Draft Offshore Wind Pathways of Effect Model for the Atlantic Regional Assessment of Offshore Wind Energy Development

Contents

Executive Summary

International capacity for offshore wind energy is growing in light of recent commitments to maintain global average temperatures below the 1.5/2-degree threshold. An undertaking such as this introduces new and existing stressors to wildlife in the marine environment, and consequently, in 2023, the Canadian government began a regional assessment of offshore wind energy development in Atlantic Canada (hereafter referred to as the RA). As part of the RA, a sector-based Pathways of Effects (PoE) model for offshore wind energy development was developed to visualize the cause-effect pathways between project activities, environmental stressors, and the resulting effects to aerofauna (birds and bats). Seven PoE models are presented for the major activities identified across all phases of offshore wind energy development (pre-construction, construction, operation, and decommissioning). Descriptions of the cause-effect pathways are reported by stressor. Key knowledge gaps are identified and related back to the stressors and effects pathways in each PoE model. These findings support ongoing information procurement, identify key knowledge gaps, and can contribute to cumulative effects work related to the development of the offshore wind industry in Canada.

Introduction

In the fight against climate change, meeting global energy demands requires the enhanced capacity of renewable energy sources. Like many countries worldwide, Canada has set renewable energy targets to contribute to keeping global temperatures below to 1.5-degree threshold. Offshore wind (OSW) energy generation is one of the renewable types proposed to substantially aid in achieving Canadian renewable energy targets. Similar to terrestrial wind energy, OSW energy developments comprise of an array of wind turbines and generators that deliver clean energy to the electrical grid. OSW energy developments can also include offshore platforms for substations and export cables that connect them to landfall stations for transmittance to the grid. Although OSW energy development is still in the planning stages in Canada, many countries internationally have operated OSW energy for decades. At present, two provinces have announced their intent to pursue OSW energy development, triggering two RAs in the Canadian Atlantic region, one in Newfoundland and Labrador (NL) and one in Nova Scotia (NS) (IAAC, 2022b, 2022a).

As the number of OSW energy developments increase on a global scale, it has become clear that effects to wildlife and associated habitat, both positive and negative, exist from its introduction to the marine environment (Boehlert & Gill, 2010). Migrating and foraging birds and bats are especially at risk of effects due to the long-standing presence of offshore structures and vessel-related maintenance (Drewitt & Langston, 2006; Fox et al., 2006; Williams et al., 2024). Marine birds are disproportionately at risk as they spend a significant portion of their life offshore, which may coincide with OSW energy developments. Environment and Climate Change Canada-Canadian Wildlife Service (ECCC-CWS) is responsible for safeguarding and protecting migratory birds, species at risk, and associated habitats through the Migratory Birds Convention Act and the Species at Risk Act. Significant work during the RA process has also been contributed by ECCC-Science and Technology Branch (STB). ECCC-CWS has developed a Pathways of Effects (PoE) model for birds and bats (hereafter referred to as aerofauna) for the NS and NL committees. The PoE model aims to visualize the linkages between OSW energy development activities, ecological stressors, and effects. PoE models have been used as a national risk assessment aid for decades, although at present, ECCC is in its early stages of adopting PoE into the risk assessment process.

Pathways of Effects Background

A PoE model is a tool used to describe the cause-and-effect relationship of federally designated projects. The model consists of a visual diagram and an accompanying narrative report describing the specific cause-effect pathways between a human activity, an environmental stressor, and a potential effect. In PoE diagrams, cause-effect pathways are represented using lines that connect activities to ecological stressors, and a potential effect on a measurable endpoint (Figure 1). Such models aid decision-makers make scientifically informed decisions and help identify appropriate mitigation measures (Government of Canada, 2012). The Department of Fisheries and Oceans Canada (DFO) uses PoE models and defines them as: “Diagrams that describe development proposals in terms of the activities that are involved, the type of cause-effect relationship that are known to exist for that activity, and the mechanisms by which stressors ultimately lead to effects” (Fisheries and Oceans Canada, 2006, p. 24).

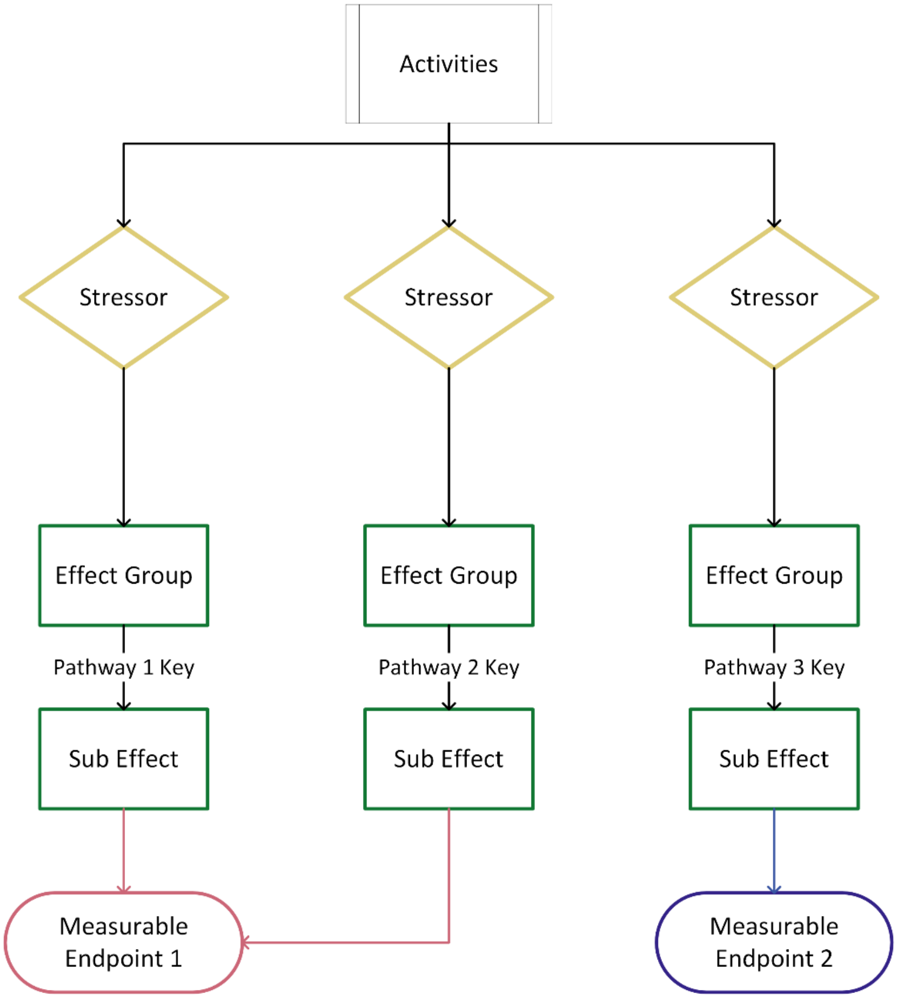

Figure 1: Example of a generic Pathways of Effects diagram.

PoE models have been used in risk assessments for anthropogenic activities in coastal and marine environments (e.g. Boehlert & Gill, 2010; Hannah et al., 2020; Isaacman & Daborn, 2011). Previously published models for marine renewable energy have been developed by the Government of Canada, however, none to date have focused exclusively on the cause-effect pathways generated by OSW energy development with respect to the effects on aerofauna and their habitat.

ECCC-CWS Approach

Generally, ecological risk models are developed using information about stressors, exposure pathways, and the potential effects on the habitat and survivability/ reproduction (EPA, 1998). A similar method was used to develop the OSW energy development PoE, which took a sector-based approach. Sector-based PoEs scope the model to a specific sector or industry, and can provide valuable information to further identify cumulative effects that can affect measurable endpoints (Government of Canada, 2012). Sector-specific activities induce stressors on ecosystems, which then lead to effects that can impact specific ecosystem components, environmental goods and services, and socio-economic cultural values (Government of Canada, 2012). In the case of OSW energy development, only the ecosystem-specific components were assessed which include aerofauna and their respective habitats according to the CWS mandate.

The model was developed using previous work developed by DFO for commercial shipping and in collaboration with the national PoE task team. Since ECCC is currently in the process of developing its own national guidance for developing PoEs, national guidance from DFO was used to develop the OSW energy development PoE. Potential pathways were identified first using guidance provided by other marine-sector PoEs developed by Hannah et al. (2020). A systematic search of scientific literature was conducted to find evidence for a sector-specific effect using the Tethys database and Google Scholar (*Tethys Knowledge Base*, n.d.). Countries such as the United States and European countries have numerous OSW energy developments currently in the operational phase. Existing literature reviews have summarized the effects of these developments on aerofauna and aerofauna habitat (e.g. Fox et al., 2006; Drewitt & Langston, 2006; Williams et al., 2024). Information was also compiled from other sectors that provided evidence for stressor-effect pathways in the Atlantic region, such as Offshore Oil and Gas. All cause-effect pathways were then grouped by OSW energy development project phase and activity to develop individual activity-based models (Hannah et al., 2020; Isaacman & Daborn, 2011).

Many disciplines study the effects of human-derived stressors on the environment with terms such as stressor, factor, and driver used to define similar phenomena across disciplines (Orr et al., 2020). The Pathways of Effects National Guidelines provide many of the definitions used for developing the model, which are summarized in Table 1.

Table 1: Components of a Pathways of Effects model and associated definitions.

Model Component	**Definition**	**Source**
Measurable endpoint	Environmental state indicators used to measure and track changes over time with respect to the objective. An explicit expression of the environmental value that is to be protected, operationally defined by an ecological entity and its attributes.	Government of Canada, 2012 EPA, 1998
Activity	Activities and sub-activities are human-induced undertakings that may result in impacts to the environment.	Government of Canada, 2012

Stressor	Any natural or anthropogenic variable (a chemical, physical or biological entity) that causes a quantifiable change (increase or decrease) in a biological response or measurable endpoint(s).	EPA, 1998; Government of Canada, 2012; Orr et al., 2020
Effect	Any change that the project may cause in the environment.	CEAA, 2009
Impact	A measurable change to an ecosystem component/function (e.g., loss of spawning habitat) as a result of human-induced pressures. An impact can be positive or negative.	Boehlert & Gill, 2010; Government of Canada, 2012
Pathway	A line used to represent a cause-effect relationship between an activity, a stressor, and an effect.	Fisheries and Oceans Canada, 2006

Phases and Activities

OSW energy development consists of multiple phases in an individual project, including pre-construction, construction, operation, and decommissioning. Activities are grouped by project phase (Table 2). An additional project phase classification has been included for accidents and spills that might occur throughout each project phase. The OSW energy development activities are further categorized into associated sub-activities to further detail each cause-effect pathway.

Although OSW energy development includes activities in both offshore and onshore environments, this PoE model only focuses on addressing the knowledge gap for the activities in the offshore environment. For cause-effect pathways associated with onshore activities, the proponent is directed to the national PoE models developed by the national PoE task team (in prep.).

Table 2: Offshore Wind Energy Development project phases, commonly associated activities, and sub-activities.

Project Phase	**Activity**	**Sub-Activity**
Pre-Construction	Site surveys	Vessel and equipment use
Construction	Site preparation	Vessel and equipment use
		Ice-breaking
		Pile driving and excavation
	Infrastructure installation	Vessel and equipment use
Operation	Electricity generation	Rotor blade rotation

		Turbine presence
	Routine maintenance	Vessel and equipment use
Decommissioning	Partial wind farm removal	Leave cables, foundations, scour protection
		Vessel and equipment use
	Full wind farm removal	Removal of all wind farm infrastructure
		Vessel and equipment use
Accidents	Accidental discharge (chemical) into environment	Turbine presence Vessel use
	Accidental discharge (solid) into environment	Vessel use
	Accidental species introduction to the environment	Vessel use; Turbine presence

Endpoints

Endpoints are practical and well-defined, and incorporate an ecological entity and measurable attribute (Government of Canada, 2012; See Table 1). The selected endpoints are of ecological importance, are susceptible to stressors and are relevant in managing risk to aerofauna associated with OSW energy development. Additionally, factors of survival and reproduction were considered in terms of the stressors in determining the endpoints (EPA,1998).

The two measurable endpoints considered in the OSW energy development PoE are:

1. Aerofauna habitat availability and distribution, including quality, quantity and connectivity. Habitat consists of locations used throughout life stages for foraging, breeding, roosting, resting, and migration.
2. Aerofauna species survival and reproduction.

Stressors

Many terms are used interchangeably across disciplines to refer to factors that arise consequentially from human activities (EPA, 1998; Orr et al., 2020). These are summarized in Table 3. In this approach, the term stressor refers to any chemical, physical or biological entity that can cause an adverse effect on a measurable endpoint (Government of Canada, 2012).

Table 3: An overview of the various terms used to refer to factors elicited by human activities that may cause environmental effects.

Term	Organization	Definition	Source
Impact-producing factor (IPF)	NS Committee	Identify factors associated with an offshore wind (OSW) development project that may cause impacts to valued physical, biological, economic or cultural components.	IAAC, 2022b
IPF	BRI	Alternative term for pressures with negative effects.	BOEM, 2020, 2024
Agent	EPA	Any physical, chemical, or biological entity that can induce an adverse response (synonymous with stressor).	EPA, 1998
Stressor	BRI	Alternative term for pressures with negative effects.	Stelzenmüller et al., 2018
Stressor	DFO	An agent, condition, or other stimulus that causes stress to an organism.	Fisheries and Oceans Canada, 2006
Stressor	EPA	Any physical, chemical, or biological entity that can induce an adverse response (synonymous with agent).	EPA, 1998
Pressure	Government of Canada	Any chemical, physical or biological entity that can cause an adverse effect on a measurable endpoint(s).	Government of Canada, 2012
Pressure	BRI	External abiotic or biotic factor exerted by an activity or other source that causes an effect.	Willsteed et al., 2018
Hazard	BRI	Alternative term for pressures with negative effects.	Goodale & Milman, 2016

The PoE model identified stressors based on the activities required of an OSW energy development project and are summarized in Table 4.

Table 4: A summary of the stressors identified in the Pathways of Effects model associated with Offshore Wind activities and sub-activities.

Stressor	Project Phase	Activity	Sub-Activities
Artificial Lighting	Pre-Construction, Construction, Operation, Decommissioning	• Site Surveys • Site Preparation • Electricity Generation • Routine Maintenance • Partial and Full Wind Turbine Removal	• Vessel and Equipment Use • Turbine Presence

Artificial Structures	Pre-Construction, Construction, Operation, Decommissioning	• Site Surveys • Site Preparation • Electricity Generation • Routine Maintenance • Partial and Full Wind Turbine Removal	• Vessel and Equipment Use • Rotor Blade Rotation • Turbine Presence
Noise	Pre-Construction, Construction, Operation, Decommissioning	• Site Surveys • Site Preparation • Infrastructure Installation • Routine Maintenance • Partial and Full Wind Farm Removal	• Pile Driving and Excavation • Vessel and Equipment Use
Habitat Loss	Construction, Operation, Decommissioning	• Site Preparation • Infrastructure Installation • Electricity Generation • Partial and Full Wind Turbine Removal	• Ice-Breaking • Pile-Driving and Excavation • Vessel and Equipment Use • Turbine Presence • Leave Cables, Foundations, Scour Protection • Removal of All Wind Farm Infrastructure
Invasive Species Introduction	Accidents	• Substance Spills and Accidental Introduction	• Vessel Use
Physical Hazard Introduction	Accidents	• Substance Spills and Accidental Introduction	• Vessel Use
Chemical Hazard Introduction	Accidents	• Substance Spills and Accidental Introduction	• Vessel Use • Turbine Presence

Potential Effects

To reiterate, an effect is the measurable change to an ecosystem component due to stressors induced by humans (Government of Canada, 2012). Although the term is often used interchangeably with the word “impact”, effect does not imply any magnitude or significance as to the outcome (Boehlert & Gill, 2010). The effects were simplified into categories for applicability between projects (Table 5), similar to the model for commercial shipping developed by Hannah et al. (2020). Detailed sub-effects were then elaborated in the diagrams and narrative. Only potential effects to aerofauna and their habitat were considered in the model, according to the measurable endpoints defined above. Migratory birds, marine birds, sea ducks, shorebirds, and bats were included in the effects assessment. Due to a lack of data, monarch butterflies were not included in the PoE assessment.

Table 5: The effects groupings used in the Pathways of Effects model.

Effect Category	**Detailed Effects**	**Source**
Change in Habitat	Change in the physical habitat of the marine environment. It includes habitat loss and changes (increase or decrease) in habitat quality.	Hannah et al., 2020
Change in Individual Fitness	Non-lethal change to the physiological condition of an organism that improves or reduces the ability to grow, survive to reproductive age, and/or produce or rear offspring. Included are behavioural effects, changes to organism health and reproduction, and injury.	Adapted from Hannah et al., 2020
Mortality	Refers to the death of an organism or group of organisms. Mortality can be an immediate or delayed response after exposure to a stressor. Mortality can also occur due to a change in individual fitness.	Adapted from Hannah et al., 2020

Limitations with the PoE Framework

Although PoE models are useful decision-making tools, it is important to recognize that there are limitations with the approach. First, none of the models considered in the PoE for aerofauna consider cumulative effects, as PoE frameworks consider cause-effect pathways independently (Clarke Murray et al., 2014; Hannah et al., 2020). As a result, all the effects considered in the models are only explained by the activities of OSW, though it is anticipated that effects of other offshore industries will interact with those generated by OSW, along with other OSW projects. PoEs are simplified conceptual models of complex interactions that often involve multiple stressors. Further analyses will be required to examine the cumulative effects from OSW energy development.

Second, none of the effects imply any quantification. For instance, collision as an effect to aerofauna has no more implication than effective habitat loss on aerofauna species survivability and reproduction. As Boehlert and Gill (2010) pointed out, it is important to distinguish between the terms *effect* and *impact*. An impact implies magnitude and significance, while an effect does not. Therefore, no one cause-effect pathway should be prioritized over another based on the PoE and a lack of consideration for cumulative effects.

A final limitation of the PoE model to consider is site- and species-specific pathways. Each OSW project will have site-specific variables that can alter cause-effect pathways (e.g. the number of turbines or platforms installed). These variables are not considered in the model as the OSW industry is in its infancy in Canada. Thus, activities are generalized across all phases, independent of site specifications. Moreover, different effects have varying levels of knowledge and evidence. Species-specific effect pathways are limited to the state of the present research, which, for aerofauna in the offshore environment, can be constrained by anthropogenic valuation of the species (e.g. whether it is of conservation value, economic value, cultural value). Where appropriate, a list of species with important vulnerability or sensitivity classification results or further species-specific reviews on the subject are identified.

Pre-Construction Phase

Considering the planning required of an OSW energy development project, the pre-construction phase of OSW energy development is considered separately from construction and subsequent phases. It mainly consists of environmental surveys to collect data about the OSW energy development area which can include seismic surveys, wildlife monitoring, and other site-related data.

[SS] Site Surveys

Pre-construction activities include site-related assessments during the planning of an OSW energy development project. Due to the remoteness of OSW locations, site assessments require vessels and/or aircraft for transportation to and from the proposed development area. Additional equipment is also needed at the site to gather baseline data, which could include drones. Which equipment is used varies depending on the targeted ecological component and chosen method of data collection.

Three stressors were identified related to pre-construction site surveys:

- Artificial Lighting
- Artificial Structures
- Noise

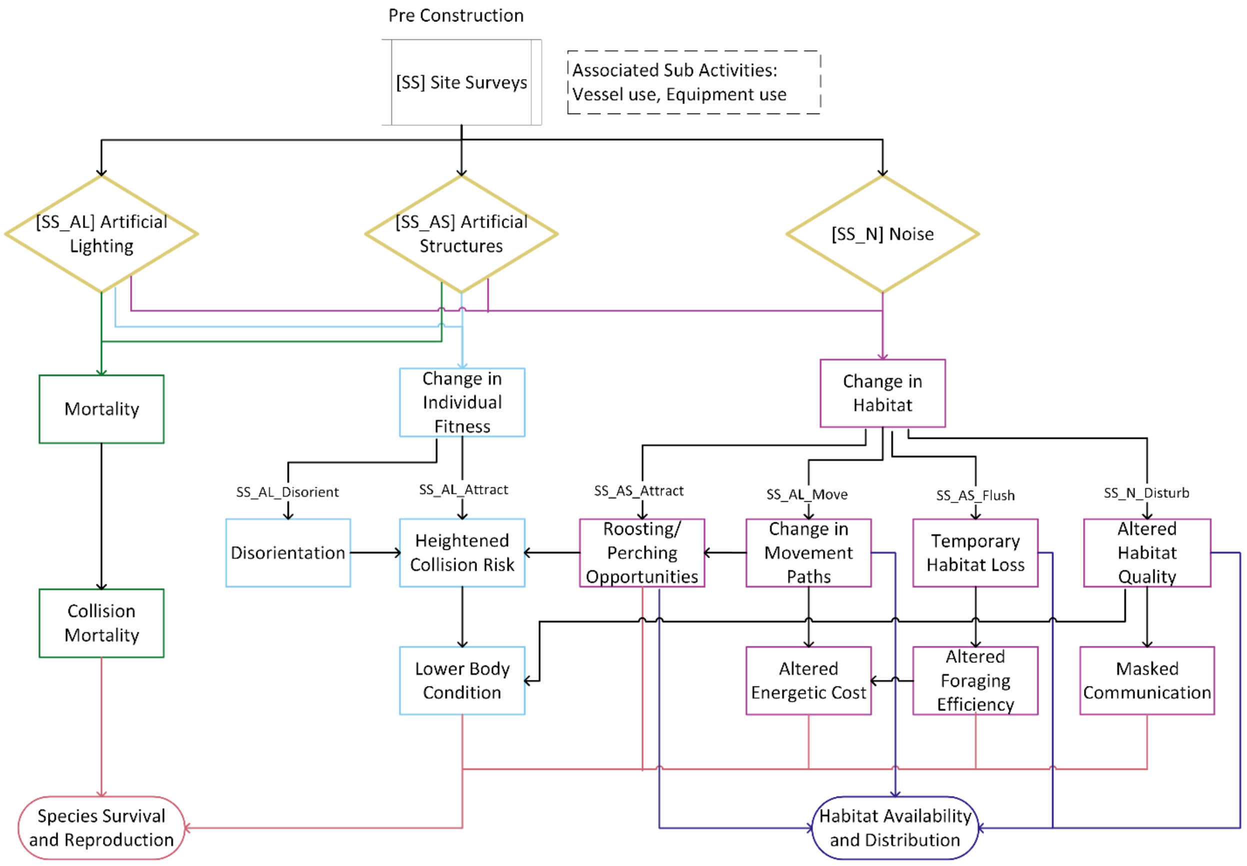

Figure 2: Pathways of Effects model for site surveys during the Offshore Wind Energy Development pre-construction phase.

[SS_AL] Artificial Lighting

Vessels used for transportation of personnel and monitoring equipment to conduct site surveys and related assessments will introduce artificial lighting. Aerofauna behaviour (e.g. attraction, avoidance) can be influenced by lighting offshore. Seabirds and bats are known to be attracted to illuminated offshore platforms and vessels (Gjerdrum et al., 2021; Montevecchi, 2006; Voigt et al., 2018). Attraction to lit offshore structures heightens the risk of collision with vessels, aircraft, and equipment that directly affects aerofauna survivability and reproduction [SS_AL_Attract]. Environmental conditions, species-specific factors, lighting characteristics, and other factors can influence attraction.

Conversely, movement pathways can be altered away from vessels and associated equipment for aerofauna that avoid in response to artificial lighting (Syposz et al., 2021). Avoidance responses in-flight alter habitat connectivity and increase energetic cost [SS_AL_Move]. Aerofauna habitat availability and distribution is affected by avoidance behaviour and collision mortality or injury due to attraction can lead to consequences for species survivability and reproduction.

See [EG_AL] for a related description of the effects of offshore lighting on aerofauna.

[SS_AS] Artificial Structures

Vessels, aircraft or equipment used in monitoring introduce artificial structures into the offshore environment. The presence of these structures can alter movement pathways by attracting aerofauna to roosting or perching opportunities, especially seabirds and bats (Ahlén et al., 2009; Dierschke et al., 2016). As a result, structures can heighten collision mortality or injury [SS_AS_Attract]. Vessels are also sources of physical disturbance which can lead to changes in foraging habitat and movement pathways due to flushing, resulting in altered energetic cost [SS_AS_Flush] (Byrnes & Dunn, 2020). Effects depend on species' behavioural response and vessel speed (Schwemmer et al., 2011). Therefore, vessel presence and traffic can affect both species survivability and reproduction and habitat availability and distribution.

See related [EG_AS] for additional details of the effects of vessel presence on aerofauna.

[SS_N] Noise

Baseline monitoring equipment, such as drones, transportation vessels, and aircraft can disturb aerofauna. Noise disturbance affects aerofauna behaviour and alters the quality of habitat [SS_N_Disturb]. Many behavioural responses are possible due to noise, including startle, escape or flushing, and abandonment (Brown, 1990; Schwemmer et al., 2011). Escape and abandonment can increase energetic cost and risk of predation, especially for breeding birds (Brown, 1990). Consistent noise disturbance can mask vocal communication between individuals or auditory cues from predators and/or prey species, leading to consequences for species survivability and reproduction, as well as habitat availability and distribution.

See [RM_N] for a detailed description of the effects of noise disturbance on birds.

Construction Phase

The construction phase of OSW energy development introduces many habitat-altering stressors. Activities take place over a smaller period of time compared to the operations phase, with stressors having less temporal emphasis for generated effects on aerofauna. However, it is worth noting that many effects from construction-related stressors still affect habitat quality, aerofauna behaviour, and can cause direct mortality. The potential effects due to stressors are discussed irrespective of the magnitude associated with them.

[SP] Site Preparation

Preparing an OSW farm site includes any activity that is required prior to installing the offshore infrastructure at the OSW project site. This could include preparation of the seabed to install turbines, platforms, and array and export cables. Specific sub-activities are icebreaking, excavation, and pile driving, which require specialized jack-up vessels. Construction activities vary between OSW energy development projects and many activities and sub-activities are site-specific.

Four main stressors were identified related to construction phase site preparation:

- Artificial Lighting
- Artificial Structures
- Habitat Loss
- Noise

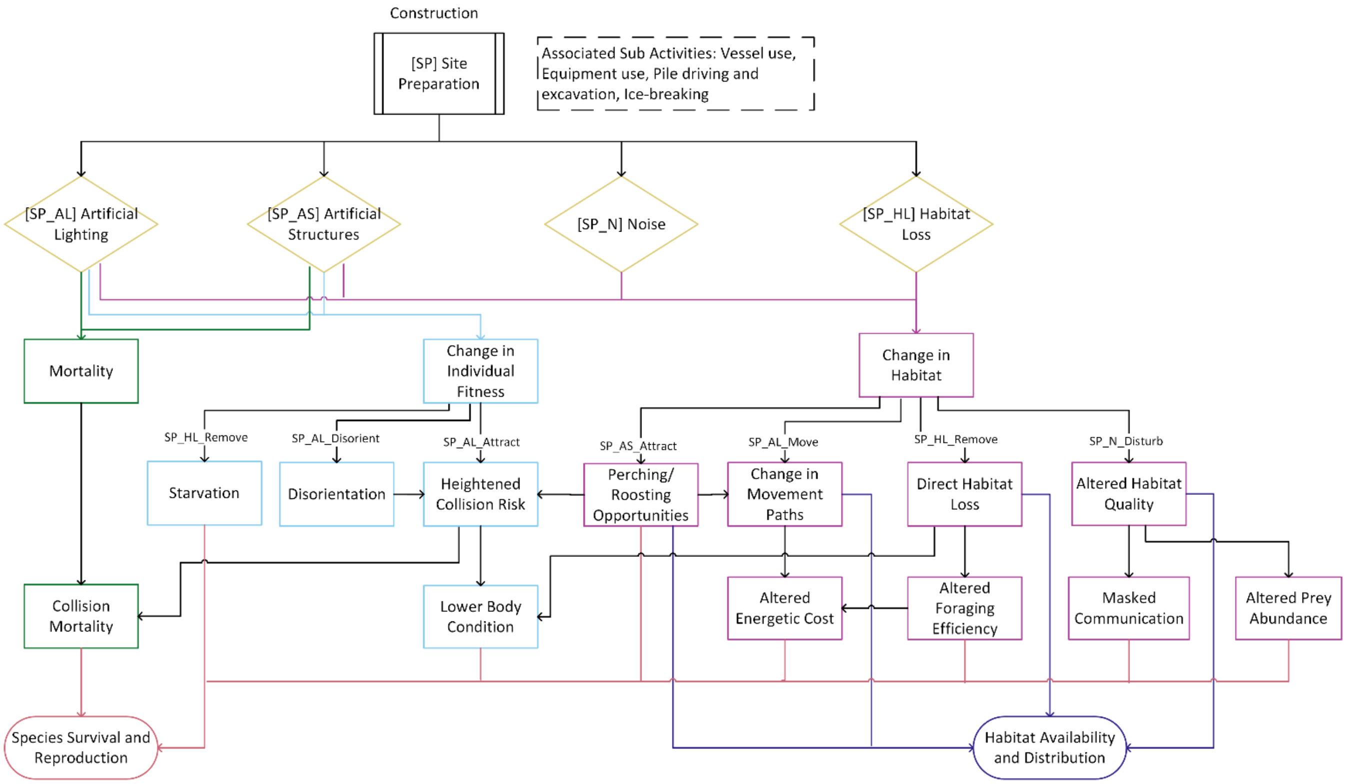

Figure 3: Pathways of Effects model for site preparation during the Offshore Wind Energy Development construction phase.

[SP_AL] Artificial Lighting

Vessels, aircraft, and equipment needed to complete construction sub-activities require artificial lighting. Artificial lighting can cause attraction or avoidance responses from aerofauna [See SS_AL]. Attracted aerofauna is vulnerable to collision mortality or injury [SP_AL_Attract]. Aerofauna that avoid OSW areas in response to artificial lighting can cause disorientation, altering movement pathways and energetic cost [SP_AL_Move; SP_AL_Disorient].

[SP_AS] Artificial Structures

Specialized vessels equipped with cranes and jacks are required for offshore site preparation. As previously discussed, vessels alter aerofauna behaviour and movement pathways and can increase risk of collision mortality or injury and energetic cost [SP_AS_Attract]. These effects would result in consequences to species survivability and reproduction, and habitat availability and distribution. See related pathway [SS_AS].

[SP_HL] Habitat Loss

Ice-breaking, pile driving, and excavation activities cause direct habitat loss by removing aerofauna habitat within the OSW farm area. Vulnerable species to disturbance such as sea ducks and seabirds can depart from, or not enter, their preferred or important habitats due to these activities (Hemery et al., 2024). This mainly affects foraging habitat for marine bird species. Ice-breaking to further facilitate site preparation activities causes direct habitat loss as some seabird species rely on sea ice, or polynyas, for foraging during breeding and/or migration [SP_HL_Remove] (Mallory et al., 2019; Stirling, 1997). Direct habitat loss can alter energetic cost depending on species-specific factors (Masden et al., 2010). Altered energetic cost affects habitat availability and distribution and species survivability and reproduction.

See [EG_HL] for a related description of the effects of habitat loss on aerofauna.

[SP_N] Noise

Marine vessels and equipment needed for site preparation introduce frequent noise from drilling and excavation. Noise disturbance can affect aerofauna communication and breeding success by changing habitat quality [SP_N_Disturb]. Noise disturbance related to construction activities changes habitat for aerofauna. Lower foraging activity has been recorded inside OSW farm areas during construction (Harwood et al., 2017). Pile driving specifically can indirectly affect foraging habitat for piscivorous birds species due to lower prey availability (Perrow et al., 2011a). Consequences of noise disturbance can have measurable effects on species survival and reproduction and habitat distribution and availability.

See [RM_N] for a related description of the effects of noise on birds.

[II] Infrastructure Installation

This activity includes sub-activities in the offshore environment. Offshore infrastructure includes array and export cables, substation platforms, and wind turbines. Constructing the wind turbines mostly takes place on land (Defingou et al., 2019).

Three main stressors were determined for installing infrastructure associated with OSW farms:

- Artificial Structures
- Habitat Loss
- Noise

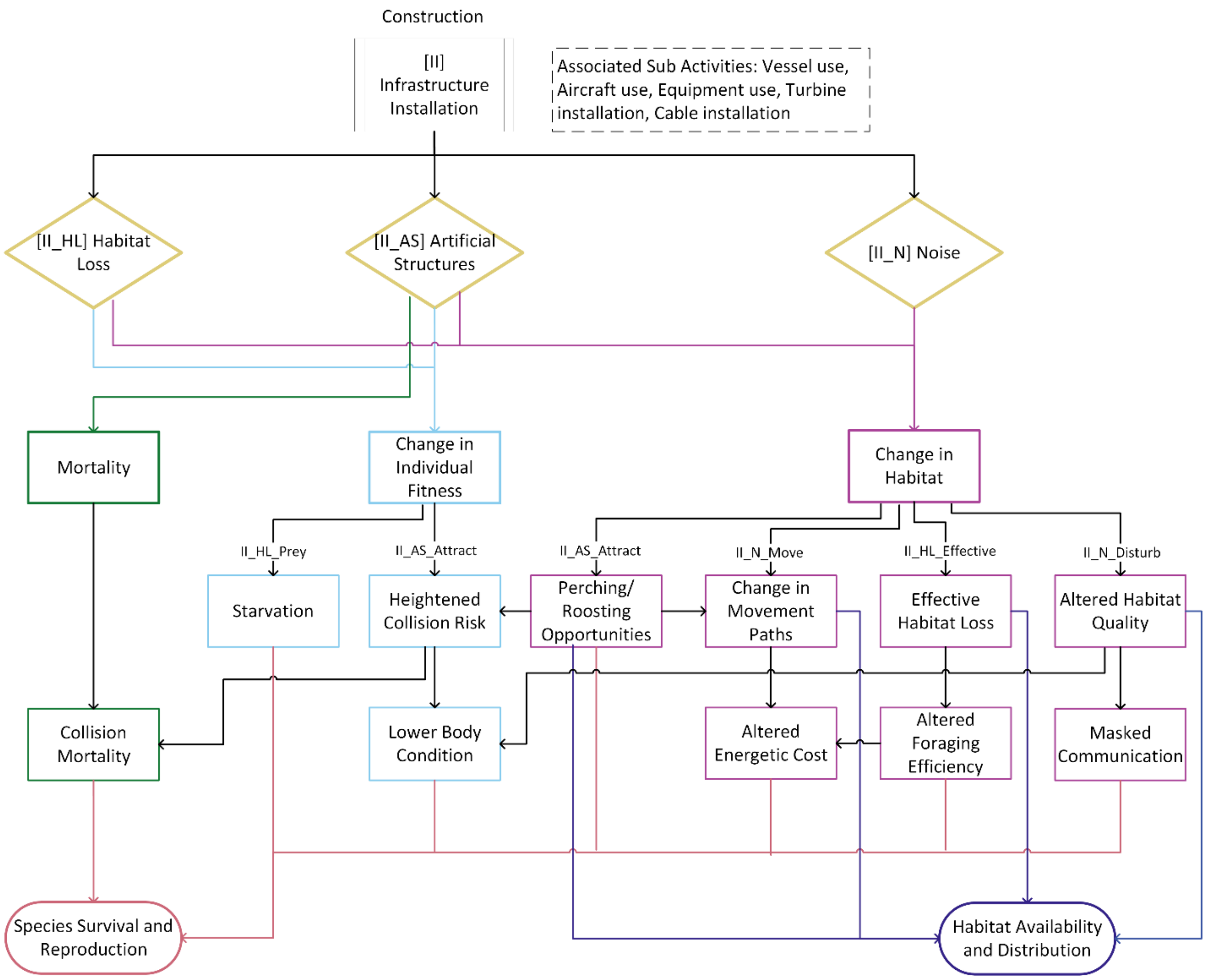

Figure 4: Pathways of Effects model for infrastructure installation during the Offshore Wind Energy Development construction phase.

[II_AS] Artificial Structures

During construction, large, specialized vessels are required for turbine, foundation, and scour protection installation. Depending on project constraints, many vessels can be used with features such as cranes and jack-ups allow for lifting offshore wind components and installing foundations (Perrow, 2019). Vessels can attract certain species and increase collision risk that could cause injury or mortality, with measurable effects to both endpoints [II_AS_Attract].

See [RM_AS] and [EG_AS] for a related description of the effects of artificial structures on aerofauna.

[II_HL] Habitat Loss

Specialized vessels and equipment increase human disturbance in the offshore environment. Installing turbine foundations and scour protection further alters foraging habitat quality which can cause habitat loss (Drewitt & Langston, 2006). As discussed previously, construction activities affect foraging habitat by lowering prey availability for marine birds [II_HL_Prey] (Perrow et al., 2011a). Subsequent energetic consequences due to habitat loss can alter breeding success and in severe cases, cause mortality [II_HL_Effective]. The effects of habitat loss caused by infrastructure installation can affect both measurable endpoints.

See [EG_HL] for a related description of the effects of habitat loss on aerofauna.

[II_N] Noise

Noise disturbance caused by installing wind turbines, foundations, and scour protection can displace aerofauna or affect individual fitness and impede communication [II_N_Disturb]. Aerofauna behavioural responses can disrupt movement and breeding success. Nest departure in response to noise disturbance can have further negative implications for breeding success and negative energetic consequences (Brown, 1990; Mooney et al., 2019; Ortega, 2012).

See [RM_N] for a related description of the effects of noise on birds.

Operation Phase

The operation phase is the most researched phase of OSW energy developments, offering the most knowledge of effects on aerofauna and associated habitat. It includes activities centered around electricity generation, which involves sub-activities such as turbine presence and moving rotor blades. It also includes regular maintenance activities that require vessels or aircraft to access OSW energy sites for inspections. Various equipment is needed to ensure the upkeep of turbines, cables, and platforms in the harsh marine environment.

[EG] Electricity Generation

The main activity associated with offshore wind (OSW) energy development is electricity generation. Rotor blades on each wind turbine are in motion while actively generating electricity. Energy is then transported to the onshore electrical grid through sub-sea export cables. The scope of this section is stressors related to the offshore features for generating electricity at an operational OSW energy development.

The stressors identified with potential effects to aerofauna species and habitat include:

- Artificial Lighting
- Artificial Structures
- Habitat Loss

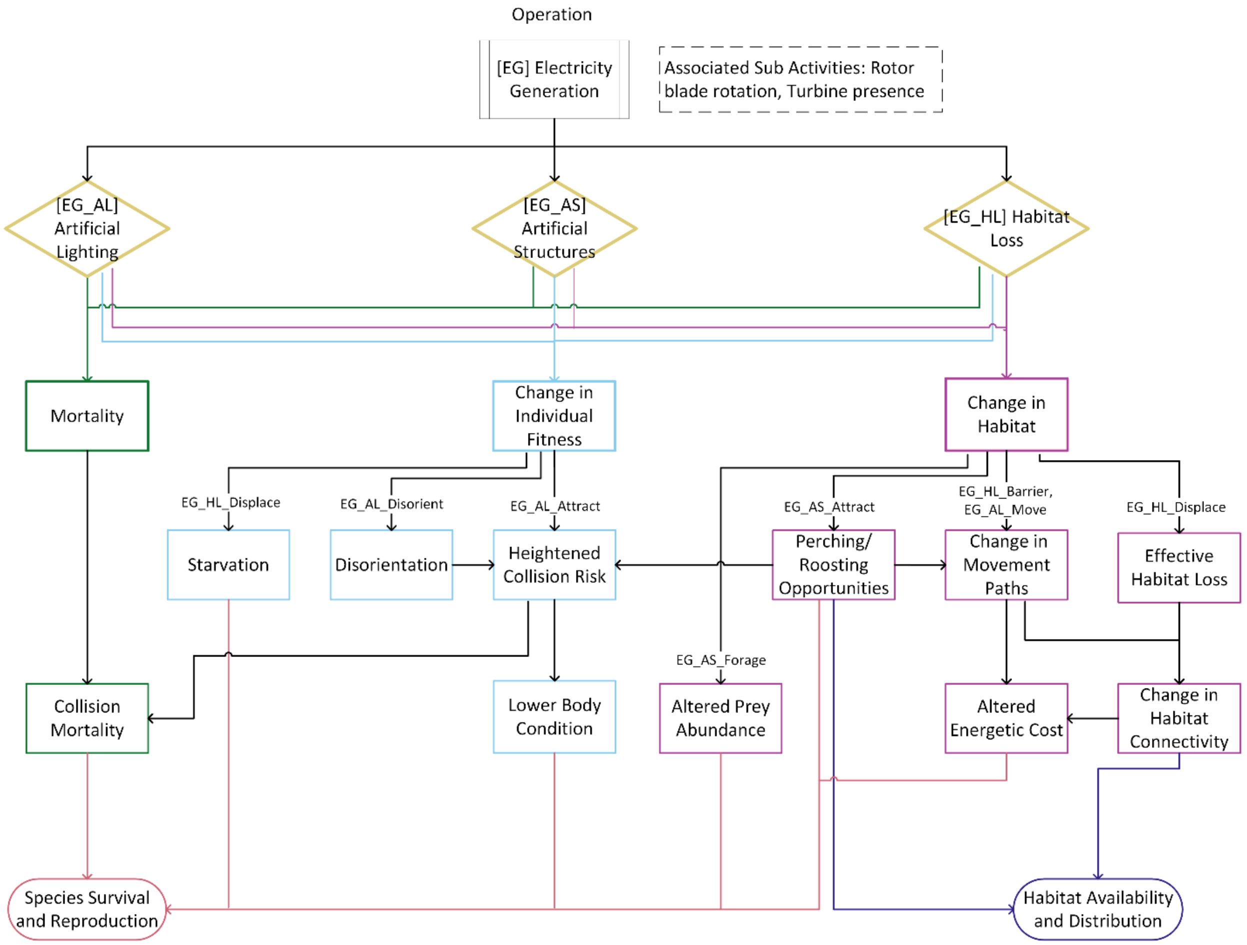

Figure 5:Pathways of Effects diagram for electricity generation during the Offshore Wind Energy Development operation phase.

[EG_AL] Artificial Lighting

OSW energy development introduces a source of artificial light in the offshore environment. Wind turbines are required to have lighting during operation for safe navigation as specified in Chapter 12 of the Canadian Aviation Regulations (2016). As such, platforms and turbines associated with OSW energy development will become sources of artificial lighting in the marine environment, which can trigger a behavioural response (e.g., attraction, avoidance) and leave individuals more susceptible to mortality through indirect pathways (personal communication, R. Thomas, July 22, 2024). Depending on the response, collision mortality and injury can occur. The extent of the effect depends on species, weather conditions, the lighting characteristics, and other factors.

Attraction is the primary cause-effect pathway associated with artificial lighting as aerofauna can be attracted to lit platforms in the offshore environment [EG_AL_Attract]. Especially at night, seabirds and nocturnal migrants can be attracted to artificial light (Hüppop et al., 2006; Montevecchi, 2006; Rebke et al., 2019). Maturity can also influence attraction, as 94% of petrels attracted to artificial lighting were fledglings and high incidences of stranded individuals aligned with fledgling flights of Leach's Storm-Petrels (Gjerdrum et al., 2021; Rodríguez & Rodríguez, 2009). However, avoidance (e.g., negative phototaxis) is also a potential response in petrels [EG_AL_Avoidance] (Syposz et al., 2021).

Attraction to OSW energy developments can directly lead to mortality from collision with the turbine, offshore platforms, or rotor blades [EG_AL_Attract]. Indirect effects can change body condition by stranding or disorienting individuals, resulting in increased energetic cost [EG_AL_Move] (Deakin et al., 2022; Gjerdrum et al., 2021; Hüppop et al., 2006; Marques et al., 2014; Montevecchi, 2006). Based on observations from oil and gas and research platforms, birds may circle aimlessly around artificial light sources until exhaustion, which increases the likelihood of collision mortality or injury [EG_AL_Disorient] (Hüppop et al., 2006; Ronconi et al., 2015). Changes in migration routes or ideal habitat distributions through attraction can have negative consequences on aerofauna survivability and reproduction if it results in substantial numbers of collisions or increases to energetic cost. Further, these changes directly influence habitat availability and distribution as connectivity between habitat locations is altered.

The extent of both direct and indirect effects are dependent on fog, wind speed, cloud cover, lunar phase and star visibility altering the degree of visibility offshore (Deakin et al., 2022; Gjerdrum et al., 2021; Hüppop et al., 2016; Montevecchi, 2006; Rebke et al., 2019). For example, when it is cloudy with no other sources of illumination, birds can be attracted to lit offshore platforms [EG_AL_Move].

Additionally, characteristics of the lighting can attract more nocturnal migrating aerofauna (Rebke et al., 2019; Voigt et al., 2018). For instance, current U.S. guidance on lighting at OSW farms recommends flashing yellow light for intermediate and peripheral structures, and only directing light where it is needed (BOEM, 2021). Birds can be more attracted to continuous blue, green or white light, and less attracted to blinking blue, yellow, or green light (Rebke et al., 2019). Similarly, some migratory bat species can be more attracted to red LED light compared to warm-white LED light, independent of hunting opportunity and dependent on species behaviour (Voigt et al., 2018). Contrasting bright light and the surrounding dark marine environment could heighten attraction and subsequent collision mortality or injury [EG_AL_Attract] (Solick & Newman, 2021). The characteristics discussed above are not meant to be an exhaustive list for attraction to artificial light. Attraction may differ depending on species, habitat, environmental conditions, and other factors (R. Ronconi, personal communication, July 15, 2024).

Foraging habitat quality can change due to artificial lighting, indirectly affecting aerofauna species survivability and reproduction and habitat availability and reproduction [See EG_AS_Forage]. Aerofauna prey species can also be attracted to light (C. Gjerdrum, personal communication, July 16, 2024; Lieske et al., 2020). Habitat enhancing effects are discussed in the next section.

For nocturnal migrating birds, movement pathways can lead to less direct effects on mortality and individual fitness. Though the mechanisms are less clear, migratory stopovers of nocturnal migrating birds are influenced by artificial lighting (McLaren et al., 2018). Nocturnal migrating birds can potentially become lost at sea or more susceptible to predation due to increases in energetic cost, and migration can be short-stopped, forcing a longer migration or altering paths (R. Thomas, personal communication, July 22, 2024). As additional effects are possible through attraction to artificial light, indirect mortality pathways can affect aerofauna species survivability and reproduction and habitat availability and distribution.

Species that might be vulnerable to attraction to artificial lighting include petrels (Leach's Storm-Petrel, Cory's Shearwater) Herring Gull, migrating shorebirds, nocturnal migrating landbirds and migratory bats (Gjerdrum et al., 2021; Hüppop et al., 2016; Rebke et al., 2019; Rodríguez & Rodríguez, 2009; Schwemmer et al., 2023; Voigt et al., 2018).

[EG_AS] Artificial Structures

Once operational, OSW energy developments include site-specific numbers of wind turbines that introduce anthropogenically engineered structures, or artificial structures, into the marine environment (Bishop et al., 2017). The cause-effect pathways linked to artificial structures are dictated by behavioural responses (e.g. avoidance or attraction) of aerofauna species to developments and habitat-mediated changes. Visual disturbances from artificial structures can lead to behavioural responses that change habitat use (Drewitt & Langston, 2006; Fox et al., 2006). As previously discussed, lighting on the structures can invoke attraction to structures [See EG_AL]. Similarly, attraction can be due to effects (e.g. artificial reef effect) introduced by the structures themselves. Flight paths can be modified by attraction to OSW farm areas [This section], or alternatively, barriers to movement through avoidance [See EG_HL] (Bishop et al., 2017; Drewitt & Langston, 2006; Fox et al., 2006).

Mortality can occur from the visual disturbance of offshore artificial structures that can attract aerofauna (Drewitt & Langston, 2006). Individuals may collide with the supporting structure, the blades (stationary or rotating), or be swept up in the wake of the rotor blades (Fox et al., 2006; Hüppop et al., 2006, 2016). Collisions can directly cause mortality or injury [EG_AS_Collision] based on species-specific, site-specific (e.g. siting location, prey availability) and development-specific factors (e.g. OSW farm configuration, lighting), as well as poor weather conditions that affect visibility (Hüppop et al., 2006; Marques et al., 2014). Lower body condition may also lead to mortality by affecting the ability to fly to other habitat areas to forage or recover.

For species-specific collision vulnerability models, additional readings that may be useful: (Furness et al., 2013).

Each wind turbine requires scour protection at the base. Scour protection is usually in the form of rock piles placed on the seabed around the turbine, introducing a hard substrate into a previous soft sediment habitat (Fox & Petersen, 2019; Perrow, 2019). The hard substrate from scour protection and turbine foundations creates an artificial reef effect by introducing new and replacement benthic habitat (Bishop et al., 2017; Degraer et al., 2020; Perrow, 2019; Wilson & Elliott, 2009). Post-construction monitoring of offshore wind farms in the Belgian North Sea show evidence of improvements to the benthic habitat, with higher biomass and epibenthos density observed (De Backer et al., 2020; in Degraer et al., 2020).

OSW turbines change foraging and resting habitat for marine birds. Within OSW farm areas, they can potentially increase prey availability and foraging habitat for aerofauna, particularly seabirds [EG_AS_Forage] (Degraer et al., 2020; Dierschke et al., 2016; Drewitt & Langston, 2006; Williams et al., 2024). For instance, it has been documented that some gull species have taken advantage of increased prey abundance due to the artificial reef effect (Vanermen et al., 2015). As well, species with strong attractance indicate changes in prey availability might enhance foraging opportunities (Dierschke et al., 2016). Conversely, since artificial reefs alter community structure, effective habitat loss could occur if prey availability decreases from competition or loss of preferred prey [EG_HL_Displace]. Above the ocean surface, turbines introduce new habitat for perching or roosting [EG_AS_Attract] (Ahlén et al., 2009; Dierschke et al., 2016). Although offshore structures can provide additional resting and foraging habitat, it can lead to negative effects by heightening collision mortality or injury.

[EG_HL] Habitat Loss

OSW energy developments introduce habitat loss as a stressor that can affect aerofauna. Behavioural responses to the turbines cause habitat loss through avoidance responses that can cause displacement and barriers to movement. In flight, bird species avoid wind farm areas at multiple spatial scales (micro, meso, macro) (Cook et al., 2018). Micro and meso avoidance are smaller scale avoidance behaviours that take place inside OSW farm areas, such as evasion of rows of turbines within the wind farm and last-second escape of turbine blades, respectively (Cook et al., 2018; May, 2015). Macro avoidance is the focus of the discussion as it relates to habitat loss and displacement (Cook et al., 2018; May, 2015). This section focuses on the subsequent habitat loss due to displacement and barriers to movement due to OSW farm areas. Displacement from ideal habitat distributions refers to changes in habitat use and habitat loss (May, 2015; Williams et al., 2024). The effects that change habitat due to attraction from artificial structures (e.g., artificial reef effect, improving habitat and prey abundance) are described in the preceding section.

Displacement removes birds from ideal foraging distributions, causing effective habitat loss that can have energetic consequences [EG_HL_Displace] (Fox et al., 2006; Garthe et al., 2023). In the worst case, habitat loss can lead to starvation due to compounding energetic cost and shift to less optimal foraging habitat preventing effective foraging (Garthe et al., 2023). Species-specific behaviour influences the extent of the effect and can often be related to vessel-related stressors during maintenance activities (Dierschke et al., 2016; Furness et al., 2013). See RM_AS for vessel-related pathways.

Additionally, OWS energy developments can impede connectivity between habitats used for foraging, nesting, breeding, and resting through the barrier effect [EG_HL_Barrier] (Fox & Petersen, 2019). Some species avoid OSW energy development areas entirely (macro avoidance) due to disturbance caused by the turbines, as recorded by studies at operational developments (e.g. Garthe et al., 2023; Vanermen et al., 2015). Consequently, turbines can act as barriers to movement between habitat locations (e.g. movement between feeding and nesting areas) that can alter energetic cost (Exo et al., 2003; Masden et al., 2009).

Since essential habitats for foraging, breeding, and migrating become fragmented (barrier effect) or completely lost (displacement), it can have consequences for aerofauna species survivability and reproduction by reducing habitat availability and distribution. These pathways reduce connectivity between populations that can hinder reproduction by causing extinction and loss of genetic diversity (Cristofari et al., 2019). Such effects of habitat loss from OSW farm electricity generation will be long term and can vary between species.

[RM] Routine Maintenance

OSW energy development operations include routine maintenance such as regular inspections or repairs. Associated sub-activities that are involved with maintenance are the use of vessels, aircraft, or other construction equipment depending on the nature of the specific maintenance undertaking. For instance, if a turbine is malfunctioning, the equipment required will vary depending on the diagnostic results of the issue. Routine maintenance is a necessary activity to ensure that all components of the development are functioning according to operational requirements. The scope of this section is constrained to components introduced in carrying out maintenance at OSW energy development sites.

The stressors identified that can lead to potential effects to aerofauna species and habitat include:

- Artificial Lighting
- Artificial Structures
- Noise

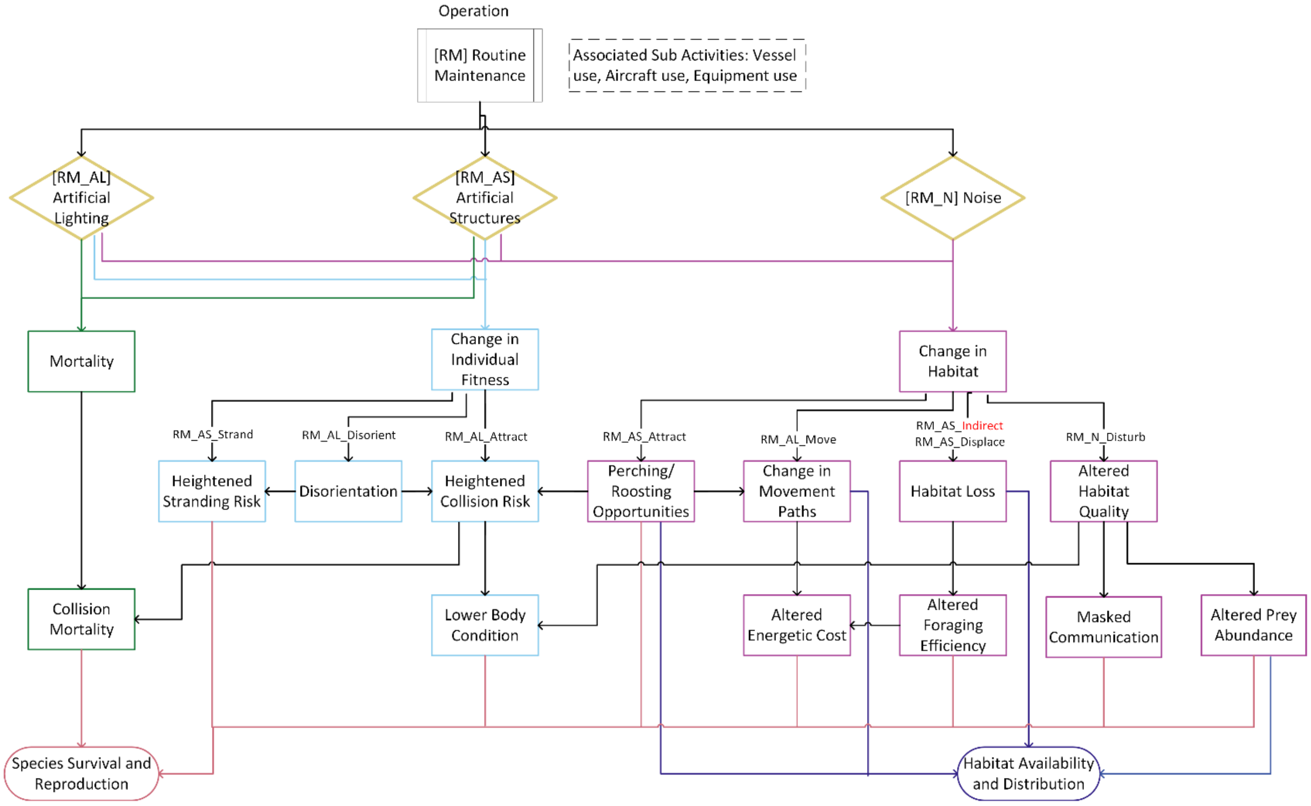

Figure 6: Pathways of Effects diagram for routine maintenance during the Offshore Wind Energy Development operation phase.

[RM_AL] Artificial Lighting

Maintenance or repairs to OSW energy infrastructure such as turbines, scour protection, and cables, will require vessels, aircraft, and equipment. Vessels and aircraft are equipped with lighting for navigation and safety purposes. Additionally, completion of work could require additional lighting if visibility is poor. Because birds can be attracted to artificial lighting in the offshore environment, it can cause mortality and changes in individual fitness by enhancing collision risk and energetic cost by displacing or disorienting aerofauna from movement paths [RM_AL_Attract; RM_AL_Move] (Gjerdrum et al., 2021; Montevecchi, 2006).

See [EG_AL] for a related description of the effects of artificial lighting.

[RM_AS] Artificial Structures

Maintenance could involve inspection or replacement of turbine or cable components. Equipment such as cranes for lifting and vessels for transportation of components, equipment, and personnel may be required depending on the type and extent of maintenance. Shipping and vessels, as artificial structures, temporarily disturb the marine environment, which can become a regular occurrence in and around OSW energy developments. Studies of the disturbance effects of shipping on birds often classify shipping as a source of human disturbance (e.g., Schwemmer et al., 2011). Since disturbance caused by vessels is not often attributed solely to one stressor, the cause-effect pathways between vessels and effects on aerofauna have been incorporated into artificial structures.

Aerofauna may respond to artificial structures with attraction or avoidance behaviours that are species-specific. By affecting bird behaviour, disturbance can alter energy intake, breeding success, and survival [RM_AS_Displace] (Goodship & Furness, 2022). It can also indirectly change behaviour through habitat loss (Goodship & Furness, 2022).

Mortality or injury due to collision can occur from increased vessel traffic around OSW energy developments. With vessel-related activities, aerofauna behaviour around vessels can increase collision and stranding risk (Gjerdrum et al., 2021). Stranding itself can lead to mortality [RM_AS_Strand] (R. Ronconi, personal communication, July 15, 2024). Introduced roosting or feeding opportunities on offshore vessels and maintenance equipment can attract bats and enhance the risk of collision mortality or injury [RM_AS_Attract] (Ahlén et al., 2009; Solick & Newman, 2021). Similar risk of collision and subsequent mortality or injury can occur in seabirds, as they are also attracted to marine vessels (Montevecchi, 2006).

Vessels disturb aerofauna, particularly seabirds and sea ducks, in the marine environment. Responses to disturbance include displacing species present in the vicinity of the vessel (e.g., foraging, swimming or resting), which can cause temporary habitat loss, especially if the displacement leads to less ideal foraging habitat [RM_AS_Displace] (Dehnhard et al., 2019; Leemans & Collier, 2022; Schwemmer et al., 2011). Foraging efficiency may decrease and the energetic cost can increase due to displacement (Schwemmer et al., 2011). Vessels also cause energetically costly escape behaviours such as taking flight or diving that reduce foraging and resting time (Dehnhard et al., 2019; Jarrett et al., 2018; Larsen & Laubek, 2005; Mendel et al., 2019; Schwemmer et al., 2011). Escape behaviour is influenced by the speed of the vessel and wave conditions (Jarrett et al., 2018). Such behaviours lead to changes in habitat use and can negatively affect individual fitness. It may also cause mortality due to lower foraging efficiency to make up for additional energetic cost (Schwemmer et al., 2011).

Species that may be highly sensitive/vulnerable to disturbance by vessels include Long-tailed Duck, Red-breasted Merganser, Red-throated Loons, Common Scoter, Greater scaup, Common Eider, Common Goldeneye, Sandwich Tern, and Roseate Tern (Dehnhard et al., 2019; Goodship & Furness, 2022; Jarrett et al., 2018; Larsen & Laubek, 2005; Mendel et al., 2019). Alcids may also be sensitive to vessel disturbance based on observations of Black guillemot behaviour (Ronconi & Clair, 2002).

While marine bird foraging habitat is affected by behavioural responses, vessels can directly affect the quality of habitat [RM_AS_Indirect]. Waves from the wakes of moving vessels can destroy nests along shorelines, reducing breeding success as documented in freshwater systems (Allen et al., 2008). Although the extent of these effects is unknown in marine environments, foraging efficiency may also increase in coastal areas from wave-induced mixing that can dislodge benthic prey (Gabel et al., 2017).

[RM_N] Noise

Equipment, vessels, or aircraft that may be required for OSW energy development maintenance can introduce noise in the marine environment. Noise disturbance can affect birds by changing the quality of the surrounding habitat. The preceding section (Stressor 2: Artificial Structures) describes the effects of vessel disturbance on aerofauna in the marine environment which can introduce noise. This section will focus on describing the PoE solely attributed to noise from maintenance activities through vessel, equipment, and aircraft use.

Noise disturbance can affect aerofauna. Seabirds, particularly Red-breasted Merganser, can be displaced from foraging habitat by vessel noise (Jarrett et al., 2018). Breeding seabirds respond to aircraft noise at various volumes, ranging from head turning to flying away (Brown, 1990). Noise from passing aircraft or equipment use can potentially interfere with auditory cues (e.g., communication between individuals or predator detection) and breeding success, especially in environments where ambient noise levels are typically much quieter and temporal exposure is extended [RM_N_Disturb] (Iasiello & Colombelli-Négrel, 2023; Ortega, 2012; A. B. Smith et al., 2023).

Similarly, underwater noise from maintenance activities may cause displacement and elicit behavioural responses from aerofauna. Depending on the frequency of the noise, seabirds may elicit various responses to underwater noise (Anderson Hansen et al., 2020; Mooney et al., 2019). Potential effects could be similar to other types of disturbance from OSW energy development maintenance and operation, such as displacement from habitat and reduced foraging area. However, noise disturbance may decrease body condition by evoking physiological effects such as increasing heart rate, changing hormone levels, and weight loss (Ortega, 2012). As described in the construction phase, indirect effects of underwater noise may alter prey availability for piscivorous birds (Perrow et al., 2011a).

Decommissioning Phase

Once an OSW farm reaches its operational end-of-life, it is either re-powered to extend its operational life or the decommissioning phase begins. With decommissioning, the OSW farm is closed, and activities focus on dismantling infrastructure. Similar to the rest of an OSW project, decommissioning is site-specific and decisions are highly influenced by commercial monitoring and maintenance costs, environmental, and social values (Kerkvliet & Polatidis, 2016).

As few OSW farms have been decommissioned, one of the main challenges of this phase is the “leaving in situ dilemma” (Hall et al., 2022; Hernandez Carrascal et al., 2021; Topham et al., 2019). Two options exist: the infrastructure is fully or partially removed (Fowler et al., 2020; Hernandez Carrascal et al., 2021; Kerkvliet & Polatidis, 2016; Topham et al., 2019). Recent discourse on the subject argues that removing infrastructure completely would produce more unnecessary disturbance to the marine environment, mainly to the artificial reefs on the offshore infrastructure (Fowler et al., 2020; Topham et al., 2019).

Some of the potential effects of decommissioning OSW farms are analogous to the construction phase (Hall et al., 2022). However, any habitat-mediated changes that occur during the operation phase are excluded if the decommissioning PoE is not considered individually. Therefore, full and partial wind farm removal decommissioning activities consider additional PoEs related to the anticipated activities of each decommissioning phase scenario.

[FR] Full Removal

All infrastructure, including turbines, scour protection, foundations, and cables, will be disassembled and transported to onshore recycling and waste management facilities that increases trucking traffic. Depending on the type of turbines foundations, explosives might be used to remove turbines foundations (Kerkvliet & Polatidis, 2016). The associated sub-activities are infrastructure removal, vessel use, and equipment use.

Four main stressors were identified with the full OSW farm removal activity:

- Habitat Loss
- Noise
- Artificial Lighting
- Artificial Structures

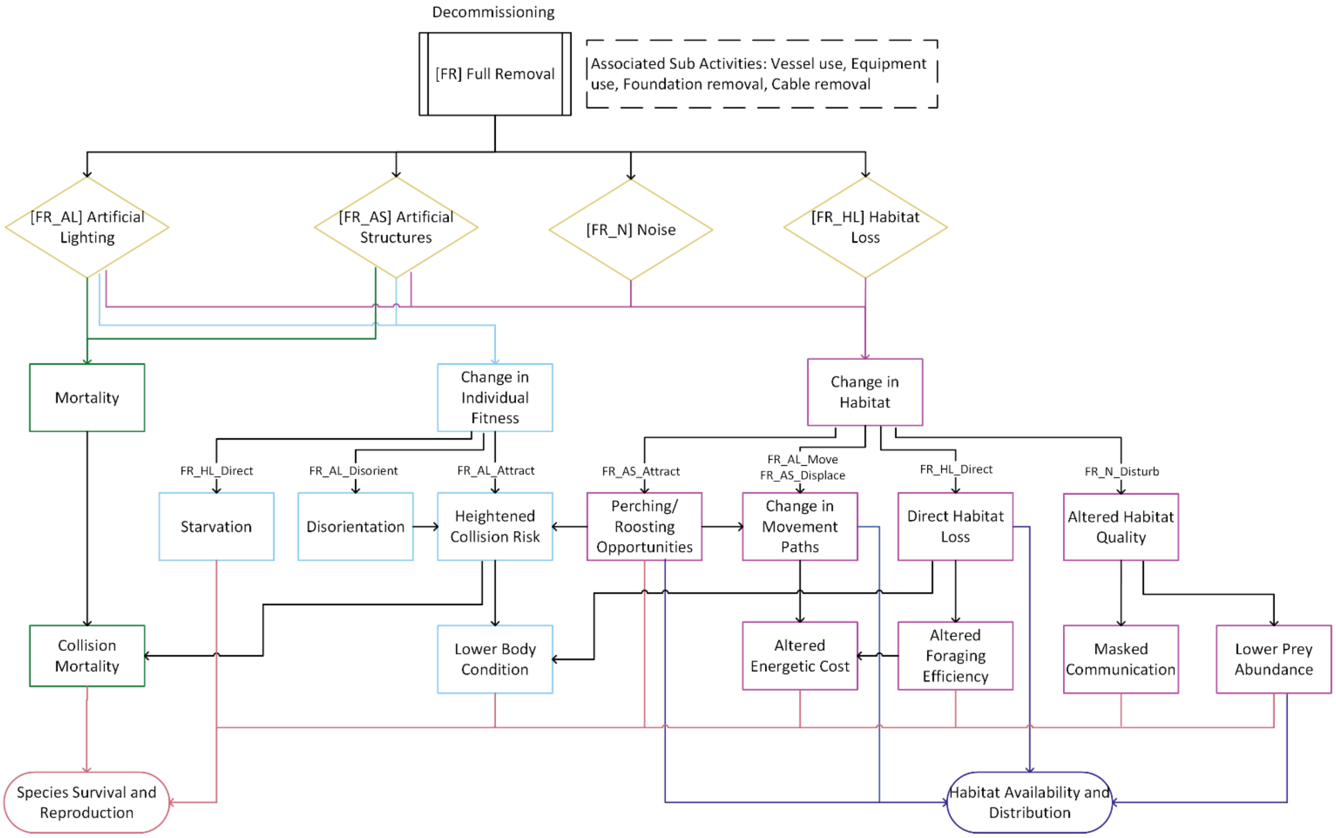

Figure 7: Pathways of Effects diagram for full removal during the Offshore Wind Energy Development decommissioning phase.

[FR_HL] Habitat Loss

Full wind turbine removal can cause potential habitat loss for marine birds. Full removal of the wind farm can alter aerofauna habitat quality and distribution which can displace species from ideal habitat distributions. It is assumed that after remaining operational for 20-30 years, habitat disrupted by the installation of turbines and platforms will have colonized and become productive foraging habitat for marine birds (Dierschke et al., 2016; Smyth et al., 2015). Full removal of the structures (e.g. turbine foundations, platforms, cables, scour protection) will cause direct habitat loss for benthic marine species (Hall et al., 2022; Topham et al., 2019). Depending on habitat use, effective habitat loss can occur as a result of lower prey abundance [FR_HL_Direct]. Structure removal or reintroducing commercial fisheries into OSW farm areas could both contribute to effective habitat loss (Fowler et al., 2020; Hall et al., 2022). This can result in changes in energetic cost, breeding success, and in extreme cases, mortality. Habitat loss can affect both measurable endpoints.

[FR_N] Noise

Offshore, linked to aircraft, vessel and equipment use during infrastructure removal. Effects would be similar to the construction phase and depend on the species-specific sensitivity to vessel disturbance (Hall et al., 2022). Noise can affect both measurable endpoints [FR_N_Disturb]. See [RM_N]for a related description of the effects of noise on birds.

[FR_AL] Artificial Lighting

Artificial lighting from aircraft, vessel and equipment use for offshore infrastructure removal is similar to the cause-effect pathways described in the construction phase. The complete removal of offshore platforms and turbines should eliminate aerofauna attraction and avoidance effects. Lighting from vessels may attract and disorient birds and increase risk of collision mortality, injury, and risk of stranding [FR_AL_Attract; FR_AL_Disorient] depending on the duration of increased vessel traffic to decommission the OSW farm. Altered movement paths and subsequent energetic cost [FR_AL_Move] would also depend on the duration of the full removal decommissioning. Artificial lighting can affect both measurable endpoints. See [EG_AL]for a detailed description of the effects of artificial lighting on aerofauna.

[FR_AS] Artificial Structures

The cause-effects pathways will be similar to artificial structure use described in the construction phase. However, with the removal of wind turbines and other platforms, attraction to these structures should diminish, lowering collision mortality or injury over the long-term (Hall et al., 2022). The energetic cost due to vessel attraction and avoidance [FR_AS_Attract; FR_AS_Displace] should further be reduced once the full removal decommissioning is complete as the OSW site may not require regular monitoring. Vessel disturbance can affect aerofauna species survivability and reproduction and habitat availability and distribution. See [RM_AS] for a detailed description of the effects of vessel activity on aerofauna.

[PR] Partial Removal

Partial OSW farm removal involves a degree of infrastructure remaining in the OSW farm area. The blades, nacelle and hub are removed from the wind turbines and the monopile is cut to a minimum height of 25 meters above the foundation (Fowler et al., 2020; Kerkvliet & Polatidis, 2016). Explosives are less preferred for partial foundation removal since most of the foundation will remain (Kerkvliet & Polatidis, 2016).

Sub-activities will be based on site-specific factors (e.g. floating or monopile foundation turbines) and regulatory requirements. It is unclear if any monitoring will be needed since legislation for decommissioning requirements are incomplete and variable for OSW farms abroad (Fowler et al., 2020). It is assumed that regular monitoring of the infrastructure left offshore will be required to ensure that no further environmental effects occur in the decommissioning of the OSW farm. Thus, sub-activities include routine monitoring, as well as infrastructure removal.

Four main stressors were identified from the partial OSW farm removal activity:

- Noise
- Artificial Lighting
- Artificial Structures

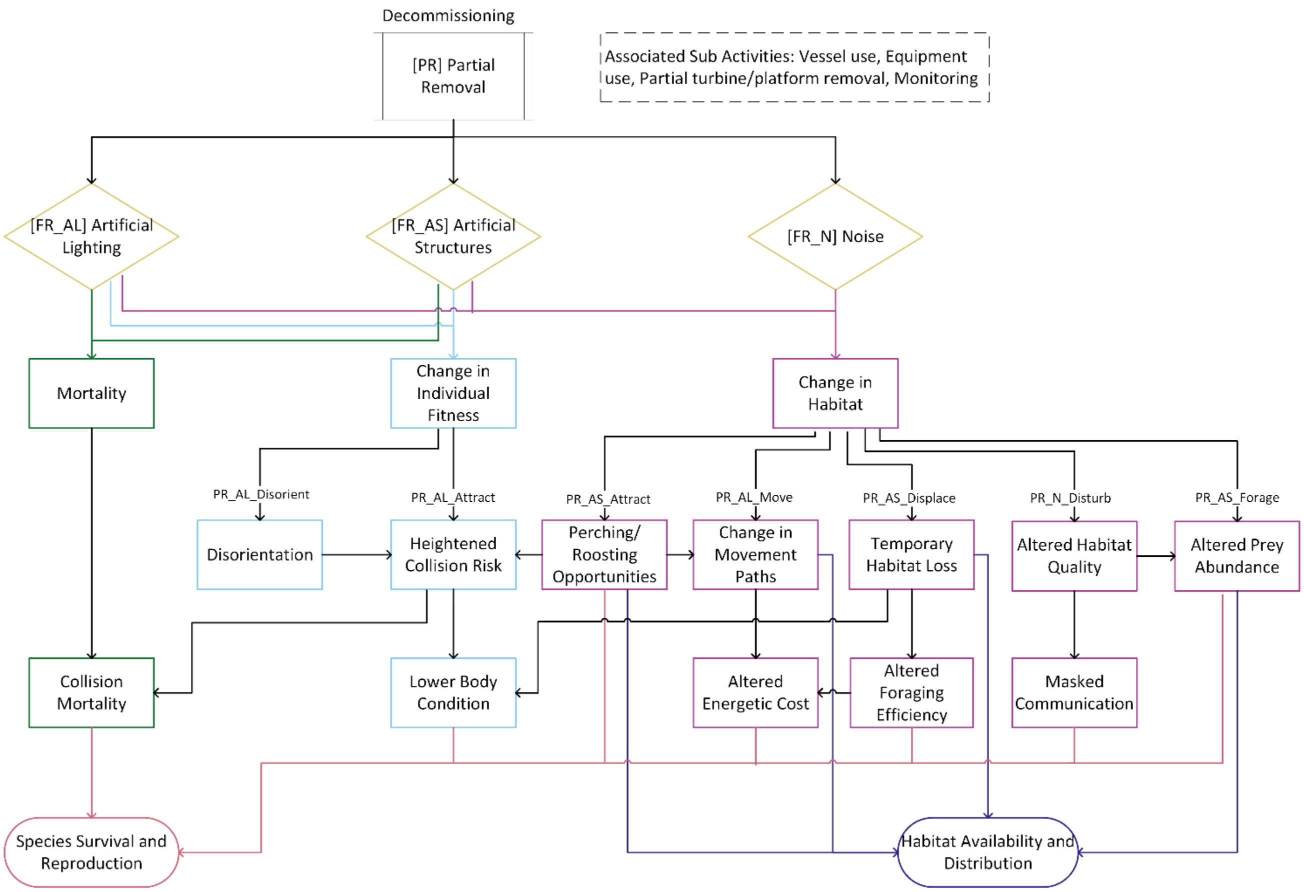

Figure 8: Pathways of Effects diagram for partial removal during the Offshore Wind Energy Development decommissioning phase.

[PR_N] Noise

The noise disturbance cause-effect pathway due to vessel and equipment use will be similar to the construction phase. Both measurable endpoints will be affected [PR_N_Disturb]. See [RM_N] for a related description of the effects of noise on birds.

[PR_AL] Artificial Lighting

The cause-effect pathways for artificial lighting in the partial removal will be similar to the construction and operation phases [See EG_AL]. Depending on the height of the remaining infrastructure, lighting may be required for navigational safety and will be associated with monitoring vessels. Attraction to lighting alters movement pathways and energetic cost [PR_AL_Move]. It also increases collision or stranding risk with monitoring vessels or collision risk with remaining infrastructure [PR_AL_Attract; PR_AL_Disorient].

[PR_AS] Artificial Structures

The cause-effect pathway of artificial structures in partial removal will be similar to the construction and operation phases [See SP_AS], depending on the size and height of the remaining infrastructure. Foundation transition pieces and marking buoys can offer roosting or perching opportunities for aerofauna [PR_AS_Attract] (Harwood et al., 2017). Although, the behavioural response to these structures would depend on the height of the remaining structures above water and whether buoys are required.

Partial removal of artificial structures can present habitat restorative opportunities [PR_AS_Forage]. For instance, some initiatives are aimed at preserving the artificial reefs created by OSW structures, or "renewables-to-reefs" (Smyth et al., 2015). Further eco-engineering opportunities may also use the habitat-creating potential of hard substrates, placing oyster tables and reef balls that can enhance the artificial reefs introduced by OSW farms (Smyth et al., 2015; see The Rich North Sea: Oysters and artificial reefs for underwater nature restoration | Van Oord).

Accidents Associated with All Phases

Many unintended stressors can be introduced during OSW energy development.

The following stressors were identified for accidents during all phases of OSW energy development:

- Chemical Hazard Introduction
- Physical Hazard Introduction
- Invasive Species Introduction

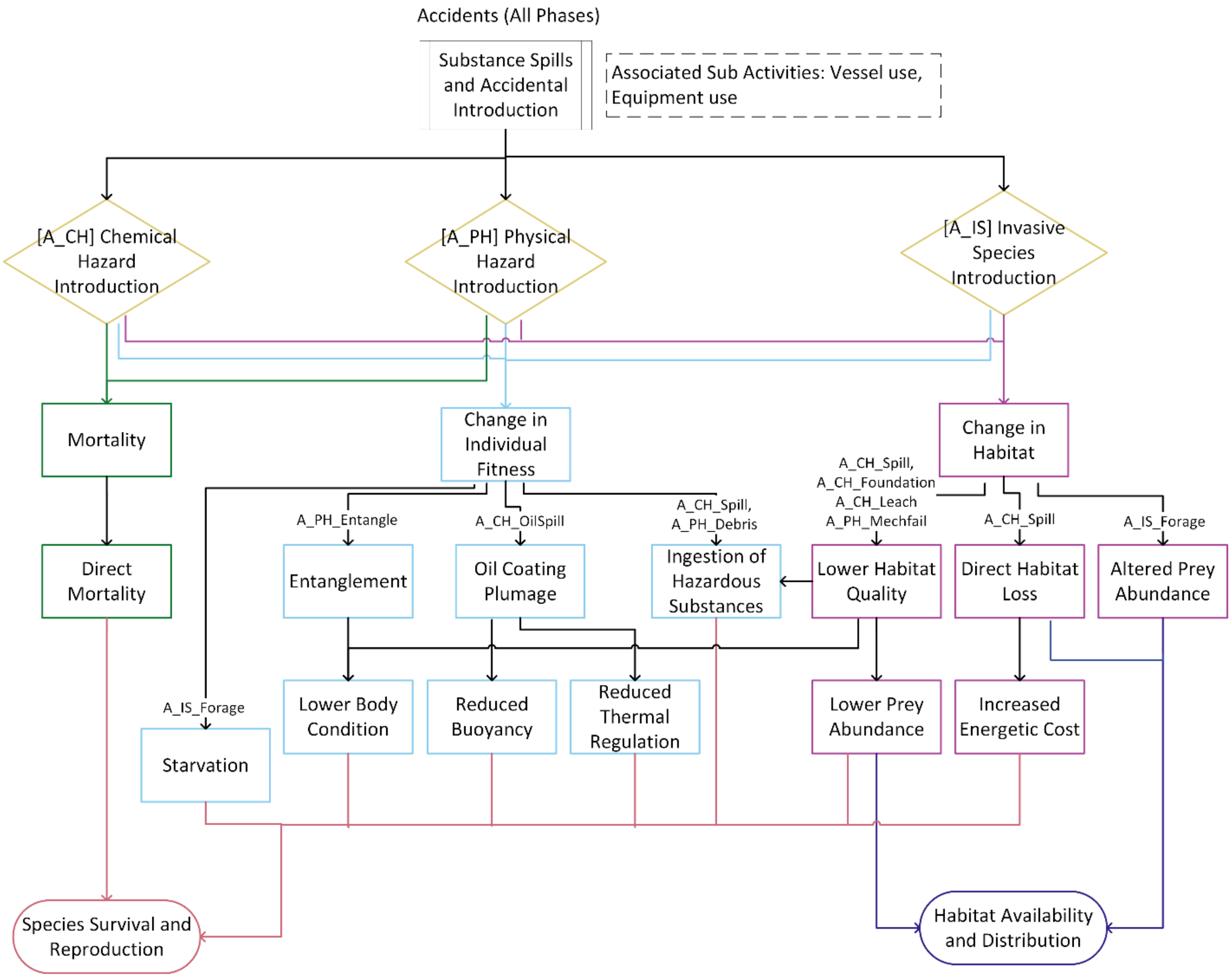

Figure 9: Pathways of Effects diagram for potential accidents during all phases of Offshore Wind Energy Development.

[A_CH] Chemical Hazard Introduction

Pre-Construction, Construction, Operation, and Decommissioning

Accidents may occur during all phases of OSW energy development. Offshore activities require fuel powered machinery, vessels, vehicles, and aircraft during all phases to transport equipment, personnel, infrastructure, and materials, prepare wind farm sites, maintain turbines and cables, and remove infrastructure once end-of-life is reached. Leaks or spills are possible from machinery during use. Vessels can be a source of chemical introduction if not managed properly.

Chemicals introduced to the environment directly lower habitat quality which can cause mortality and lower individual fitness in marine birds [A_CH_OilSpill]. Oil on plumage affects thermoregulation and can lead to hypothermia (Jenssen, 1994). Chemicals coating plumage lowers body condition and can cause mortality as oiled birds are less buoyant and prone to drowning (D. W. Smith & Herunter, 1989). Additionally, oiled birds spend more time preening and cleaning their plumage than feeding, increasing energetic cost and weakening birds further (D. W. Smith & Herunter, 1989). Toxic effects from ingestion due to preening or feeding on contaminated prey can directly cause mortality and lower breeding success (Jenssen, 1994). Chemical spills affect both endpoints depending on the chemical, seasonality, spatial extent, and weather conditions that influence the trajectory of the spill (Benjarano et al., 2013).

Operation-specific considerations

Operational OSW farms can introduce an additional chemical introduction pathway as infrastructure must sustain the harsh offshore conditions for long periods of time. The most common chemical types used at operational wind farms are lubricants, fuels, biocides, corrosion inhibitors, paints, and grouts, with a low release likelihood for most (Perrow, 2019). Electrical service platforms and wind turbine generators use and store petroleum, mineral oils, glycols, and sulfuric acid (Benjarano et al., 2013). Chemical diffusion and spills can affect foraging habitat quality by lowering water quality in the vicinity of the event [A_CH_Spill]. As well, lower water quality can lead to toxic effects from ingestion. As discussed previously, altering habitat quality can affect aerofauna species survival and reproduction by changing individual fitness and causing mortality.

Decommissioning-specific considerations

The full removal option involves heavy disruption of the OSW area. It is the reverse of the construction phase activities, which re-disturbs the offshore environment. Unlike in the partial removal option, chemical hazards are introduced by removing turbine foundations [A_CH_Foundation]. Foundation removal disturbs the drill cutting piles beneath and around the footings of the jacket of the turbine (Fowler et al., 2020). It directly reduces the quality of habitat for aerofauna and can lead to effects on aerofauna species abundance and distribution.

In partial decommissioning, some potential effects could arise from leakage from structures left over time [A_CH_Leach] (Fowler et al., 2020). For instance, flaking paint and corrosion from remaining foundations could potentially lower water quality (Van Maele et al., 2023). Both habitat distribution and availability and species survivability and reproduction could experience effects for marine birds.

[A_PH] Physical Hazard Introduction

Improperly managed solid waste from vessels and equipment can be introduced to the marine environment at any phase of OSW energy development. Pollution from plastics, metals, and other debris directly lowers habitat quality, causing mortality and lowering individual fitness. The rate of plastic ingestion in seabirds increases as more plastic is introduced in the marine environment, lowering individual fitness and causing mortality due to starvation or digestive tract blockage [A_PH_Debris] (Lavers et al., 2014; Wilcox et al., 2015). Entanglement from released debris can lower body condition or cause mortality [A_PH_Entangle]. Many seabird and coastal bird species are at risk of entanglement with plastic discarded in offshore foraging habitat (Ryan, 2018). As a result of habitat pollution, entanglement and ingestion effects can cause changes in aerofauna species survivability and reproduction, and habitat availability and distribution.

Operation-specific considerations

Accidents during the operation phase may include unplanned mechanical failure. Structural components of the turbines are subject to additional offshore conditions including corrosion, physical loading, biological attack, and mechanical damage that can result in structural failure (Price & Figueira, 2017). Although requirements exist to prevent mechanical failure, unplanned events can, and have, occurred. Mechanical failure resulted in sharp debris from turbine components washing ashore at Vineyard Wind (O'Laughlin, 2024). As discussed above, sharp fiberglass shards and debris can lower breeding and foraging habitat quality, although the environmental implications of the debris are not yet not clear (Arcadis US Inc, 2024). Exposure to the debris can injure and lower body condition or cause direct or indirect mortality for aerofauna [A_PH_MechFail].

Decommissioning-specific considerations

Some considerations specific to the decommissioning phase exist. Foundation removal can require using explosives in full removal decommissioning. Aerofauna mortality can be caused directly if individuals were present nearby at the time of detonation. For aerofauna nearby, startle and escape responses can change habitat use and remove aerofauna from habitat [See SP_N]. It leads to direct habitat loss for aerofauna. Both measurable endpoints are affected. Partial removal decommissioning can lower body condition or mortality of diving seabirds due to secondary entanglement could be caused by ghost fishing gear caught in the remaining infrastructure [A_PH_Entangle] (Benjamins et al., 2014; Maxwell et al., 2022).

[A_IS] Invasive Species Introduction

All phases of OSW energy development require vessel use for transportation to and from the offshore site. Invasive species can potentially cause changes to foraging habitat for aerofauna in two ways. First, vessels and associated ballast water discharge can be vectors for invasive species introduction to new locations, especially if they are brought in from foreign ports (Gillespie, 2007; ICF, 2020; Johannessen & Macdonald, 2009). Second, turbine foundations can become "stepping stones" for invasive species colonization

(Boehlert & Gill, 2010). Analogous with the artificial reef effect, foundations can serve as invasive species vectors, especially for benthic species with free-floating larvae that can travel long distances in the water column (ICF, 2020).

Changes to foraging habitat, and consequently, prey or forage availability for marine birds and bats are possible effects of invasive species introduction [A_IS_Forage]. Invasive species can alter ecosystem structure and function as they outcompete native species for common resources (Bax et al., 2003). Monitoring has documented some evidence of invasive species colonization in artificial reefs at OSW farms and invasive insects at onshore wind farms (Coolen et al., 2020; Dudek et al., 2015). However, how invasive species affect aerofauna prey remains unknown. Ultimately, mechanisms of invasive species introduction may lead to effects on marine bird species survivability and reproduction by potentially altering foraging habitat quality. Habitat availability and distribution can also be affected by invasive species establishment.

Knowledge Gaps

Although OSW energy development is in its infancy in Canada, a wealth of information is available from international experiences with OSW construction and operation. The results of many years of monitoring at operational OSW farms indicate that effects are highly variable depending on aerofauna species' behaviour, site characteristics, and environmental conditions, among other factors. This emphasizes the critical need for before studies (e.g. baseline surveys during project planning) and during/after studies (e.g. continuous monitoring during operation) throughout the entire duration of OSW energy development.

The construction and operation phases of offshore wind projects are most often the focus of assessments, and less is known about the pre-construction and decommissioning phases. Many reviews exist discussing the effects to aerofauna and possible pathways to these effects during operation, but less is known about effects to aerofauna generated during pre-construction and decommissioning. Activities during these phases are highly project- and site-specific, and as such, less information is available on the potential cause-effect pathways of relevant activities. Since not many OSW farms have been decommissioned, this phase should be considered as early as possible during OSW energy development to help address information gaps.

Contrasting to the wealth of knowledge available on offshore artificial structures (e.g. collision and displacement effects), other stressors and species are less studied in the context of OSW energy development. A clear linkage to OSW energy development activities and stressors is less readily available for noise, vessel-related activities, and artificial lighting, leading to a reliance on related offshore industries and activities for knowledge (Isaacman & Daborn, 2011). For instance, offshore industries, such as oil and gas and commercial shipping, offer insight on the cause-effect pathways for artificial lighting and artificial structures (vessels) for marine birds. Moreover, the scope of stressor-specific knowledge for the offshore is highly focused on attraction and avoidance of several marine bird, migratory bat, and passerine species. Information gaps remain for terrestrial and shorebird bird species related to pathways of effects from attraction or avoidance of offshore turbines and platforms.

Finally, it is difficult to discern potential effects that arise due to habitat loss, as species will have varying levels of adaptability to displacement-caused habitat loss (e.g. prey requirements, site fidelity, etc.) (Defingou et al., 2019). Many studies report displacement and avoidance at variable spatial scales, however, direct effects due to habitat loss are less documented related to OSW energy development. Definitions and classifications of OSW effects can differ substantially, especially for complex interactions involving multiple stressors, such as avoidance and displacement (Hemery et al., 2021). It is critical to define effects at relevant scales using similar definitions.

Research concerning other stressors related to OSW energy development is ongoing. Emerging evidence indicates that terrestrial birds might be at risk of effects from OSW artificial structures (Robinson Willmott et al., 2023). Moreover, while the effects of noise on individual fitness is evident for marine mammals and fish, researchers are only just beginning to shed light on the mechanism of hearing underwater for marine birds (e.g. Anderson Hansen et al., 2020). Scarce evidence for electromagnetic fields (not considered in the PoE) exists for birds and bats, though it is highly researched in marine mammals and fish.

Further, the analysis presented demonstrates that OSW energy development can indirectly influence individual fitness and mortality through habitat-mediated changes. Pathways for indirect effects such as altered prey abundance are still understudied (Croll et al., 2022; Garthe et al., 2023; Perrow et al., 2011b). Though it is evident that OSW energy development is likely to alter energetic cost, the consequence of these cause-effect pathways on individual fitness is still largely unknown (Burger et al., 2011). Indirect processes might prove to be more informative to quantifying population-level responses (Defingou et al., 2019).

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