and Pouting (*Trisopterus luscus*) congregating around OSW farms in the Belgian North consisting of 54 fixed-bottom turbines between 18 and 24 meters of water depth .[81] The results of their study indicate that for Atlantic Cod and Pouting, the OSW farms sampled did not act as ecological traps. The length of Atlantic Cod samples was similar in the reference and OSW farm areas. Similarly, no significant differences in ecological conditions for pouting were found between individuals in the OSW farm and reference areas. Importantly, they conclude that the results of their study do not eliminate OSW farms as ecological traps through higher commercial or recreational fishing caused mortality.[82]

Karama et al. (2021) recorded the spatial and temporal occurrence of Japanese Red Seabream (*Pagrus major)* and Yellowtail (*quinqueradiata)* surrounding a single OSW turbine 5 km off Fukue Island at 100 m of water depth. The turbine has a total spar length of 172 meters and an 80-meter rotor diameter[83]. 160 artificial reef structures up to 4 m^3, 56 and 90 m deep, and between 1.6 to 3 km from the turbine were placed in the study area in 1993 and 2015.[84]

They observed a low affinity of *P. major* and *S. quinqueradiata* to the OSW turbine in relation to the neighboring habitats[85]. They note that the turbine had only been deployed for a year and cite previous studies that suggest fauna of marine sessile animals in artificial habitats

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[81] Ibid, 68-9.
[82] Ibid, 73.
[83] Ibid, 301.
[84] Ibid.
[85] Ibid, 305.

become stable after 1.5–2 years in coastal areas of Japan.[86] Although the Kuroshio and California currents are western and eastern boundary currents, respectively, and subject to different oceanographic processes, this study provides a vital analog, showing that the effects of introducing new infrastructure to marine ecosystems may have a delayed response.

Potential impacts from OSW on California's fish species and fishery ecology include noise and EMF effects, habitat alterations, and displacement and avoidance of OSW infrastructure. The absence of pile driving to install fixed-bottom turbines significantly decreases the noise pollution generated by OSW construction in California. The artificial reef effect may lead to permanent communities surrounding OSW turbines and expose more species to noise and EMF impacts. However, an increased understanding of species likely to occur in California's WEAs and their response to EMFs and noise pollution is needed. Signals from government and industry on infrastructure specifics can help facilitate this research. Anthropogenic EMFs and noise can lead to a spectrum of behavioral and development changes across fish species. Monitoring and mitigation efforts should prioritize understanding floating turbines's noise, EMF, and artificial reef impacts potential on species expected within California's current and future WEA.

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[86] Ibid.

3.4 Habitats and Ecosystems (HE)

Figure 14. Impacts on Habitats and Ecosystems

		Impact			
		Anthropogenic Emissions and Pollution	**Invasive Species**	**Primary Productivity**	**Physical Processes**
Author	Bang et al (2019)	X			
	ICF (2020)		X		
	Slavik et al. (2019)		X	X	
	Bell et al. (2020)	X		X	
	Rueda-Bayona et al. (2022)	X			
	Floeter et al. (2017)			X	X
	Raghukumar et al. (2022)				X
	Raghukumaret al. (2024)			X	X
	Siederslebenet al. (2018)				X

The impacts identified on HE include pollution, the spread of invasive species, changes in primary productivity, and changes in physical and oceanographic processes. A recent life cycle assessment (LCA) of a deployment scenario for OSW in California highlights the lower life-cycle GHG emissions of OSW compared to solar, natural gas, and coal.[87] Anti-corrosion materials used in steel contents may have the potential for heavy metal trophic transfer.[88] Furthermore, petroleum-based materials used in OSW infrastructure are the highest sources of abiotic depletion, eutrophication potential, and acidification potential.[89] Primary productivity fluctuations of up to 10% can occur in OSW farms.[90] Specifically, floating turbines present a higher risk of spreading invasive species.[91] Modeling by the CEC suggests California OSW could lead to regional fluctuations in upwelling, though the consequences are undetermined.[92] Impacts on HE present significant unknowns based on the information documenting these impacts and demand robust monitoring. However, the proliferation of OSW energy in Europe may suggest a degree of feasibility in managing and mitigating impacts that arise.

Anthropogenic Emissions and Pollution

Bang et al. (2019) conducted a LCA of the greenhouse gas (GHG) emissions from delivering 1 MWh of OSW energy to California's grid. Their LCA model utilized the following assumptions for the size and scope of the OSW farm:[93]

- 75 8 MW turbines (150 m hub height & 164 m rotor diameter)
- 600 MW total generation capacity, 50% capacity factor

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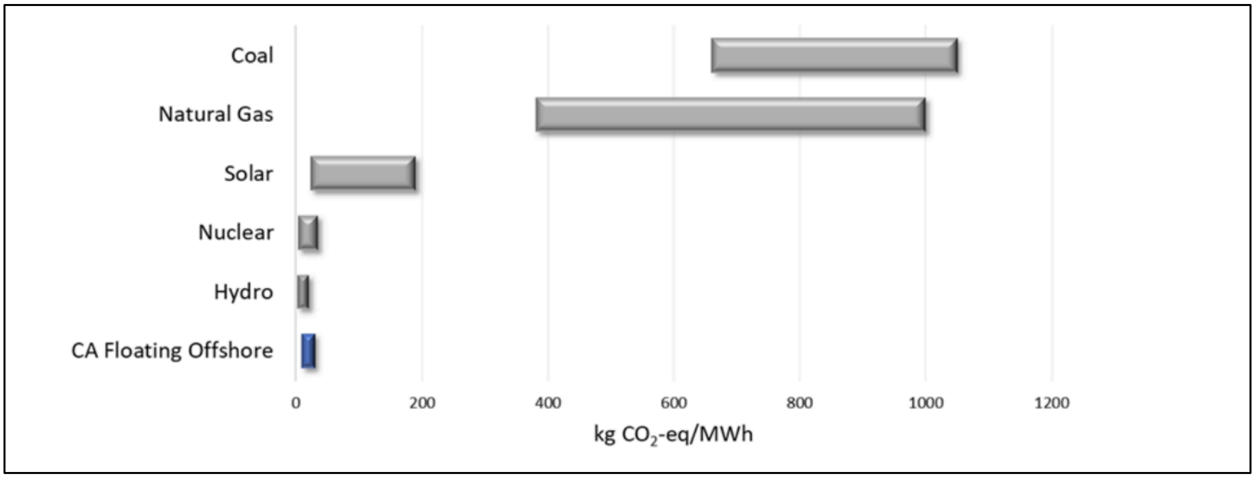
[87] Bang et al. (2019), 2.
[88] Bell et al. (2020).
[89] Rueda-Bayona et al. (2022), 12.
[90] Wang et al. (2023), 241.
[91] ICF (2020).
[92] Raghukumar et al. (2022), 28.
[93] Bang et al. (2020), 14.

- 70, 800 MWh generation per year over 25 years
- 35 km from shore in 450 m of water

They found that 1 MWh of electricity from OSW generates ~15.35 kg CO2-equivalent (8.58 - 30.17 kg CO2-eq/MWh uncertainty range) over its lifetime.[94] Figure 13 (below) displays their CO2-eq/MWh estimate compared to other energy sources.[95] Their maximum estimate for OSW (30.2 kg CO2-eq/MWh) is less than 1/10th the value of the minimum estimate for natural gas and 1/20th the minimum for coal.[96] The minimal lifecycle GHG emissions for OSW are key to the technology's sustainability. However, the decommissioning process, including the disposal, reuse, or recycling of turbine components, is an unknown source of environmental impact and warrants extensive planning and regulation.

Figure 15. Comparison of GHG emissions from OSW and Other Energy Sources



Source: Bang et al. (2019).

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[94] Ibid, 33.
[95] Ibid, 38.
[96] Ibid, 33.

To protect steel components on OSW turbines from corrosion in marine environments, aluminum-zinc-indium alloys (galvanic anodes) are applied.[97] Bell et al. (2020) cite a 2018 estimate that OSW farms in Europe release 1900 t of aluminum and 90 t of zinc to the North Sea annually.[98] They argue there is little known about the impacts of galvanic anodes on benthic organisms.[99] Bell et al. (2020) tested the acute toxicological effects of galvanic anode exposure on a laboratory scale on three benthic organisms. [100]

The luminescent bacterium (*Aliivibrio fischeri). A. fischeri* showed no significant effects for any of the tested materials. For the marine diatom (*P. tricornutum)*, the dissolved anode and Al at saturation concentration at pH=8.1 caused an average growth inhibition of 28.3±6.3% and 26.0±2.6%, respectively.[101] The sediment-dwelling mud shrimp (*C. volutator*) showed no increase in residual metal content compared to the control group in the experiments with sediment. Zn concentrations in the tested organisms were elevated by approximately 28% at the highest exposure level compared to the negative control.[102] They conclude that galvanic anode concentrations in seawater showed a positive correlation with residual metal concentration in biota and that enrichment expressed no linear relationship in terms of applied test concentration of the dissolved galvanic anode.[103]

Bell et al. (2020) recommend further research to understand the potential trophic transfer of these metals. The potential for bioaccumulation of heavy metals across all trophic levels from materials used in OSW energy requires priority attention and substantial monitoring efforts.

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[97] Bell et al. (2020).
[98] Ibid, 2.
[99] Ibid.
[100] Ibid, 2-3.
[101] Ibid, 5.
[102] Ibid, 7.
[103] Ibid, 7.

In a literature review of OSW life cycle assessments (LCA), Rueda-Bayona et al. (2022) identified the most environmentally impactful impact materials used in OSW. They found that the most impacted LCA categories were abiotic depletion, acidification potential, human toxicity potential, eutrophication potential, NOx, SO2, ozone layer depletion potential, global warming potential, and PM 2.5. Petroleum-based materials (PBER) reported the highest impact on abiotic depletion (59.4 kg Sb eq), eutrophication potential (6.6 kg PO 4 -eq), and acidification potential (40.3 kg SO2 eq).[104]

They report that floating foundations, such as tension-leg platforms or ballast, utilize aluminum, low-alloy steel, and zinc (Figure 1, p. 8). The mooring lines use aluminum, plastic, and copper in manufacturing. They also found that zinc, rare earth (used for generators with permanent magnets), and carbon fiber (blades) were the least studied materials.[105]

Primary Productivity

OSW farms have been shown to cause impacts on nutrient cycling and primary productivity and have the potential to introduce non-native species to OSW farm areas. Slavik et al. (2019) investigated the large-scale impact of OSW farms on pelagic net primary productivity (NPP) in the southern North Sea. They focused on productivity changes caused by the accumulation of epifauna, primarily the blue mussel (*Mytilus edulis)*, on turbine infrastructure between 2003 and 2014[106]. They found an overall moderate effect on ecosystem function caused by the accumulation of blue mussels on OSW infrastructure.[107] They estimated a maximum loss of NPP of 8% within the OSW farm. The average loss of NPP was 3.7 ± 1.5% across the

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[104] Rueda-Bayona et al. (2022), 12.

[105] Ibid.

[106] Slavik et al, (2019).

[107] Ibid, 48.

simulated years. Furthermore, the maximum and minimum observed daily increases of NPP of the entire study area occurred within the OSW farm boundary.[108]

Floeter et al. (2017) conducted biophysical surveys of the Global Tech I (GTI) and BARD Offshore 1 (BARD) OSW farms. Each contains 80 fixed-bottom turbines at a water depth of ~40 m, and ~100 km offshore in the German EEZ.[109] They found that both OSW farms decreased the local summer water column stratification. They also found that the nutrient supply to the surface mixed layer was enhanced in the OSW farm area.

Nevertheless, a subsequent increase in phytoplankton biomass was not observed at the broader spatial scale of the OSW farm. Additionally, primary production below the thermocline increased due to enhanced vertical mixing, shallower and less intense stratification, and the increased nutrient influx into the surface layer, which will enhance the primary production of the surface layer. Finally, the OSW farms were not found to affect pelagic fish distribution significantly.[110]

Wang et al. (2023) estimated the presence of OSW can cause up to a ± 10% fluctuation in primary productivity.[111] Notably, fishing prohibitions within OSW farm boundaries can provide an ecological restoration period for fish populations and marine vegetation.[112] Zoobenthos can be negatively impacted by benthic habitat destruction. However, zoobenthos can also receive an ecological restoration period supported by the artificial reef effect and trawling prohibition during the operation phase.

Slavik et al. (2019), Floeter et al. (2017), and Wang et al. (2023) demonstrate that while OSW farms can produce impacts on nutrient cycling and primary productivity, the consequences

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[108] Ibid, 45.

[109] Floeter et al. (2017).

[110] Ibid, 171.

[111] Wang et al. (2023), 241

[112] Ibid, 240

and magnitude of these effects vary, highlighting a priority monitoring area and the subject of needed further study.

Invasive Species

In addition to NPP changes, Slavik et al. (2019) discussed how constructing OSW farms can provide a medium for colonization by exotic or invasive species. They describe how the marine splash midge (*Telmatogeton japonicus)*, a species usually found in Australasian waters, has been observed at OSW farms in Denmark and along the Swedish Baltic coast, likely through transportation on the hulls of ships.[113] Towing floating turbines from ports presents a greater risk of spreading invasive species than fixed-bottom turbine installation. Additionally, floating foundation types have a smaller footprint throughout the water column, which may not lead to enhanced feeding opportunities and decrease the artificial reef effect.[114]

Physical Processes

Relevant studies on OSW's impact on oceanographic and atmospheric processes (upwelling and atmospheric circulation) within the California Current system include modeling studies by Raghukumar et al. (2022) and (2024) and an analogous study on impacts on the marine boundary layer (MBL) in the North Sea by Siedersleben et al. (2018).

Raghukumar et al. (2022) utilized a Weather Research and Forecasting (WRF) mesoscale model and a wind farm parameterization (WFP) module to estimate the impacts on the

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[113] Ibid, 48.
[114] ICF (2020).

atmospheric circulation of a build-out of the Humboldt and Morro Bay WEA.[115] Their model includes the following assumptions:[116]

- 100 km x 100 km WEA
- Humboldt: 152 10 MW turbines, 1.8 km apart
- Morro Bay: 230 10 MW turbines, 1.8 km apart

Overall, their model found that the length scale of wind speed reductions was several times the internal Rossby radius of deformation. Additionally, an OSW farm with an aerial extent of approximately 20 km × 20 km is on the order of spatial scales at which upwelling occurs off the California coast.[117]

Their model found wind speed reductions over one m/s, or a ~5% reduction of maximum wind speeds off Central California. The horizontal extent of the wake in wind speed reductions for the Morro Bay WEA was approximately 200 km, extending south past the Channel Islands. The following impacts were also found:[118]

- Cooling effects on the order of 0.1°C (background temperature ranges from 12 to 20°C),
- Surface pressure perturbations on the order of 0.06 mbar (background air pressure on the order of 1,000 mbar)
- Changes in specific humidity on the order of 0.1 g/kg (background range of 0–10 g/kg)
- Perturbations to the downward longwave radiation on the order of 2 W/m2 (300 W/m2 background)

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[115] The study also modeled the original BOEM Diablo Canyon call area but the results are not discussed here.

[116] Raghukumar et al. (2022), 5-6.

[117] Ibid, 1-2.

[118] Ibid, 11-12.

They discuss uncertainties created by the model's accuracy but point out that OSW's impact on atmospheric circulation deserves attention, considering the importance of upwelling within the California Current System.

Raghukumar et al. (2024) expanded the work of Raghukumar et al. (2022) to estimate the potential impacts on California coastal upwelling based on similar modeling assumptions. This study expanded to include the use of larger 15 MW turbines in addition to 10 MW turbines.[119] Utilizing 15 MW turbines for a 20 GW build-out resulted in the following parameters:[120]

- Humboldt: 152 turbines
- Morro Bay: 318 turbines
- Cape Mendocino: 297 turbines
- Del Norte: 567 turbines
- 150 m hub height, 240 m rotor diameter (D), ~9D apart
- 800-2,000 m water depth, 30-50 km from shore

Their model found upwelling decreased on the nearshore side of the simulated wind farms but was mostly offset by increases in upwelling on the offshore side. This may suggest an increase in offshore upwelling. Additionally, cross-shore changes to upwelling were observed above levels of natural variability.[121] Most significantly, they conclude that "the consequences of these changes in the physical upwelling structure on the ecosystem are currently unknown" (Raghukumar et al. 2022, p. 28). The uncertainty with the ecosystem-wide implications of upwelling changes induced by OSW in California demands this as a priority subject of research efforts and monitoring efforts.

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[119] Raghukumar et al. (2024).
[120] Ibid, 11.
[121] Ibid, 28.

Through flight surveys and model simulation, Siedersleben et al. (2018) attempted to determine the micro meteorological impacts of OSW farms on the marine boundary layer (MBL) in the North Sea. Their study includes 3 OSW farms in depths between 20 and 25 m, containing 3.6 and 6.2 MW fixed-bottom turbines with 90 and 95 m hub heights and 120 and 126 m rotor diameters, respectively.[122] Through 26 flight surveys and modeling, they determined:[123]

- Large OSW farms can impact the MBL.
- Micrometeorological impacts exist only in the case of an inversion below or at the rotor area.
- A breakup of the inversion results in a mixing of dryer air downward
- The inversion in the rotor disk region caused potential temperature (PT) to increase by up to 0.6 K within the wake 45 km downwind (5 flights)
- PT increase led to a decrease in the total water vapor mixing ratio by up to 0.5 g kg−1
- Shallow inversion below hub height associated with a cold SST causes a cooling of the same magnitude above and at hub height downwind (3 flights)

They point out that temperature and moisture changes could impact local microclimates. Additionally, they note that a limited number of studies have investigated the impact of OSW farms on the MBL.[124] Consequently, they present another uncertainty in addition to Raghukumar et al. (2022) and (2024) on the impacts of OSW on physical and oceanographic processes.

The impacts identified on HE due to OSW energy encompass pollution, invasive species, changes in primary productivity, and alterations in physical and oceanographic processes. Initial modeling suggests OSW in California may output lower life-cycle GHG emissions than solar, natural gas, and coal.[125] Furthermore, modeling results and previous studies reveal potential

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[122] Siedersleben et al. (2018).

[123] Ibid, 11.

[124] Ibid, 1-2.

[125] Bang et al. (2019).

impacts on nutrient cycling and physical processes such as upwelling and atmospheric circulation. Despite these impacts' significant uncertainties, the experience gained from OSW energy in Europe provides vital insights for initial monitoring efforts in California. Therefore, while challenges remain, proactive monitoring and adaptive management strategies can minimize adverse effects on HE and ensure the sustainability of OSW development in California.

Conclusion

The impacts from OSW identified on marine ecosystems include noise effects, displacement, entanglement, collision with OSW infrastructure and vessels, attraction to or avoidance of OSW infrastructure, habitat alterations, anthropogenic emissions and pollution, and EMFs. The least studied impacts within the literature review were nutrient cycling (2.6%) and physical process (5.3%). The least studied receptors were sea turtles, bats, and benthic communities (>25%). The literature reviewed provides important parallels for floating turbines' potential impacts on California's marine ecosystems. Floating turbines remain a novel technology and should be approached in this manner. California is pursuing OSW at a revolutionary speed and scale under environmental conditions where floating turbines have not been deployed before.

This project seeks to provide a resource to all stakeholders engaged in current and future environmental reviews of OSW in California. Floating turbines will not be exclusive to California; this effort can serve as a framework for other states and nations contemplating and managing future projects.

This study contains a sample of the available literature on OSW impacts on marine ecosystems. The research objectives directed the literature review when this research was conducted. This study attempted to focus on the available literature relevant to California's development of OSW. Future work should continue to expand the knowledge base of the potential impacts of floating turbines on California's marine ecosystems and species. Systemic and comprehensive environmental review, monitoring, and public engagement are needed to develop OSW energy sustainably in California. Creating a centralized and accessible communication structure for the knowledge base on the impacts of OSW on marine ecosystems can contribute to an equitable adoption of OSW in California that prioritizes engaging stakeholders, mitigating impacts, and protecting marine ecosystems.

Appendix A: Database Description and Userguide

The literature was organized into an Excel spreadsheet to create a database and allow retrieval and cross-referencing on an online platform. The metadata tags at the top of the spreadsheet enable keyword filtration. Metadata includes author information, literature type, research question(s), monitoring methods, technology, impact source/stressor, development phase, receptor, geographic area (study location), spatial and temporal scales of the studies, and main findings.

Abbreviated citation	Full citation	Literature Type	Research Question	Monitoring Method	Technology	Impact source/Stress	Development Phase	Receptor	Geographic Area	Spatial Scale	Temporal Scale	Main Findings
Bang-et-al._2019	Bang, J.; Ma, C.; Tara	Scientific paper	What are the lifecycle GHG	Labroatory experimnet		Ecosystems (atmospheric)	Operation and…	Ecosystems (Atr	California	Humbolt, Morro Bay WE	multi-year	-1 MWh of electricity through floating offshore wind power generates ~15kg CO2-equivalent GHG emissions over its life cycle, which is comparable with the literature for conceptual floating offshore wind turbine models. -Monte Carlo simulation establishes a 90% confidence interval range of emissions from 11.60 to 25.04kg CO2-equivalent
Bell-et-al._2020	Bell, A.; von der Au, M	Scientific paper	Does galvanic cathodic pro	Laboratory experiment		Chemicals	Pre-construction	Fish	N/A	Laboratory	months - years	-Galvanic anodes for cathodic protection produced no direct envirmental impact on the tested organisms. Potential for biomagnification of metals.
Duffy-et-al._2023	Duffy, O.; Chumbinho	Grey Literature	What are the impacts of ge	Desktop Study report		Noise	Operation and…	Fish	Ireland		multi-year	-It is generally accepted that most research instruments used in site, investigation surveys do not cause significant impacts to fish and shellfish. Instant mortality of both fish and shellfish due to site investigation surveys is very unlikely
Harnois-et-al._2015	Harnois, V.; Smith, H.	Scientific paper	How do different mooring s	Model		Engtanglment	Operation and…	Marine Mammal	Scotland	Labratory	days - weeks	-The taut configuration has the lowest relative risk of entanglement, while the highest relative risk occurs with catenary moorings with chains and nylon ropes or with catenary moorings with accessory buoys. However, the absolute risk of entanglement is found to be low, regardless of the mooring configuration
Harsanyi-et-al._2022	Harsanyi, P.; Scott, K	Scientific paper	What are the effects of antl	Laboratory experiment		EMF	Construction	Fish	Europe	Laboratory	months - years	-Chronic exposure to 2.8 mT EMF did not affect embryonic development time, larval release time, or vertical swimming speed. Decreased carapace height, total length, and maximum eye diamete
Hesestetun-et-al.2023	Hestetun, J.; Ray, J.;	Scientific paper	How effective is eDNA data	eDNA metabarcoding	eDNA metabarcoding	**Monitoring**/Displacement	Pre-construction	Fish	North Sea	Hywind FOSW Pilot Park	days - weeks	-As a non-invasive tool, we conclude that eDNA has a high potential in future environmental monitoring of OWFs. We recommend further ground-truthing and biomass correlation of eDNA data with catch data and establishing eDNA time series as next steps towards implementation of eDNA in OWF environmental monitoring.
Holdman-et-al._2023	Holdman, A.; Tregenz	Scientific paper	What is the spatial and tem	Passive Accoustic	F-PODS, echolocation-clicl	**Monitoring**/Displacement	Operation and…	Marine Mammal	East Coast, USA	Gulf of Maine Proposed \	months - years	-Time of year, hour of day, lunar illumination, and temperature are significant contributors to porpoise presence and/or foraging effort. European studies show that harbor porpoises exhibit behavioral changes, disruption of foraging, and displacement due to wind energy development.
Hutchinson-et-al._2023	Hutchison, Z.; Gill, A.	Scientific paper	How does anthropogenic E	Labroatory experimnet		EMF	Operation and…	Fish	East Coast, USA	Labratory	days - weeks	-We demonstrate a striking increase in exploratory/foraging behaviour in skates in response to EMF and a more subtle exploratory response in lobsters.
ICF_2020	ICF. 2020. Compariso	Grey Literature	What are the potential envi			Attraction, Avoidance, Cha	Pre-construction	Marine Mammal	Atlantic Coast U.S.,		multi-year	-Approximately up to 113 m2 of habitat lossper foundation (for suction caisson anchors). Larger risk of invasive species spread than fixed-bottom monopile.
Klinck-et-al._2015	Klinck, H.; Fregosi, S.	Grey Literature	What is the effectiveness o	Passive acoustic monitorin	Mobile Autonomous Platforms	Noise	Operation and…	Marine Mammal	Europe	Baltic Sea	months - years	-These systems (a) are effective at detecting the acoustic presence of high-frequency cetaceans such as porpoises, and (b) could be a valuable tool to monitor potential negative impacts of renewable energy
Kordan-et-al._2024	Kordan, M.; Yakan, S	Scientific paper	What are the changes in pl	Labroatory experimnet		Habitat Change	Operation and…	Fish, Habitats ar	North Sea	19 OSW farms in the Nor	months - years	-The events that have a diminishing effect on the phytoplankton population include foundation installation, array cable installation, and fully commissioning. Turbine installation was the only event where primary producers experienced growth afterward. The occurrence and duration of phytoplankton population changes during different eutrophication zones vary
Michel-et-al._2024	Michel, M.; Guichard,	Conference Proc	What is the role of passive	Passive acoustic monitorin	hydrophones & autonomous a	**Monitoring**/Displacement	Pre-construction	Marine Mammal	Europe	Confrence	days - weeks	-This article highlights the role of passive acoustic monitoring as a complementary approach to traditional methods (mainly plane and boat surveys)
Pereksta-et-al._2022	Birds, Bats, and Beyo	Grey Literature	1. How can networked VH	networked VHF (e.g., Motu		**Monitoring/Displacement**	Pre-construction	Birds and Bats	West Coast	BOEM Southern Californ	multi-year	-BOEM and others will have the ability to fill critical data gaps for small-bodied, high-vulnerability species
Pereksta-et-al._2022	Seabird and Marine M	Scientific paper	1. What is the current statu	Seasonal aerial surveys off		**Monitoring/Habitat Chang**	Pre-construction	Birds and Bats, I	West Coast, USA	BOEM Southern Californ	multi-year	-This study will provide up-to-date information on species composition, distribution, abundance, and seasonal variation of seabirds from the southern limit of the Monterey Bay National Marine Sanctuary to the U.S.-Mexico border. In addition, data will be opportunistically collected on marine mammals that are observed during the surveys
Pereksta-et-al._2023	Offshore Acoustic Ba	Scientific paper	1. What is the temporal and	A sustained, multi-year dep		**Monitoring/Collision**	Operation and…	Birds and Bats	West Coast, USA	California OCS planning	multi-year	-Provided Federal/State resource agencies and developers with key metrics to evaluate mortality risk associated with offshore wind energy development. Such data would boost our ability to manage risks to bats associated with offshore development by providing critical baseline data regarding the spatial and temporal occurrence of rare and otherwise vulnerable bat species within California.

‘Literature type’ refers to the classification of the resource, including scientific publications and government reports (often termed "gray literature"). ‘Research Questions(s)’ refers to the specific question of each resource the author(s) attempted to answer. ‘Monitoring

Method’ describes the technique used for monitoring impacts (e.g., aerial or boat surveys). ‘Technology’ describes the specific technology used in monitoring (e.g., eDNA). Impact Source/Stressor’ refers to the cause of the impact, such as noise, habitat alteration, or collision. ‘Development Phase’ refers to the phase of development (pre-construction, construction, operation and maintenance, decommissioning) in which the impact occurs. ‘Receptor’ refers to the affected entities, such as marine mammals, birds, fish, or habitats. ‘Geographic Area’ describes the specific geographical regions where studies were conducted. Spatial/Temporal Scale describes the spatial and temporal scope of each study. ‘Main Findings’ describes the key findings of each resource.

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