Managing the effects of offshore wind farm noise on marine animals: Lessons learned after 25 years of research in Europe and beyond

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ABSTRACT

Offshore wind is expanding worldwide, including in Australia, where the industry is still emerging. Over 25 years, Europe has shown that underwater noise from surveying, construction, operation, and decommissioning can affect marine life from mammals to fishes and invertebrates. Policy has evolved from fragmented mandates to more science-based regulation, though international methodologies remain poorly standardised. The EU Marine Strategy Framework Directive represents one attempt to address impacts at the ecosystem scale. Research has shifted from descriptive studies to more quantitative approaches, yet population-level effects remain uncertain and will likely require multi-pressure frameworks. Innovation has advanced mitigation technologies and monitoring tools, but the 'animal's perspective' is still underappreciated: effective management must begin with the sensitivities of the animals themselves.

1 INTRODUCTION

The early 21st century marked a global shift from fossil fuels to renewables, with offshore wind becoming a cornerstone of the new energy mix. In the EU, early leaders such as Denmark, the UK, and Germany quickly faced a critical challenge: underwater noise from turbine construction and operation and its effects on marine mammals, fish, and invertebrates. By the late 1990s, knowledge of underwater noise impacts was limited and virtually nothing was known about offshore wind. The central question was how to expand offshore wind while safeguarding the marine environment from this poorly understood threat.

This paper reflects on how the question has been addressed in the EU and beyond over the past 25 years of offshore wind. I have been fortunate to work both as a consultant responsible for EIAs and as a government advisor. Drawing on this experience, I examine three interconnected pillars: Policy, Science, and Innovation (Fig. 1). While the paper aims at objectivity, I also offer personal reflections intended to stimulate discussion. From this review, I outline guiding principles for sustainable management of offshore wind, with relevance for the emerging industry in Australia.

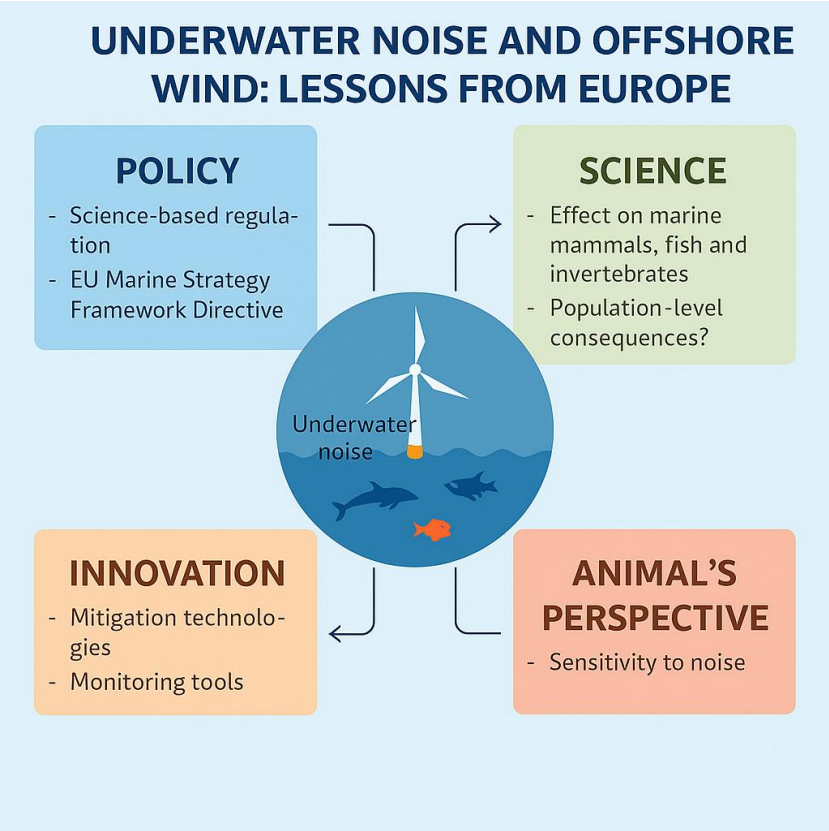

Figure 1 Three pillars - Policy, Science, and Innovation - converge into guiding principles for the sustainable management of offshore wind farm noise.

2 POLICY

From the outset, ambitious offshore wind plans in EU member states had to be reconciled with strict nature conservation law. Early studies in Denmark and the UK showed that pile driving produced substantial effects on harbour porpoises (*Phocoena phocoena*), the most common marine mammal in northern Europe (Tougaard et al. 2003; Nedwell et al. 2003; Madsen et al. 2006; Thomsen et al. 2006). These findings triggered alarm under the EU Habitats and EIA Directives. Regulators needed to act, but an early progress was constrained by vague mandates, fragmented authority, and limited scientific knowledge.

Experience across Europe and beyond shows that regulation only makes progress when it is coherent, unambiguous, and science-based. Coherence means that when multiple authorities are involved, their roles fit together without contradiction. Unambiguous means that developers know exactly what is required for a permit. Science-based means that the process is grounded in evidence, not assumption.

It is key that regulators actively manage scientific input into the permitting process. In Germany, the responsible agency BSH (Federal Maritime and Hydrographic Agency) developed binding standards for offshore wind EIAs, covering monitoring, assessment, and reporting (BSH 2013). These were compiled with expert groups organised by topic. Having been part of this process, I found it time-consuming but ultimately valuable: it forced compromise on details and gave the standards high scientific credibility and broad acceptance.

Another lesson is that effective governance depends less on institutional design than on competence, coordination, and keeping ecology at the centre. At the European level, the Marine Strategy Framework Directive (MSFD) requires Member States to achieve “Good Environmental Status” (GES) and to report every six years. Of its 11 descriptors, one addresses underwater noise. Task Group 11, of which I was a member, advised policymakers to design noise indicators based on biologically relevant problems, displacement from impulsive noise and masking from continuous noise, at ecosystem scales (Tasker et al. 2010; JRC et al. 2014). On this basis, the EU adopted two indicators in 2010: one for impulsive sounds such as piling, and one for continuous low-frequency sound including operational offshore wind farm noise.

The methodological framework was intended to complement, not replace, EIAs. In practice, the same experts who developed national EIA criteria often contributed to the MSFD, which should have created a coherent bridge between national and EU-wide noise management. Under this paradigm EIAs provide immediate management tools, while the MSFD establishes common indicators and, more recently, EU-wide thresholds for impulsive and continuous noise (Borsani et al. 2023; Sigray et al. 2023).

From my involvement in the MSFD process from the beginning, I conclude that the framework addresses the right issues and is vital for transboundary management. The challenge is to keep methodologies practical and avoid drifting into academic exercises. EIA criteria still vary considerably between member states, with little standardisation (Thomsen and Verfuss 2019).

In sum, governance must remain coherent, unambiguous, and centred on biology, with regulators actively managing scientific input and translating it into frameworks that are both biologically meaningful and workable.

3 SCIENCE

A benchmark in the science of offshore wind noise came with the MaRVEN project (Thomsen et al. 2015), the first EU-wide synthesis of evidence about two decades after the first wind farms were built. MaRVEN confirmed that pile driving caused large-scale behavioural responses in harbour porpoises and possibly seals, while operational noise was of far lower concern. It also showed that noise effects are not limited to marine mammals: fishes are affected as well, underlining that underwater noise must be treated as a cross-taxa issue.

MaRVEN identified three key research priorities:

- Effects of pile driving on fish and invertebrates of commercial or conservation importance, and whether such effects translate to population-level consequences.
- Effects of pile driving sound on baleen whales.
- Sediment vibration during construction.

Subsequent research addressed these areas (Technische Universität Hamburg-Harburg et al. 2015; Roberts and Elliott 2017; Iafrate et al. 2016; Hawkins et al. 2021; Jézéquel et al. 2022), but significant gaps remain in all three of them.

At the international level, research has shifted from project-specific impacts to population- and ecosystem-level questions. Conceptual breakthroughs include the Population Consequences of Disturbance framework (PCoD; Pirotta et al. 2018), its extension to multiple stressors (PCOMS; Tyack et al. 2022), and proposals to embed noise into broader multi-pressure frameworks that reflect ecological reality (Thomsen and Popper 2024).

The key lesson is that science is evolving from describing responses to modelling interactions between noise and other pressures at population and ecosystem scales. Multi-pressure approaches remain largely conceptual, but they must inform the next generation of project-based EIAs. The challenge ahead is to develop workable approaches for integrating cumulative and multi-stressor assessments into decision-making. Offshore wind has both generated the demand and supplied resources for this shift, leaving a legacy of methods and frameworks to drive the next phase.

4 INNOVATION

Alongside policy and science, technological and methodological innovation has reshaped how offshore-wind underwater noise is measured, modelled, monitored, assessed, and mitigated. Key developments include:

- Sound source definition & scaling to large monopiles: Modelling and measurement campaigns now cover monopiles exceeding 10 m in diameter (Technische Universität Hamburg-Harburg et al. 2015; von Pein et al. 2022; 2024).
- Particle motion (PM) during piling: First field measurements using novel PM sensors (MaRVEN) demonstrated that PM is detectable by fishes and that mitigation can substantially reduce PM (Sigray et al. 2022).

- Operational-noise risk assessment: Early extrapolations, assuming a linear link between turbine size and noise emissions, predicted behavioural effects at considerable ranges (Tougaard et al. 2020; Stöber and Thomsen 2021). Later, larger datasets showed no such relationship (Betke and Bellmann 2023; Bellmann et al. 2024).

- Piling criteria: The first quantitative comparison of exposure criteria, with and without mitigation, demonstrated how choice of metric/criterion alters predicted effects (Stöber and Thomsen 2019).

- Population-level tools: Agent-based and related models now simulate movements and behaviour under noise exposure, linking individual responses to population consequences (Nabe-Nielsen et al. 2014; Mortensen et al. 2021).

- Technical mitigation: Substantial advances have been made in construction equipment (e.g. hydro hammers), noise abatement technologies, and low-noise foundation designs (Merchant & Robinson 2020). In principle, mitigation measures must be aligned more closely with the animal's perspective - the ecological and physiological sensitivities of organisms to specific noise exposures (Popper et al. 2020).

5 CONCLUSIONS

Australia has a unique opportunity to build on Europe's 25 years of experience in managing offshore wind noise. By embedding systems thinking, adopting regulation that is coherent, unambiguous, and science-based, assessing noise within a multi-pressure context, and designing mitigation that reflects ecological and physiological sensitivities, Australia can avoid early missteps and establish sustainable offshore wind practices from the outset.

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