Workshop Report – Determining variations in the body condition of harbour porpoises and use for modelling the effects of disturbance

19 – 21 November 2025, Utrecht University

Workshop jointly funded by Ecowende and the Dutch Government

Authors: Floor Heinis (HWE), Meik Verdonk (RWS), Lonneke IJsseldijk (UU), Eva Schotanus (UU), Magda Chudzinska (SMRUC), Cormac Booth (SMRUC) & Marije Siemensma (MS&C-RWS)

Final report: 21 September 2026

This report is to be cited as:
Heinis, F., M. Verdonk, L. IJsseldijk, E. Schotanus, M. Chudzinska, C. Booth & M. Siemensma (2026). Workshop Report – Determining variations in the body condition of harbour porpoises and use for modelling the effects of disturbance. Report HWE 26.206.

HWE

Contents

1 Introduction 4
1.1 Background 4
1.2 Goals of the workshop 4
1.3 Report structure 5
2 Introduction to the workshop and scope 6
2.1 Setting the scene 6
2.2 General outline of the workshop 7
2.3 Post – mortem demonstration 8
3 Part I: Knowledge exchange on parameters as input for modelling 9
3.1 Life history of harbour porpoises 9
3.1.1 Life history and PCoD – Lonneke IJsseldijk 9
3.1.2 On methods to determine age in harbour porpoises – Sanne Hessing 10
3.1.3 Age- and seasonal-related changes in harbour porpoises – Magnus Wahlberg 11
3.1.4 General discussion/conclusions on life history 13
3.2 Harbour porpoise energetics 13
3.2.1 Harbour porpoise energetics – Ron Kastelein 13
3.2.2 Small bodies in cold waters: harbour porpoise energetics and effects of disturbance – Laia Rojano-Doñate 15
3.2.3 General discussion on harbour porpoise energetics 17
3.3 Harbour porpoise body condition and health 17
3.3.1 Seasonally slim: body condition variability in harbour porpoises from the North Sea – Eva Schotanus 17
3.3.2 Diagnosing emaciation vs starvation at Utrecht University – Andrea Gröne .. 18
3.3.3 General discussion on presentations by Schotanus & Gröne 19
3.3.4 Physiology and pathology – Andrew Brownlow 20
3.3.5 Using molecular techniques to find novel markers – Davina Derous 21
3.3.6 General discussion on (parameters for) body condition and health 23
4 Part II: Informing iPCoD and application in KEC 23
4.1 Introduction 23
4.2 Importance of pathways affecting vital rates by exposure to underwater noise ... 24

4.2.1 Noise effects on porpoises – Magnus Wahlberg 24
4.2.2 Opinions of experts on relative importance of impact pathways 26
4.3 Key factors for modelling effects of disturbance – Cormac Booth 27
4.4 Improving understanding of Population Consequences of Disturbance – Magda Chudzinska 30
4.5 Potential future developments 32
4.6 Mapping ideas for future work 34
5 General discussion and outlook 35
5.1 To DEB or not to DEB 35
5.2 Outlook 36
5.2.1 Research on harbour porpoises at Utrecht University 36
5.2.2 Model development 36
5.2.3 Framework for Assessing Ecological and Cumulative Effects (KEC) 37
5.2.4 Other ongoing and planned research in the Netherlands 38
6 References 42
ANNEXES 47
Annex 1 Workshop participants 48
Annex 2 Results of polls 49
Annex 2.1 Answers to questions sent in advance of workshop 49
Annex 2.2 To DEB or not to DEB 51
Annex 3 Ideas for future work 52
3.1 Short term priorities 52
3.2 Medium term priorities (until end of 2027) 54
3.2 Long term priorities (after 2027) 58

1 Introduction

1.1 Background

In November 2025, a group of 30 international experts from science, conservation and policy met at the Faculty of Veterinary Medicine of Utrecht University for a three-day workshop focusing on the condition of harbour porpoises (*Phocoena phocoena*) in relation to offshore wind energy. The workshop was prompted by the research being conducted in the context of the Ecowende windfarm under construction (Hollandse Kust West, 50 km offshore IJmuiden). Part of this research is a 4-year PhD project by Utrecht University on body condition, reproduction and health of harbour porpoises. One of the first objectives of the project was to bring together the most up-to-date knowledge on these topics by means of a dedicated workshop with international experts. The knowledge and insights shared during the workshop were thought to be useful for discussions on how population models assessing the consequences of disturbance for harbour porpoises could be improved, especially by leveraging data gained during post-mortem examinations of stranded and bycaught harbour porpoises. Therefore, the programme was designed in such a way to facilitate this.

The expertise of the participants was fairly evenly distributed as can be seen in Figure 1-1 (see Annex 1 for a list of participants). The majority (69%) was engaged in research and the remainder in policy (10%) and industry/consultancy (21%), respectively. The participants came from the Netherlands (69%), the United Kingdom (14%), Denmark (10%) and Sweden (7%).

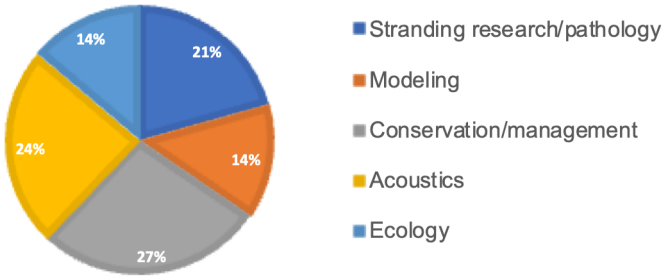


Figure 1-1 Expertise of participants (n = 29)

1.2 Goals of the workshop

Results from post-mortem examinations of stranded harbour porpoises can provide valuable information to consider when modelling the effects of disturbance from underwater sound. This information could be used more than is currently the case. To date, these data have been mainly collected to determine the cause of death of stranded harbour porpoises and to establish the extent to which the animals die as a result of human activity. Modellers, pathologists, ecologists and policy officers were, therefore, brought together in the workshop to get:

- A mutual understanding of each other's research fields and/or information needs by
- Discussing how data from post-mortem studied harbour porpoises can be integrated into population models assessing the consequences of disturbance. And, more specifically, how to improve use of the (interim) Population Consequences of Disturbance (PCoD) models and the models overall.

1.3 Report structure

This report summarizes the results of a workshop, held in November 2025 in the Netherlands, the background and purpose of which are described in sections 1.1 and 1.2. Chapter 2 contains an introduction to the workshop, its set-up and a brief description of the post-mortem demonstration of a stranded porpoise, which preceded the workshop. Chapter 3 summarizes the presentations, grouped according to the topics Life history (3.1), Energetics (3.2) and Harbour porpoise condition and health (3.3), including the subsequent discussions. Chapter 4 contains the summaries of presentations on the importance of different pathways through which underwater noise can influence the vital rates (4.2), key factors in modelling the effects of disturbance (4.3), the (modelled) influence of disturbance on different life stages and sensitivity to variations in input parameters (4.4), views of participants on future developments (4.5) and ideas for future work (4.6). Finally, chapter 5 summarizes the outcome of the discussion on which of the two versions of the iPCoD model is preferable (5.1) and an overview of current and future research related to the Dutch part of the North Sea (5.2). The report concludes with a list of references and three annexes.

Disclaimer
It should be noted that the text in this report represents the viewpoints of the presenters and does not represent the viewpoints of the whole group. The same applies to the discussions summarized.

2 Introduction to the workshop and scope

2.1 Setting the scene

The conservation of harbour porpoises in the Netherlands relies for a large part on modelling. The Dutch government uses the PCoD framework to assess the effects of disturbance by underwater noise (Figure 2-1). Because empirical data on the parameters affected by behavioural and/or physiological changes are largely lacking (green 'health' box in Figure 2-1), the Interim PCoD model was developed by the Sea Mammal Research Unit (SMRU)/University St. Andrews (Harwood et al., 2013). In this model, the relationship between behavioural change (= number of days during which the normal behaviour of an animal is disturbed) and vital rates (purple box) is derived by means of a formal expert elicitation (EE) process. This process involves the use of a range of techniques to weigh the experts' opinions independently of each other and providing a numerical estimate of the uncertainty in the relationship (Booth et al., 2019)[1]. Recently, a bioenergetic component was integrated in the Interim PCoD model, replacing the expert elicitation (Harwood et al., 2023). In this workshop report, the two versions of the model are referred to as iPCoD EE, where EE stands for expert elicitation, and iPCoD DEB, where DEB stands for dynamic energy budget.

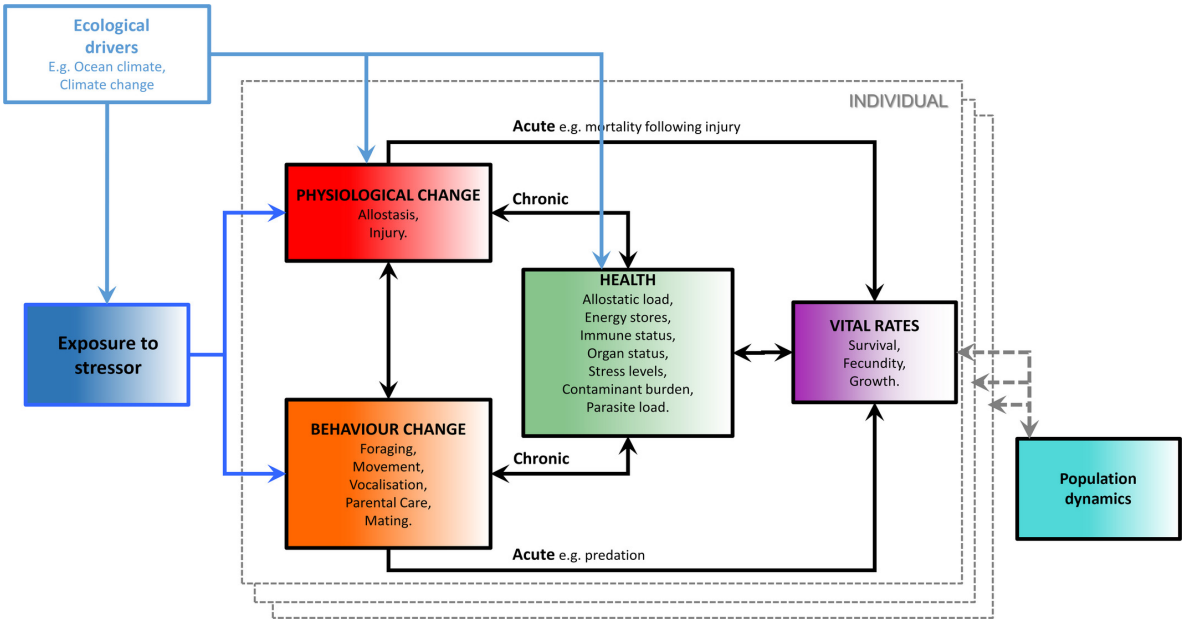


Figure 2-1 The Population Consequences of Disturbance (PCoD) conceptual framework (Pirotta et al., 2018)

In the Interim version of the iPCoD EE model used until now in the Dutch framework for Assessing Ecological and Cumulative Effects (KEC[2], see Box 1), much of the input is based on data from other regions and other decades. As outlined in Section 1.2, it is assumed that the results of post-mortem research on (locally) stranded harbour porpoises could provide valuable information to improve the input data of the model and thereby increasing the confidence in the outcomes.

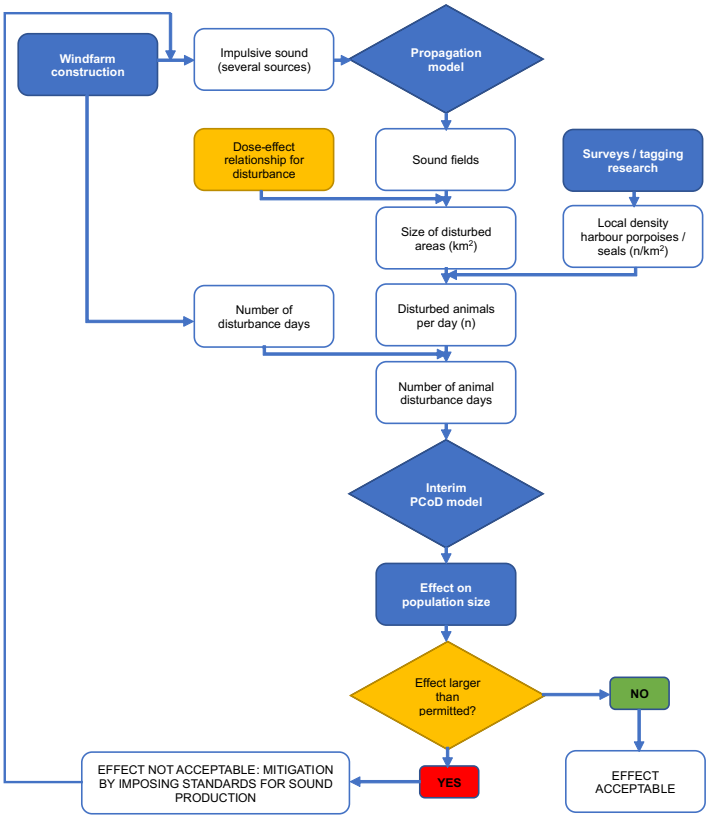
[1] A similar process involved deriving the relationship between Permanent Threshold Shifts (PTS) and vital rates (Booth & Heinis, 2018).

[2] https://noordzeeloket.nl/en/functions-use/offshore-energy-transition/offshore-wind-energy/ecology/offshore-wind-ecological-programme-wozep/framework-assessing-ecological-cumulative-effects/kec-5-0/

Box 1
Assessing cumulative effects of offshore windfarm development on marine mammals

KEC staged procedure:

1. Calculate sound distribution for a single pile-driving strike per location → Single Strike Sound Exposure Level (SELss)
2. Calculate the area over which piling sound disturbs animals, using a dose-effect relationship based on SELss
3. Calculate the number of animals in that disturbed area
4. Sum disturbed animals over piling days and projects → '*animal disturbance days*'
5. Estimate the possible impact of the cumulative disturbance on the animal population using the Interim PCoD model (SMRU)
6. Compare estimated population reduction 95th percentile with ecological standard
7. Calculate the SELss (750 m) limits required to meet the ecological standard



A preparatory webinar was held prior to the workshop (on 4th November 2025) to explain the overall scope of the workshop, introduce the basics of PCoD, bioenergetic modelling and the Dutch KEC framework. The participants were asked to read the report by Harwood et al. (2023) as a preparation for the webinar. Following the webinar, a questionnaire was sent out to the participants to get an idea of the expertise present at the workshop, ideas about the pathways most likely to be impacting vital rates resulting from disturbance by piling noise, and views on which uncertainties in the PCoD framework should be the focus on in the near future (2 – 3 years). The results (see Annex 2) were used to structure the second part of the programme about improving the modelling and application in the (Dutch) approach to assess the cumulative effects of offshore windfarm construction. Participants were encouraged during the preparatory webinar to bring ideas and present upon relevant research during the workshop, which helped to define the agenda.

2.2 General outline of the workshop

The workshop was structured in two parts, in which the first part consisted of knowledge exchange on harbour porpoise parameters as input for modelling and the second part focused on how these parameters could be used in the PCoD framework and applied to the Dutch KEC framework. In the first part of the programme, the PCoD framework from Figure 2-1 was used to allocate the information presented by experts in a given field to one or more of the boxes in the framework. The second part of the workshop focused on the (potential)

implementation of the information shared in the first part of the workshop in modelling the population consequences of disturbance (iPCoD) and application in the KEC-framework.

Part I – Knowledge exchange on parameters as input for modelling

- Life history of harbour porpoises (PCoD: vital rates)
- Energetics (PCoD: behaviour change, health, vital rates)
- Body condition and health (PCoD: health)

Part II – Informing iPCoD & Application in KEC

- Implement learning form Part I to consider how to improve use of iPCoD (including which version of the model to use in the future, iPCoD EE or iPCoD DEB)
- Key sensitivities for informing iPCoD, including results from questionnaire, such as:
  - Movement ecology (informing probability of exposure)
  - Response to disturbance (in terms of energetic costs)
  - Compensation abilities
  - Density dependent effects on population recovery

2.3 Post – mortem demonstration

The first day of the workshop started in the necropsy room with a demonstration by biologist Lonneke IJsseldijk. She showed how the post-mortem examination of a stranded harbour porpoise works. IJsseldijk: "The autopsy reports are full of up-to-date knowledge about the health and reproduction of porpoises from the southern North Sea. By making this data available, we can feed the models with real-time data. This makes the results more reliable and the confidence in the population predictions greater."



Figure 2-2 Lonneke IJsseldijk and workshop participants around the necropsy table. The harbour porpoise was found stranded on the Dutch coast and was transferred to the Faculty of Veterinary Medicine of Utrecht University for post-mortem investigation, as commissioned by the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature, aiming at determining the cause of death and condition of the animal. Photo: Eva Schotanus

3 Part I: Knowledge exchange on parameters as input for modelling

3.1 Life history of harbour porpoises

3.1.1 Life history and PCoD – Lonneke IJsseldijk

Pregnancy rate (PR) is an important parameter in both iPCoD models ('fecundity'). However, there is a large variation in PR in stranded and/or bycaught harbour porpoises reported (IJsseldijk et al. 2021), ranging from 0.283 (Salish Sea) to 0.986 (Icelandic waters) (IJsseldijk et al., 2021). The average PR of harbour porpoises from Dutch waters was 0.35 for all 119 individuals investigated (95% CI: 0.26 – 0.43), which corresponds with average values for UK waters reported by Murphy et al. (2015). Calculated PRs for Dutch waters depend on death categories (PR = 0.58 for anthropogenic trauma or predation vs. PR = 0.24 for infectious diseases or emaciation).

Note that data reported in literature are not always easily comparable, because of the period from which the PR is calculated. Most studies calculate PR from adult female harbour porpoises, based on the presence of a foetus in the uterus. When calculating the PR, it is important to exclude animals which died in the calving period (as calves might have been born already) as well as in the conception period, (as early pregnancies can be missed when embryos are too small to detect with the naked eye) to avoid undercalculation of the PR.

Prey quality (measured as energy density) is an important factor determining PR. Pregnancy rates are generally higher in areas where porpoises feed on prey with a higher energy density. Females in poor condition do not seem to sustain pregnancy throughout gestation (see Figure 3-1). In PCoD DEB, PR is only linked to resource availability and is parameterised to result in one, stable, North Sea population.

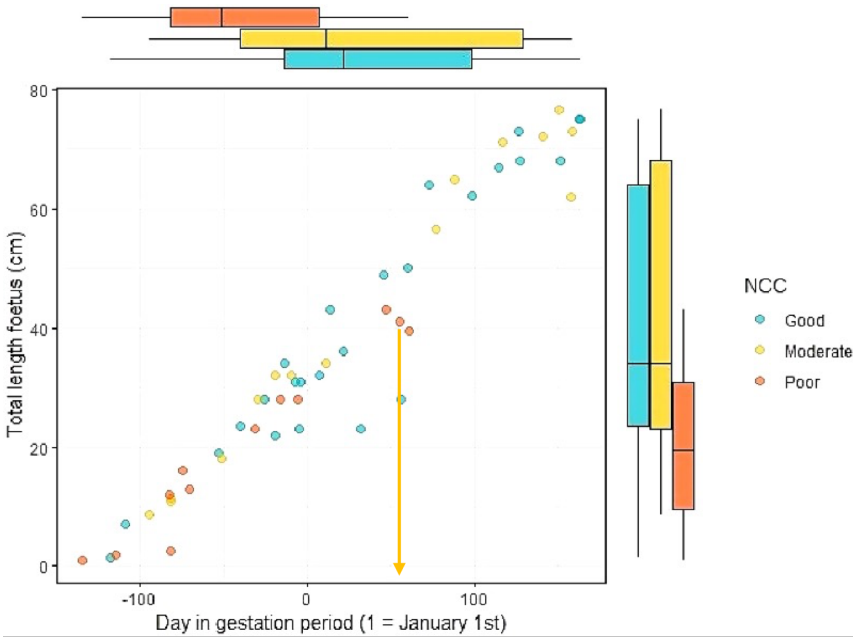


Figure 3-1 Combined scatterplot and boxplots of foetus length (y-axis) throughout the gestation period (x-axis). Coloured by nutritional condition category (NCC, based on blubber thickness, visceral fat and muscle mass assessed during post-mortem examination) of the mother (n = 50), with blue = good, yellow = moderate and orange = poor. From: IJsseldijk et al., 2021.

The orange arrow was added, to indicate the potential time which could be used as 'decision day' (end of February/early March).

Questions related to PR:

- Can we consider one PR for the harbour porpoise population, or do we need regional PRs?
- How fixed is the conception period?
- Which group of harbour porpoises represents the best reflection of the living population (in terms of sample occurrence/cause of death)? Or: do we need to determine PR in relation to body condition?

Lactation and calf survival

One of the parameters in iPCoD is the age at which calves are completely independent of their mother and must find their own food (referred to as **'age of independence'**). Their survival depends on the amount and quality of their mothers' milk and, in a later stage on how efficient they are in finding and catching (good) quality food. In iPCoD DEB, parameters related to this are 'age when calf's foraging efficiency is 50% of adult level' (Tr) and 'calf age at which female begins to reduce milk supply' (Tn). The quality of milk varies in lipid content (presumably also depending on reproduction state of female) but can also contain variable amounts of persistent organic pollutants with potential negative effects on calf survival (Van den Heuvel et al., 2021). Age at independence is therefore likely not a fixed number, so a probability or density should be determined.

A way to explore is to assess lactation and neonatal diet from post-mortem examined individuals. A previous study revealed that early deaths were most likely related to problems in gestation, birth or nursing (IJsseldijk et al., 2022). Of the 63 neonates assessed in that study, five had hard prey items in their stomachs. These were mainly gobies and shrimp with a median summed reconstructed prey mass of 2.5 gram. As the nutritional benefits of this prey is likely near zero, it may indicate early adaption to solids while still being dependent on milk. Zooming into necropsied porpoises of <120 cm (animals assumed to be < 1 y), and assessing their diet, could give more clues on age at independence.

3.1.2 On methods to determine age in harbour porpoises – Sanne Hessing

Relevant 'age' parameters in PCoD DEB are 'minage (Age at Sexual Maturity (ASM))', 'maxage' and 'age'. The actual age of harbour porpoises is only known for animals born under human care or from long-term photo-id studies. Several methods could be used to estimate the actual age of stranded and/or bycaught wild animals, all with their advantages and disadvantages, summarized below in Table 3-1:

Table 3-1 Methods to determine aga of standed/bycaught harbour porpoises.

Method	Pros	Cons	References
Standard body length	Easy, cheap, widely used	Inaccurate for > 3 years old	IJsseldijk et al., 2020a
Dental ageing	Widely used	• Invasive procedure • Requires experience readers/equipment • Less accurate for older animals • Not possible to look at months	Henriksen et al., 2024
Bone maturation by pectoral fin radiography (PFR)	• Real time • Non-invasive • Physeal plate closure appears good proxy for ASM	• Less accurate for older animals • Not possible to look at months	Barratclough et al., 2019 Hessing et al., in prep.
Epigenetic clock	• Promising • Proxy for health (in combination with info on cause of death)	• More expensive • Less accurate for estimating 'calendar age' • Animals of known age needed for proper evaluation • Not yet explored for harbour porpoises	Hanninger et al., 2025

Concluding:

- No single ageing method is perfect, and the accuracy of most methods decreases as animals get older;
- Initial scoring results from PFR look promising and may guide a more accurate estimation of ASM;
- Epigenetic clocks look promising and could also provide insight into mortality risk and overall individual and population health.

Coming back to the PCoD parameters:

- **minage** (ASM) could be predicted more accurately using PFR;
- **maxage** remains difficult to estimate; however, animals under human care or individuals from photo-ID studies provide valuable opportunities as control cases;
- **age**, may be improved through the development of new methods, such as a bone-maturation scoring model; or an epigenetic clock.

Combining of methods is probably the best way forward. In Utrecht, many tissue and blood samples taken are stored for future analyses with existing or new methods. Currently, a pectoral fin bone-maturation scoring model is developed and validated using data from known-age animals. Research results are expected in early 2027.

3.1.3 Age- and seasonal-related changes in harbour porpoises – Magnus Wahlberg

Natural behaviour and physiology in captive animals

Harbour porpoises are most active at twilight as is shown by Osiecka et al. (2020). The acoustic activity of two harbour porpoises kept under natural conditions in the porpoise pen of the Fjord&Bælt facility (Kerteminde, Denmark) was monitored during a full year. The porpoises showed significantly greater activity at night, and a clear peak around sunrise and

sunset. They were fed during daytime hours, excluding potential increased prey activity at night. As most studies with trained animals occur during daytime hours, we could miss important information on the natural behaviour of harbour porpoises.

Population development, age at various life stages and health
Occurrence in the field is studied by aerial surveys (such as SCANS[3]), but citizen science could add valuable information about fine-scale distribution of harbour porpoises and seasonal changes in the distribution (Jakobsen et al. 2025). Results of the mini-SCANS survey (2022) suggest that the Danish porpoise population of the inner waters is declining whereas the North Sea population remains approximately stable (Gilles et al., 2023).

To reliably model the population development (without disturbance) it is important to know the actual life stage composition (immature to mature ratios, or: actual numbers of neonates, juveniles and adults), and the % transfer from one stage to another or from age to age + 1 (harbour porpoise population model by Jones, submitted). However, existing population data derived from strandings and bycatches show a large spread (Lockyer & Kinze, 2003).

Porpoises of known age should be used to validate results of other methods, such as dental aging (Baier-Stegmaier et al., 2023; Henriksen et al., 2024). There are many data collected from porpoises of known age from Fjord&Bælt, Harderwijk and Ecomare (Stepien et al., 2023) and analyses show a consistent seasonal variation in age-related weight. Season is considered important: there are clear differences between summer and winter, which can amount to changes in weight of up to 20 kg. Body mass index (BMI) also shows very large variations, but it is still a question whether seasonal BMI could be used as a proxy for health. It is worthwhile to further explore the use of (drone) recordings of wild animals and measurements of length and various widths to assess condition and population structure (Irschick et al., 2020; Stepien et al., *in review*).

Mother-calf behaviour was studied by Hamel et al. (2024) on NotchSure, which is a recognisable, wild female harbour porpoise. This animal often swims close to the port of Kerteminde and can be identified from the shore or with drones. Between 2016 and 2025, NotchSure was observed in this area for almost nine consecutive years (one year there were no observations of this animal) and this animal returns to the area with a new calf almost every year. Detailed measurements of calves born in 2024 and 2025 and their mother by a PhD candidate based on drone recordings revealed a consistent and realistic body length. Developments in length and fluke width were also measured in NotchSure and in the calves from their birth until an age of approximately 3.5 months. The relationship between width and length shows that young calves are rounder than their mother.

During the following discussion on Wahlberg's presentation, it was stressed that it is important for population modelling and assessing the impact of human activities to:

[3] SCANS (Small Cetaceans in European Atlantic waters and the North Sea) is an international survey to determine the population size and distribution of cetaceans in the North-East Atlantic waters. These coordinated studies are conducted approximately every 6 to 10 years in the summer by a collaboration of several European governments and scientific institutes. The most recent edition (SCANS-IV) took place in the summer of 2022.

- Have better population estimates with information on size and age;
- Know mother-calf ratio as well as ratio mature-immature because they are powerful metrics for modelling

Note that it is hard to distinguish males from females in the field.
Currently, the initial age structure of HP population in both iPCoD EE and iPCoD DEB is derived from values suggested by Sinclair et al. (2020).

3.1.4 General discussion/conclusions on life history

The information shared in the various presentations on life history was discussed by the participants which lead to the following conclusions/questions:

- The juvenile/adult ratio is an important metric for modelling
- It is unclear if the harbour porpoises in the North Sea should be considered as belonging to one population, or whether there are subpopulations.
- The presenters so far indicate that there is a lot of valuable information about pregnancy rate, calf survival and age-specific survival in the stranding and field data that can be used in the models.
- Interim PCoD baseline scenario (population being stable) is most sensitive to calf mortality and birth rate depending in assumption about demographic rates (low survival/high reproduction or the other way around).
- The difference between pregnancy rate (fixed) and birth rate (dynamic; female can abort calf) should be clear. It is also a question whether it can be determined if smaller females give birth to smaller calves (age specific), and whether we consider the effect of environmental conditions the same for small (or premature) calves compared to larger calves. It is, for instance, reasonable to think that the demands of the mother vary depending on calf size (assumed to be higher for smaller calves due to larger heat loss and possibly also increased milk needs).
- It is stressed that variance/spread around means should be included in statistics instead of fixed numbers (such as for age at independence).
- Age distribution can be derived from stranding data, also to get better estimates of adult mortality rates. However, there is a need to assess the representativity of strandings data in terms of population assessment, as there might be an overrepresentation of juveniles, and animals in poor health condition among stranded animals.
- It should be considered if results of aerial surveys or photogrammetry could be used to determine differences in population demographics, or life history parameters between living and stranded populations.
- There is a need for better cross-national coordinated population monitoring.

3.2 Harbour porpoise energetics

3.2.1 Harbour porpoise energetics – Ron Kastelein

Harbour porpoises have a large geographic range, living singly or in small groups in the temperate generally coastal waters of the northern hemisphere. Compared to other odontocetes they live a ‘life in the fast lane’, as suggested by the relatively short juvenile period (3-4 years), the high potential reproductive rate (1 per year) and the relatively short

lifespan. Data presented are all based on studies on rehabilitated harbour porpoises from the rehabilitation centre at Dolfinarium Harderwijk (Read et al. (eds.), 1997; Kastelein, 1998).

Physiology
Females are larger than males. Porpoises are among the smallest toothed whales, which has consequences for heat loss. Due to their large surface-to-volume ratio, and because water as a medium conducts heat 25× better than air, they lose a lot of heat. Porpoises have two main strategies to cope with this:

- Reduce heat loss by insulation (blubber);
- And eating a lot (± 8% of body weight per day), exploiting a wide range of (small) fish- and squid species.

By having many mitochondria per cell, they have a high metabolic rate. Food passes their digestive system quickly: likely within 2.5 – 3 hours it is faeces (referred to as passage time), which is fast compared to other, larger odontocete species.

Compared to common dolphins, bottlenose dolphins and beluga whales, the heart rate of harbour porpoises is high with a clear respiratory arrythmia (i.e. faster heart rate immediately after inhalation, enhancing oxygen uptake in the blood).

Blubber, temperature and body condition
Harbour porpoises have a blubber type that provides good insulation. As animals get larger the blubber layer gets thinner. Girth at axilla appears to be a good indicator of body weight. Fins do not contain blubber as they function as a counter current system for heat preservation and to dump that heat during strenuous exercise. From studies conducted in a large (outside) floating pen at Neeltje Jans, a clear relationship between water temperature and blubber thickness was seen. There is also a seasonal variation in food intake and body condition as was seen in studies at SEAMARCO Research Institute (Kastelein et al., 2018). It is concluded that harbour porpoise body mass, blubber thickness, and food consumption vary seasonally with water temperature.

Effect of 24-h fasting on body condition (Kastelein et al., 2019a)
This is a study conducted in a controlled environment to investigate how (two) harbour porpoises could be affected if disturbance reduces foraging and if the degree of the effect of fasting could be seasonal. The results were:

- Body mass loss occurred in every season (~ 4% of body mass/24 h of fasting).
- Blubber thickness reduced by 0-3 mm/24 h.
- Mass loss was greatest in autumn and least in summer.

Main conclusions of this study (in a controlled environment) are:

- Body condition should always be assessed in relation to season.
- Harbour porpoises are most susceptible to the effects of fasting due to disturbance in autumn.

Note that food availability in the wild may vary (seasonally).

Maximum food intake after fasting (Kastelein et al., 2019b)
In another study with 4 individuals, it was investigated how quickly porpoises can compensate for low food intake and restore lost blubber. The conclusion was that if suitable prey is abundantly available after a period of fasting, harbour porpoises can eat a large percentage of their daily energetic requirement in one feeding bout (and fill their forestomach again 2.5 hrs later as their passage time is determined at 2.5-3 hours, as earlier reported).

Summarizing the results on harbour porpoise energetics:

- High metabolic rate (food intake 7-10% of body weight per day)
- Porpoises change their food intake and body condition seasonally, as an adaptation to changing water temperature.
- Porpoises can lose ~4% of their body mass if they fast for 24 h; the greatest rate of loss was in autumn.
- Porpoises can eat up to 95% of their daily food requirement in one meal.

Fish-catching success during pile-driving sound (Kastelein et al., 2019c)
To investigate the relationship between pile-driving sounds and fish capture, an experimental set-up was designed to measure the effects of impulsive, intermittent sounds on the ability of harbour porpoises to catch fish. The results suggest that loud pile-driving sounds are likely to affect foraging negatively in some harbour porpoises, by decreasing their catch success rate and increasing the termination rate of their fish-catching attempts; the severity of the effects is likely to increase with increasing pile-driving sound exposure level. However, individual differences in responses to sound, termination rates, and fish-catching success (even in quiet conditions) complicates the quantification of the impacts of pile-driving sounds on harbour porpoises.

A variety of suggestions for potential research was presented by Kastelein, which can be provided upon request.

3.2.2 Small bodies in cold waters: harbour porpoise energetics and effects of disturbance – Laia Rojano-Doñate

While PCoD models are widely used, relevant information lacks about how physiological and behavioural changes translate into health- and vital rates disruptions. More importantly, it is currently unclear how this can be translated into a metric that allows us to quantify disturbance.

Animals need energy for survival, and this energy is obtained through food. It is necessary to keep an energetic balance between energy acquisition and expenditure. Breaking this balance between energy acquisition and energy expenditure can have fitness consequences for individuals and, ultimately, for the population. Defining this ‘breaking the balance’ point can be a useful as a metric to quantify disturbance.

To understand the effects of breaking the balance, information is needed about:

- Energetic consequences of being an endotherm in water (thermoregulation),
- How energy acquisition and expenditure is balanced, and

- Effect of disturbance on energy balance and vital rates.

Research is done by a combination of data from harbour porpoises in captivity (> 20 years) in a controlled environment and wild harbour porpoises by tagging.

Due to their small size, harbour porpoises have

- shorter fasting periods (eat more often);
- a high surface-to-volume ratio: high heat loss; blubber is used for insulation (and varies through the year); high field metabolic rate (FMR) of approximately 20 MJ/day with little seasonal variation (see Fig 1 in: Rojano-Doñate et al. 2018).

The harbour porpoises studied had a high feeding rate (> 2000 attempts/day), predominantly at nighttime. They were mainly feeding on small prey (< 10 cm), had an approximate 90% prey-capture success rate, were > 60% of the time feeding, and had low hunting costs.

They maintained a high FMR regardless of behaviour (also while resting). High foraging rates make them more vulnerable to lost foraging opportunities (Wisniewska et al., 2016), although the hunting costs are low (Rojana-Doñate et al. 2024), but consist of many small items with relatively low caloric content.

Recent – not yet published – results (Rojana- Doñate et al., *under review*) of research on 28 tagged wild harbour porpoises aimed at quantifying the effect of vessel noise disturbance on energy acquisition and expenditure to assess the effects on energy balance (and potentially individual fitness). For an average porpoise of 60 kg, 11 vessel events per day resulted in a 4.6% net energy lost per day, if the daily energy expenditure would not change (proxy: daily respirations).

Implications of a 4.6% daily offset depend on:

- Ability to compensate, which depends on
  - Time left/quality of environment
  - Health and reproductive status
- What are the consequences for fitness if they cannot compensate for a 4.6% energy loss (which is equivalent to 10 – 12 kg blubber in a year):
  - Go through winter → harbour porpoises increase blubber layer to offset cost of thermoregulation;
  - Pregnancy and lactation (10% of yearly energy budget) → will they be able to successfully produce calves?

Conclusions

- Porpoises cyclically change blubber thickness → 10 kg of blubber a year;
- High FMR with small seasonal changes;
- Prey on small prey with high success rate;
- Low cost of foraging, but very long proportion of time foraging → high FMR regardless of behaviour, making them vulnerable to lost foraging opportunities;
- Reduce energy acquisition during vessel noise exposure:
  - Nighttime exposures to stressors is extra costly because harbour porpoises predominantly forage at night;

    - Effects seem to increase with noise level;
- Average vessel exposure rates offset their energy budgets → 4.6% net energy lost;
- Fitness of individuals is likely to decrease if they are unable to compensate.

Final step: feed data into population models to predict future outcomes.

3.2.3 General discussion on harbour porpoise energetics

Following the presentations on energetics, various remarks were made and questions were raised:

- It is stressed that ability to compensate is a very important factor. Energy acquisition is very sensitive to energy content of prey items (4 or 5 cm fish is a very big difference).
- How much time does it take to compensate for a body mass loss of ca. 4%? Harbour porpoises burn energy fast but can recover fast as well (estimates of approximately 1 kg a day).
- Is digestive efficiency during diet switching (different prey fish) the same? It suggested that this is probably not optimal, which is indicated by observed changes in faeces colour (beige is poor digestion, dark green is good digestion).

3.3 Harbour porpoise body condition and health

3.3.1 Seasonally slim: body condition variability in harbour porpoises from the North Sea – Eva Schotanus

In the iPCoD DEB model body condition is used as a proxy for health (Harwood et al., 2023) with the following parameters:

- Target body condition set as maximum blubber/body weight (varying with season)
- Starvation body condition threshold
- Starvation mortality rate (rate at which mortality occurs after being under starvation threshold)

The body condition of harbour porpoises is linked to survival and reproduction as is shown by IJsseldijk et al. (2021) from necropsies of stranded and bycaught animals. The results of these investigations suggest that the harbour porpoises studied live on an energetic knife-edge (IJsseldijk, 2021). Various studies of harbour porpoises in captivity or in the wild demonstrated that body condition, exemplified as Body Mass Index (BMI) (Stepien et al., 2023) and the blubber thickness (Siebert et al. 2022) vary seasonally.

Measurements on 1700 stranded porpoises from six regions around the North Sea and Northern part of the English Channel demonstrated regional differences in the seasonal variation of the BMI for juveniles as well as for adults (Schotanus et al., 2026). This puts doubts to the assumption that the body conditions of harbour porpoises in the North Sea are uniform, based on the BMI. This raises the question whether the resilience of the population would be the same for all porpoises in the North Sea and which other parameters could show potential heterogeneity.

The 1700 individuals included in the study by Schotanus et al. (2026) were divided into three mortality categories, related to the presumed causes of death:

- Acute: bycatch (majority), direct predation (such as by grey seals, or attacks by bottlenose dolphins)
- Non-acute: infectious disease, indirect predation
- Other: starvation & emaciation (see next presentation by Andrea Gröne), live strandings and unknowns

For the six assigned regions studied, the average BMI was highest for adult harbour porpoises that died of acute causes, estimated at 22.27 for females. This suggests that the acute mortality category would be the best reflection/proxy of healthy animals, even though bycaught animals are not always healthy (IJsseldijk et al., 2020b). Adult males had on average a lower estimated BMI than females, but not in the non-acute or other causes of death, where the BMI was higher in males. Could this sex-specific difference be related to an effect of reproduction?

In the iPCoD DEB model various parameters relate to the life-history and health of calves (Harwood et al., 2023):

- Calf survival
- Target body condition for calves
- Milk supply reduction
- Age at weaning

There is a potential for future necropsy studies on ca. 200 neonates. Preliminary results show that neonates from earlier months (May/June) have a lower BMI than from later months (July/August).

Necropsy data could probably provide estimations of the following iPCoD DEB parameters:

- Target body condition of adults & calves
- Starvation body condition threshold
- Starvation mortality scalar/rate

Comments:
It is evident that regional differences exist and are most likely caused by differences in temperature. Porpoises in the southern North Sea can afford to have a lower blubber thickness because of higher temperatures. Thresholds at which animals die are very different depending on (natural) environmental conditions. It is important to try to estimate how much an animal can lose before it dies, i.e. heat loss (depending on water temperature) in relation to body condition (and energy needed to maintain a 'healthy' state).

3.3.2 Diagnosing emaciation vs starvation at Utrecht University – Andrea Gröne

There are challenges around definitions and, more specifically discerning emaciation from starvation.

Some definitions (all from Cambridge Dictionary):

- Emaciation: state of being very thin and weak, usually due to illness or extreme hunger

- Starvation: state of having no food for a long period, often causing death
- Hypoglycemia: medical condition resulting from dangerously low levels of sugar in the blood
- Hypothermia: serious medical condition in which body temperature falls below the usual level as a result of being in severe cold for a long time

At Utrecht University emaciation *versus* starvation as a cause of death is diagnosed as follows:

- Emaciation
  - Reflects a non-acute / chronic process
  - Debilitated animals
  - Very thin blubber layer (<10 mm)
  - 'Peanut' head
  - No other major findings
- Starvation
  - Reflects an acute / quick process
  - Decent blubber layer & reserves
  - Fatty (yellow) liver
  - Often newborns

Emaciated animals lack energy because too much energy is needed to fight diseases and/or to keep warm (can be diagnosed potentially by presence of Wischnewski spots, needs further investigations) and/or to reproduce.

Deaths due to acute events:

- Neonates (starvation/abandoned)
- Trauma
- Grey seal attacks
- Bycatch; N.B. Bycaught animals are not always healthy; they are sometimes not fast enough to flee because of some illness.

Questions to be discussed that were raised by Andrea Gröne:

- What evidence do we need to determine starvation as a cause of death?
- How can we overcome diagnosing differences for starvation among the stranding networks, as not every network defines emaciation and starvation in the same way?

3.3.3 General discussion on presentations by Schotanus & Gröne

The discussion boils down to

- A need for consensus among pathologists about terminology and diagnosis of starvation
- What do the modellers need exactly from the pathologists to feed the models

Modellers and pathologists use a different terminology and different definitions for the same terms (such as starvation). Pathologists do not often say an animal died of starvation but look for underlying causes to explain nutritional conditions of animals. For the modellers starvation is a point of no return, which is a physiologically state, where it can't get back to a healthy body condition. For the model it is not important how the animal died, but it is its

condition that matters and the way disturbance affects it. Terminology in the model appears confusing. It is, therefore, needed to find another term or make very clear what is meant by a certain term. It is important that terminology is clear in order to be able to compare results and value them as model inputs.

Wild harbour porpoises are not necessarily healthy, as any wildlife will have e.g., parasite burden. A completely healthy animals can be seen as an exception, not the rule. Porpoises are populous and therefore obviously able to cope with signs of 'abnormalities' (such as the presence of microorganisms) in most regions. Many data are collected, and there is a need for asking the correct questions to make use of these data. The models should be improved without making it too computationally intensive.

Monitoring data should converge with modelling results. It would be useful to identify monitoring goals for the next 2 – 3 years to improve the models.

3.3.4 Physiology and pathology – Andrew Brownlow

In Scotland strandings are continuously monitored and investigated since 1992. Around 400 – 500 cetaceans are reported annually of which 10% is necropsied.
Of 1001 harbour porpoises stranded top 3 causes of death are:

- Bottlenose dolphins attack (31%)
- Starvation/hypothermia (15%)
- Parasitic pneumonia (10%)

The individual health of an animal is affected by stressors on the one hand and the resilience of the animal on the other hand. Ancillary tests are carried out to support diagnosis of proximal cause of death and increase information about individual animal health/condition:

- Necropsy findings – gross and histopathology, diagnostic tests
- Disease ecology – pathogen presence/prevalence
- Life history – age and sexual maturity
- Feeding ecology – diet, stomach content, stable isotope and fatty acid analysis
- Contaminant burden – persistent organic pollutants, metals, algal toxins

It is not always possible to assess the effects of disturbance/noise or environmental factors.

A theoretical framework for this progression might run as follows. It should be stressed that this is a conceptual model rather than an established validated sequence, and the pathway described represents likely tendencies rather than a fixed or inevitable trajectory:

- If an event disrupts normal feeding such that intake falls below the animal's baseline energetic requirements, then a shift into negative energy balance would be the expected consequence.
- If that deficit persists, then the animal would likely begin drawing on endogenous reserves, with a gradual erosion of body condition and mobility as the probable result.
- If depletion continues, then general physiological resilience would be expected to decline, leaving the animal less able to withstand additional stressors such as infection.
- And if reserves become sufficiently exhausted, then existing burdens (for example, parasitic infection) may become progressively harder to regulate, which could in turn

compound the loss of function and further raise energetic demand potentially establishing a self-reinforcing decline.

Various metrics are available to get information from detailed post-mortem analyses of stranded animals to entangle the possible pathophysiological cascade:

1. Feeding disruption – chronic disease or acute trauma/disturbance prevents normal feeding behaviour
2. Fat mobilisation – free fatty acids released from blubber exceed hepatorenal (liver and kidney) processing capacity
3. Organ failure – hepatic and renal lipidosis (fatty changes in liver and kidney) creates positive feedback loop of metabolic deterioration
4. End stage – multi-organ misfunctioning, circulatory collapse etc.

It is important to note that an external body assessment may not be enough to predict survival capacity following acute stress, because animals with excellent reserves can die from an acute negative energy balance within 24 – 48 hours. Conversely, chronic disease burden (e.g. indicated by a fatty liver) establishes baseline metabolic vulnerability, rendering animals susceptible to decompensation from otherwise survivable acute stressors.

Next steps foreseen:

- Integration of more detailed necropsy data to assess health and individual resilience
- Identify biomarkers for these processes
- Assessing how resilience changes seasonally
- Consider impacts of both slow burn loss in body conditions and acute metabolic starvation

Potential further steps:

- Layer pathology data with environmental and risk data
- Integrate information across stranding networks to consider wider ecosystem impacts
- Identify spatiotemporal areas of most vulnerability

3.3.5 Using molecular techniques to find novel markers – Davina Derous

The focus is on finding robust health markers indicative for the relationship between stressor (*i.e.* foraging disruptions) and physiology (energy metabolism) as a way to contribute to the 'health' box in the PCoD model.

Blubber thickness is a poor marker of health as relationships between health and blubber thickness are not always evident (Derous et al., 2020). Therefore, the mechanisms detecting changes in energy status must be understood to find improved markers of health. Fasting experiments in a controlled environment on bottlenose dolphins by Houser et al. (2021) showed that disrupted foraging led to an immediate switch to lipid oxidation and amino acids (muscle tissue), which is in contrast to what terrestrial mammals do.

There is limited information from free-ranging species. There are examples from plasma analyses of healthy and diseased bottlenose dolphins (Derous et al., 2022) and blubber

biopsies from free-ranging baleen whales (Kershaw et al., 2024). Due to difficulties in obtaining enough information from live animals, studies are executed to investigate if useful information could be gathered from stranded animals.

Omics[4] are named after the information they could give:
Genomics (what can happen) ⇒Transcriptomics (what appears to be happening) ⇒ Proteomics (what makes it happen) ⇒ Metabolomics (what has happened).

The omics to be used should meet the following criteria:

1. Detectable: yes!
    a. Proteomics: in this category the largest number of proteins from stranded cases of harbour seal, bottlenose dolphin, beaked whale and pilot whale is found so far;
    b. Metabolomics: in harbour seal a large number of metabolites is identified.
2. Stability in dead animals – was tested in time series of 5 days at various storage methods for 3 omics. Proteomics change little in time (Tranganida et al. *in prep*).
3. Give information about biology – a *proof-of-concept* study on the blubber layer comparison in a female lactating-juvenile pair by Derous et al. (2026). After method described by Khudyakov et al. (2022). Results indicate that liver proteome matches the pathology.
4. Give an indication of natural variability – study on 55 mass stranded pilot whales consisting of various reproductive groups (lactating, pregnant vs 'resting' adults; males vs females; adults vs juveniles) by Tranganida et al. (*in prep*.).
5. Reflect fasting states – is currently being worked on by PhD students Alexandra Tranganida (pelagic delphinids) and Alex Witchell (harbour porpoises).

Examples from a model species (mouse) will be used to study the regulation by the hypothalamus of tissue weight changes related to calorie restriction (Mitchell et al., 2015), using machine learning. The gene expression of 20 genes changed with degree of caloric restriction (0, 10, 20, 30, 40% reduced foraging), which makes biological sense. Changes were non-linear suggesting a 'tipping point' and a potential restriction level. Does this also predict an impact on biology (see Derous et al., 2021 for pathways)?

Summarizing – potential use of these methods in stranded animals:

1. Find biomarkers with proteomics of animals in different stages of fasting/starvation;
2. Predict what the biological impact might be of a protein:
    - Specific pathways
    - Biological processes
    - System-level effects

For applying this kind of information in the PCoD framework, it is necessary to make prediction level scenarios based on evidence-based physiology and molecular changes.

[4] Omics is the collective characterization and quantification of entire sets of biological molecules and the investigation of how they translate into the structure, function, and dynamics of an organism or group of organisms.

3.3.6 General discussion on (parameters for) body condition and health

Main question is how to improve communication between modellers and physiologists/pathologists. Modellers need a lot of input data (and assess their validity) but need to be able to interpret the output too. How realistic is the output? So, what is the correct input and does the output look right for the right reasons? The theoretical framework with the potential sequence of physiological events/responses presented by Brownlow (see 3.3.4) would probably be nice to cross-check with PCoD in the future.

4 Part II: Informing iPCoD and application in KEC

4.1 Introduction

The goal of the second part of the workshop was to have a discussion on parameter settings, and stimulate a conversation between pathologists, ecologists and modellers, in order to gain insights from different disciplines.

This part focused on ways to implement the learning and discussions from the first part, summarized in the previous chapter, in the modelling of PCoD. What should be done to implement the available knowledge in the iPCoD models, which of the two versions[5] of the model should be used, and how could the models be improved overall? Also, the timeline of the implementation of potential improvements of the model was placed alongside the one of windfarm developments in the Netherlands and the planning of future KECs related to that.

At the webinar preceding the workshop, it was proposed to centre the discussion on the bioenergetic model (iPCoD DEB) around the following questions:

1. Is the model based on our best understanding of the effect of disturbance? Results of a pre-workshop questionnaire sent out to the participants should give an idea of their opinions (see section 4.2.2 for results);
2. Is the bioenergetic model based on the best available science and, if not, how can we utilise the available data from necropsies?
3. Is the energetic path covering the essentials? In other words, has the EE-version of the iPCoD model included an important non-energetic path which is missing from the DEB-version (see section 4.2.2)?

Regarding the second question, the following topics are relevant for the model:

- Parameters related to reproductive cycle, life history and demographics – gestation length, calving season, growth of foetus, max age and age of first reproduction, demographics (currently fixed for the entire North Sea)
- Seasonal changes in body condition
- Starvation induced mortality rate

[5] The two versions of the iPCoD model (see 2.1):

- iPCoD EE = the relationship between disturbance and vital rates is derived by means of a formal expert elicitation (EE) process;
- iPCoD DEB = the relationship between disturbance and vital rates is based on bioenergetic modelling (Dynamic Energy Budget DEB), replacing the expert elicitation.

- Field metabolic rate
- Links between body condition and birth rate/fertility/conception/weaning rate
- Effect of age on resource foraging efficiency ('age at independence')

Most of these topics were touched upon during the first part of the workshop (see Chapter 3). From this, it is obvious that there are many data from necropsies having potential for use in the iPCoD DEB model. It is, however, not always clear how they could be incorporated.

4.2 Importance of pathways affecting vital rates by exposure to underwater noise

4.2.1 Noise effects on porpoises – Magnus Wahlberg

As an introduction to the discussions an overview is given of the various ways underwater noise, from explosions to pile driving and shipping, affects harbour porpoises. The noise effects range from (direct) mortality and effects on hearing (Permanent Threshold Shifts PTS/Temporary Threshold Shifts TTS) to behavioural change and masking. In the presentation, an overview is given of the available data (from the Kerteminde[6] perspective) on the various underwater noise effect types. Also, information is shared about the potential effects of interaction with other species, such as dolphins.

Mortality
The most serious effect of loud noises is (almost) immediate mortality caused by blast injuries or other acoustic trauma as is reported by Siebert et al. (2022). After the detonation of British ground mines from World War II that were dumped into the sea, 24 harbour porpoises were found dead along the surrounding coastline. Postmortem examinations showed that for 14 of these animals, the suspected cause of death was blast trauma and/or blunt force trauma.

Permanent or Temporary hearing Threshold Shift (PTS/TTS)
Regulators rely heavily on metrics for PTS and TTS to set noise limits, but the real question is what a temporary or permanent elevation of the hearing threshold means for the animal. It could be important if it affects communication, predator detection or the foraging ability, but it depends on the part of the hearing range that is affected. Kloepper et al. (2010) showed a decreased echolocation performance following high-frequency hearing loss in a false killer whale. Harbour porpoises, being high frequency echolocators too, could experience the same effect. Porpoises click from the 'cradle to the grave', and echolocation develops within days after birth (Wahlberg et al., 1971). Empirical data on thresholds for TTS-onset in harbour porpoises were compiled from various, mainly Dutch and Danish sources by Tougaard et al. (2022) showing a relationship between frequency of the received sound and the sound level at which TTS-onset occurs. It is, however, not known what the biological effects of TTS are, if any.

[6] The Marine Biological Research Centre in Kerteminde is part of the Department of Biology of the University of Southern Denmark. It is situated at the inlet to Kerteminde Fjord, opposite the fishing port of Kerteminde town.

Behavioural reactions
Results of two studies on the behavioural response of harbour porpoises after exposure to Acoustic Harassment Devices were shown. The behavioural response of six harbour porpoises tagged with suction-cup DTAGs to the sound of an Acoustic Harassment Device (AHD) was investigated by Elmegaard et al. (2023), which demonstrated that AHD exposure can at many km evoke startle, flight and cardiac responses. Brennecke et al. (2022) showed that there is a strong individual variation in the response of harbour porpoises to pingers. In another study Hao et al. (2024) showed by means of drone recordings that harbour porpoises respond to recreational boats by speeding up and moving away from the boat path. The behavioural response to sound is a function of perceived loudness and depends on the audiogram of the animal. Based on the results of various studies on the behavioural response of harbour porpoises to sound, Tougaard et al. (2014) suggest that the threshold for a behavioural response lies at ca. 45 dB (SPL) above the audiogram.

Noise can **mask** echolocation and communication, affecting navigation and foraging. Bakkeren et al. (2023) demonstrated, however, that visual stimuli also play a role in harbour porpoises. Note that not all audible signals have masking effects. It depends on the Sound Level. Prolonged exposure to low-level pile driving (100 – 140 dB re 1 μPa) on land appears to affect porpoises in the pool next to it making them less responsive to training.

Finally, it is questioned by the presenter if the focus is on the right risks for the porpoise population. Fishing nets causing incidental bycatch and predation by dolphins/seals may pose greater threats. Filatova et al. (2024) studied the interaction with solitary bottlenose dolphins, that can disturb and even kill porpoises.

Discussion
When presenting sensitivity to noise it is noted that there is no relationship between AEP (Auditory Evoked Potential) and behavioural thresholds.

Regulators often rely on PTS/TTS-based thresholds, but this does not reflect real behavioural impacts. However, before shifting fully to behavioural metrics, there is a strong need for population-level understanding of behavioural responses: this is a major missing step. It is proposed that (part) of the solution would be careful, long-term population monitoring**.**

In a discussion about the response of harbour porpoises to pingers, shipping and pre-construction activities related to windfarms (including the presence of ships) it is concluded that the key unknown is how ‘heavy’ any behavioural response is. In other words: is it a normal stress response or something more disruptive?

Bycatch is already included in the models (implicitly) as part of natural mortality, but there is an option in the model to add extra by catch explicitly.
Construction impacts accumulate, but windfarms may have positive effects during the operational phase because fishing activity within the windfarm is at present not allowed. In that respect, it is comparable to what a Marine Protected Area would achieve.

4.2.2 Opinions of experts on relative importance of impact pathways

The PCoD framework (see Figure 2-1) has many pathways by which behavioural (orange box) or physiological (red box) change can impact health and vital rates (which is what the expert elicitation transfer functions covered). In the pre-workshop questionnaire (see Annex 2.1), the invited experts were asked about the relative importance of different pathways through which vital rates of porpoises could be affected as a result of disturbance following exposure to noise from offshore wind construction. The experts could select their top 3 of these pathways:

- Direct mortality from injury
- Increased risk of predation
- Reduced reproduction / increased risk of calf mortality (e.g. mother-calf separation)
- Reduction in energy reserves due to reduced foraging or increased energetic costs
- Changes in physiological condition (e.g. stress hormones, contaminant burden, parasitic load, organ or immune status)
- Allostatic load (i.e. 'cumulative wear and tear from chronic stresses' potentially leading to physiological dysregulation and increased risk of disease)
- Other

The results of the different expert opinions (Figure 4-1) suggest that the most likely pathways would be the reduction of energy reserves (34%), and that there is a concern about long-term population effects resulting from reduced reproduction, including increased calf mortality (23%). A relatively large proportion of the expert opinions highlighted the importance of acute or chronic stress responses (21%). Indirect ecosystem effects and direct mortality from injury were considered less likely.

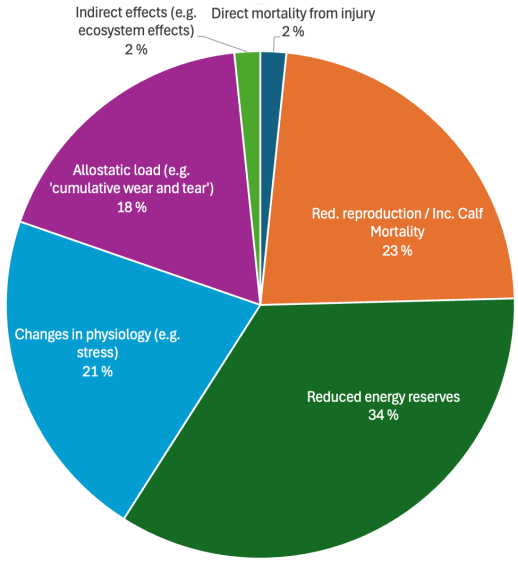


Figure 4-1 Answers to question on impact pathways

The question remains which iPCoD model should be used in future KEC-calculations: iPCoD EE or iPCoD DEB?

- If the pre workshop questionnaire is representative, the current state of knowledge points to sufficient uncertainty/concern over non-energetics pathways

- Perhaps the EE version has broader application currently or should both models be used?

Discussion
In the discussion some technical comments on interpreting the results of the questionnaire were named:

- The respondents were allowed to select their top three most likely pathways (without putting weight on them). The results might be different if the answers were weighted.
- The composition of the group makes a difference too. In the expert group of the 2025 questionnaire pathologists were included whereas no pathologist was present in the 2018 Expert Elicitation (EE) group (see Section 2.1 and Booth et al., 2019 on the setup of a formal Expert Elicitation).

The results of recent calculations on the KEC 5.0 international scenario show that the outcomes of the two versions of the model do not differ much (Chudzinska et al., 2026), so the question is whether a choice should be made in this case. However, the DEB model is more flexible, which makes it easier to explore the effect of variations in key sensitivities on the outcomes of the DEB model. It is also easier to adapt the DEB model when new information on parameters becomes available compared to the implementation of new information in the EE model. Adapting the EE model would require a new expert elicitation.

4.3 Key factors for modelling effects of disturbance – Cormac Booth

Key factors in the current models for estimating population effects of disturbance (iPCoD EE/DEB & DEPONS, see Box DEPONS and iPCoD below) are:

- Probability of disturbance (+ multiple exposure risk)
- Effect of disturbance (i.e. once exposed)
- Compensation abilities (i.e. what happens after disturbance)

To establish the probability of disturbance, movement ecology plays an important role and the assumption about if we are dealing with a resident or a nomadic population. In a nomadic population many individuals are disturbed relatively infrequently and in a resident population fewer individuals are disturbed frequently (Figure 4-2). PCoD simulates over a period of 20 – 30 years. In the context of probability of exposure, model assumptions about animal movement, therefore, need to be robust over that timeframe as much as possible.

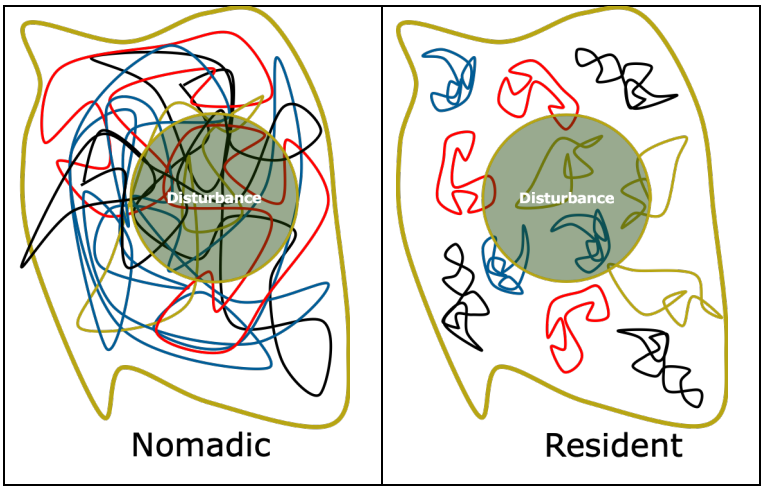


Figure 4-2 Probability of disturbance of individuals in a nomadic and resident population (after: Costa et al., 2016)

An overview is given of the available information about the movement ecology of harbour porpoises, based on tagging data (Read & Westgate, 1997; Sveegaard et al., 2011; Nielsen et al., 2018; Scheidat et al., 2024). Do harbour porpoises have a 'homerange' and if so, what is the size of it? Most information is from research on tagged animals by Denmark.

Conclusions from the available data:

- Maximum individual home range in Gulf of Maine = ca. 50,000 km^2 (Read & Westgate, 1997);
- There is a large individual variation in area used and distance travelled;
- In the Greenland tagging study (Nielsen et al. 2018) it was seen that juvenile individuals of less than 1-year old already travelled offshore. The study also demonstrated seasonal variation combining extensive movements by individuals leaving the continental shelf with strong site fidelity to the (coastal) tagging site in the following summer;
- There is a relationship between the number of days since tag deployment (max. 115 days) of the tags and the average distance from the place of deployment, ranging from app. 60 to 100 – 120 km (data from 34 tagged porpoises from the Kattegat and Belt Seas, Teilmann et al., 2008);
- Movements of harbour porpoises in the Southern part of the North Sea are not yet known, since none of the tagged animals in Danish waters went into the southern North Sea. A recent pilot study commissioned by the Dutch Ministry of Agriculture, Fisheries, Food Security and Nature, and the Wind at Sea Ecological Program (Wozep) that is still ongoing aims to investigate the feasibility of tagging harbour porpoises in the Dutch waters.

Within the context of iPCoD: are there subpopulations within the porpoise population of the North Sea and is that the case for 20 – 30 years? Necropsy data show regional differences in condition, health state and reproduction rates between porpoises stranded in different areas. Can information on genetics give insights?

Chudzinska et al. (2023) estimated the probability of exposure to- and disturbance by underwater noise for individual harbour porpoises in regions where intensive development of offshore windfarms is planned or has occurred. Two areas, each with a 30 km radius were

chosen, at locations where high and low densities of animals were expected, respectively. Based on Graham et al. (2019) it was assumed that 30 km was the limit of disturbance effects for a typical piling event. The DEPONS model (see BOX below) was used to simulate the movements of 150 individuals over five years. The results presented in Figure 4-3 show that in areas where the porpoise density is low (black bars), the probability of exposure is smaller than in high density areas (red bars). However, the probability of disturbance per individual is the same as anywhere else at the same distance and noise level. Individual porpoises are not more sensitive in high-density areas, but because more animals are being disturbed and lose foraging time, siting wind farms in high density areas leads to larger predicted impacts. See next section 4.4 for the relationship between the probability of exposure and the disturbance effect (number of foraging hours lost).

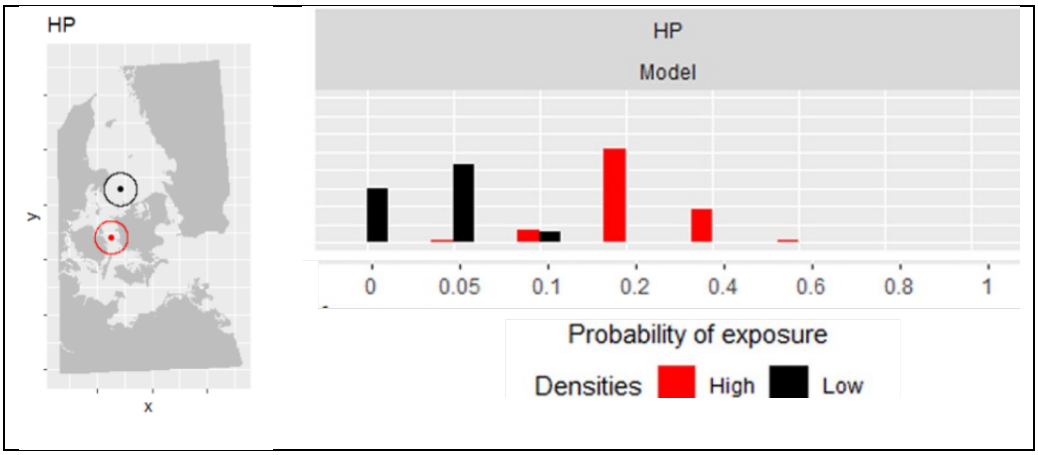


Figure 4-3 Locations of low (black circle) and high densities (red circle) of harbour porpoises in the Inner Danish waters (left picture) and the proportion of modelled days individuals of harbour porpoises spent in the areas of high (red bars) and low densities (black bars) (right picture. After: Chudzinska et al. (2023).

iPCoD en DEPONS

Both the Interim PCoD (Population Consequences of Disturbance) and DEPONS (Disturbance Effects on the Harbour Porpoise Population in the North Sea) models assess how anthropogenic noise – such as pile-driving or shipping noise – affects marine mammal populations. However, they use fundamentally different mathematical frameworks and modelling resolutions. The iPCoD EE and DEB models are primarily stage-based matrix population models that track proportions of populations categorized by demographic stages (calves, juveniles, adults). DEPONS is an individual-based model where each porpoise has its own movement rules and reacts to pile-driving noise by moving away when received levels exceed a threshold, potentially resulting in reduced foraging opportunities affecting energy levels and, ultimately, survival and reproduction (https://depons.eu/). The model simulates how many animals are exposed to pile-driving in different areas, depending on movement patterns and local density. In DEPONS, each harbour porpoise is an individual agent with its own movement history. It is, therefore, more likely to be exposed repeatedly if an individual harbour porpoise happens to be in the area more frequently, but this is a stochastic process. A similar approach is possible in iPCoD (both EE and DEB) where a user can specify vulnerable local populations where some individuals are more likely to be disturbed repeatedly. So, both models allow more modelling repeated exposure but the implementation mechanism is different. Finally: iPCoD is flexible and adapted for multiple marine mammal species (including seals, minke whales, and dolphins) across various regions. DEPONS is highly specialized and principally calibrated for harbour porpoises.

See Nabe-Nielsen & Harwood (2016) for a more extensive comparison of the models.

4.4 Improving understanding of Population Consequences of Disturbance – Magda Chudzinska

Chudzinska et al. (2023) explored the relationship between the probability of animals being present to be disturbed and the disturbance effect (expressed by number of foraging hours lost) for:

- birth rate,
- pup/calf mortality rate by starvation,
- adult mortality rate by starvation,

The actual disturbance effect is determined by various factors, such as the baseline foraging duration and swimming (i.e. fleeing) speed (Appendix I in Harwood et al. (2024)):

- The longer the baseline foraging duration the larger the disturbance effect;
- The slower the animals swim, the larger the disturbance effect.

These effects vary with the distance of the animals from the piling activity: within the disturbance area, a higher proportion of females is located further from the noise source (piling activity) than those that are located closer to piling and experience larger effects of disturbance (because they have to swim further and experience a longer period of lost foraging opportunity). The maximum disturbance distance, i.e. the maximum distance up to which animals can be disturbed by piling noise, therefore, also determines the disturbance effect. Chudzinska et al. (2023) demonstrated that model results are largely affected by assumptions about the disturbance effect as can be seen in Figure 4-4.

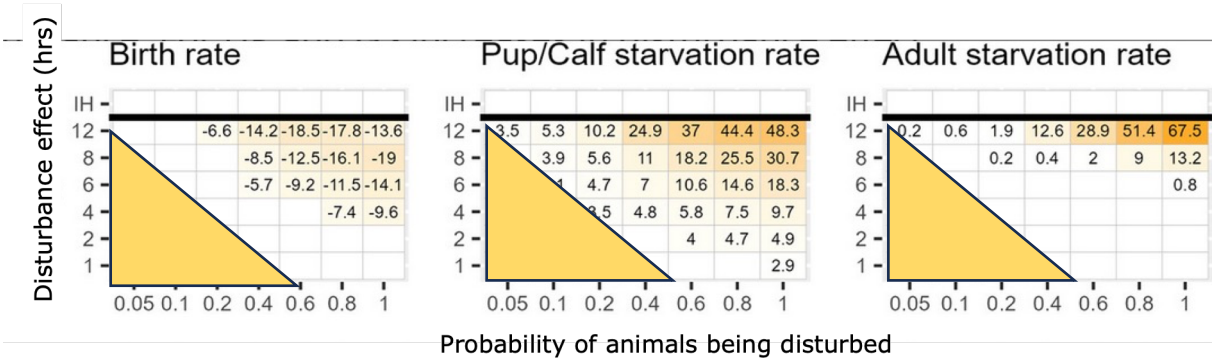


Figure 4-4 Percentage change from disturbance for different combinations of probability of disturbance and disturbance effect (hours of lost foraging) for harbour porpoises; yellow triangles represent combinations of probability of disturbance and disturbance effect with no or negligible impact (after Chudzinska et al. 2023).

For KEC 5.0, the number of animals being disturbed by piling noise was estimated by calculating the number of animals within the area where the Sound Exposure Level (SEL) exceeds the threshold for a behavioural response and applying a sound dose-response curve derived from Graham et al. (2019). This results in a lower probability of animals being affected that are located further from the noise source, where the SEL is lower. The local porpoise density is derived from the map drawn up by Gilles et al. (2020). In both iPCoD EE and iPCoD DEB a fixed value of 6 hrs was assumed that animals stop foraging as a result of disturbance. In a separate study, commissioned by Rijkswaterstaat/Wozep, it will be explored how the model results for the KEC 5.0 international scenario for wind farm

development (2016 – 2030) will be affected using two different Erlang[7] distributed disturbance effect instead of the default 6 hrs (Chudzinska et al., 2026, to be published on www.Noordzeeloket.nl). Preliminary results were shown during the workshop.

Differences between iPCoD EE & iPCoD DEB include:

- Duration of disturbance (disturbance effect) is fixed at 6 hrs in iPCoD EE and can be replaced by a distribution around a mean value in iPCoD DEB. This not possible in iPCoD EE; a new expert elicitation would be needed.
- In iPCoD EE, it does not matter whether an animal is disturbed for 10 consecutive days or for 10 days spread throughout the year. This is different in iPCoD DEB because of the modelled compensation ability and seasonal differences.
- In iPCoD DEB, each individual female in a (sub)population builds up a calendar of disturbance events, which is not the case in iPCoD EE. In the latter, individuals are drawn from the North Sea population at the beginning of each year from scratch. In the current settings of iPCoD DEB for KEC, every individual porpoise of the North Sea population is equally susceptible for exposure. Because they build up a calendar, individual porpoises could (in theory) experience disturbance for three consecutive days, which they cannot compensate anymore. As said before, movement ecology dictates exposure and effects, and as it is not known how porpoises in the Southern North Sea move (how resident are they?), the probability that disturbances of an individual porpoise for three consecutive days could occur is not known.

Another important aspect concerns the compensation ability after temporary loss of foraging opportunity. In iPCoD DEB, compensation for lost energy intake only begins the day after disturbance, even if piling lasts 2-3 hours. This is a worst case, because no within-day compensation is included. If the animal is not disturbed for several consecutive days, it does not matter whether compensation begins immediately after the disturbance or the next day. Piling schedule (when and how many piling events per year) probably strongly influences model outcomes (see also Chudzinska et al. (2026), to be published on www.noordzeeloket.nl). Ship presence (before actual piling activity) reduces local harbour porpoise presence, complicating assumptions about disturbance duration. Displacement and competition for food, reducing foraging efficiency, is accounted for in the model. Compensation for the remainder of the day is not, as explained before.

Remaining points:

- There is interest in a comparison between the DEPONS and the iPCoD DEB model for identical piling schedules. This is foreseen in the 2026 planning of Rijkswaterstaat/Wozep.
- Realistic piling schedules are important. In the current KEC 5.0 scenario pile driving of two piles per three days is assumed. It is noted that pile driving three piles per day has already been done. This reduces the number of days with piling activity considerably. Compensation ranges are parameterised in the model (based on results from controlled experiments), but questions remain about how well they reflect wild animals.

[7] By using an Erlang distribution, variation in disturbance effect among individuals is introduced. This was used to capture the expected heterogeneity in individual responses.

- It is noted that the difference between night and day activity of porpoises should be taken into account. This is partly incorporated in the model, and piledriving is happening 24/7.

The iPCoD models also have the option to include the relationship between available resources and population size (density dependence). This relationship was extracted from a DEB model by Hin et al. (2019) on pilot whales. The mechanism is that birth rates change via food availability (prey density). The hypothesis is that a reduction in population size might result in an increase in resource density and a consequential increase in calf survival and fecundity. The assumption is also that any increase in prey density would be available to all individuals in the porpoise population. This may not be the case as there are many other generalist predators in the North Sea that consume similar prey species and prey sizes as harbour porpoises do. It is therefore unlikely that all the 'surplus production' of prey will be available to the harbour porpoise population. The speed with which the population returns to its equilibrium will probably be overestimated.

Another uncertainty concerns the potential differences in demographic parameters between various North Sea regions (why do they differ?) and how these would affect model outcomes (also with respect to density dependence). Currently both versions of the iPCoD model are parameterised to fixed demographic rates for the entire North Sea harbour porpoise population as recommended by Sinclair et al. (2020). Data presented and discussions held suggest that these rates may not be uniform for the entire North Sea, or there may be more than one population in the North Sea.

4.5 Potential future developments

Coming back to the goals of the second part of the workshop: "Informing iPCoD & Application in KEC":

- Implement learning form the first part to consider how to improve use of iPCoD (including which version of the model) and potentially the model overall
- Informed by poll & key sensitivities for informing iPCoD, such as:
  - Movement ecology (informing probability of exposure)
  - Response to disturbance (in terms of energy cost)
  - Compensation abilities
  - Density dependent effects on population recovery

In the poll sent out before the workshop took place, the last question concerned the most important knowledge gaps according to the participants (Figure 4-5 and Annex 2.1). The opinions showed a large variety indicating that knowledge gaps exist in all fields ranging from physiological changes due to disturbance to ecosystem effects.

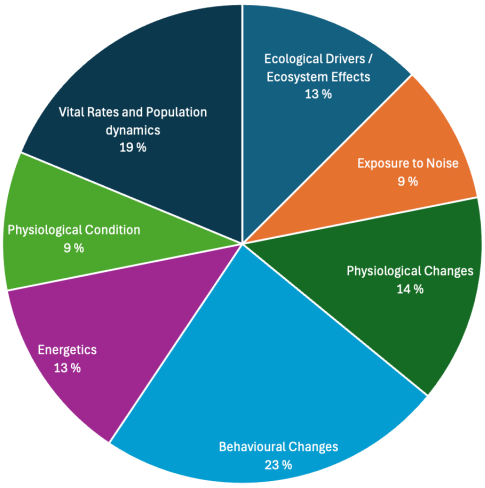


Figure 4-5 Answers to question: "Which uncertainties or gaps (grouped into PCOD framework boxes) do you think should be the focus on over the next 2-3 years to help improve KEC assessments?"

The PCoD framework was developed because it can give an early warning of potential population declines. Such an early warning is important because it is not possible to detect precipitous declines for most marine mammal species based on the results of population monitoring (Taylor et al., 2007).
Modelling the (potential) effects of disturbance helps to forecast:

1. What can happen
2. When (if)
3. For how long
4. What happens after

The question remains how to monitor best for population changes? What could be early warning signs?

SMRU Consulting developed via the 'MSM4PCoD[8]' project an integrated approach to robustly monitoring marine mammal populations (Booth et al., 2026). The principle in this approach is to use information from various datasets and integrate the various jigsaw pieces. The simulations performed in the case study, described by Booth et al. (2026) highlighted that there was a significant increase in power generated from integrating datasets. In particular, including a calf:adult ratio was a key element driving the increase in power from these integrated approaches. The ratio was generated from photo-ID surveys in the simulation but also could be derived from visual surveys and photogrammetry. The case study was based on data from beaked whales. For harbour porpoises, monitoring body condition could also be an important metric to improve the detection of population change. It is important to stress that the model was a simulation. Future efforts using different declines, fitting different population models and increasing uncertainty around parameters could help to determine the robustness of this integrated approach.

For harbour porpoises, integration of data from various sources could be promising, combining results from:

- Long-term monitoring,
- Demographic rate monitoring,

[8] MSM4PCoD = Marine Species Monitoring for the Population Consequences of Disturbance

- Analysis of extensive PAM data,
- Utilize telemetry data,
- Expand analytical toolbox to maximize what can be done with existing datasets.

In a Ørsted sponsored project on deterrence ranges and dose response functions for piledriving (PEDROW[9]) metadata of individual projects are collected, which could give a good starting point for setting up a database.

4.6 Mapping ideas for future work

In the last part of the workshop participants were asked to map their ideas for future research to fill identified knowledge gaps. The timeline for future KECs was leading in the planning. Ideas for future research, to be executed/started:

A. Short term (0 – 3 months); KEC 6.0, to be reported end of 2026
B. Until end of 2027; knowledge base update KEC 6.0
C. > 3 years; KEC 7.0 and later

Participants could give recommendations for future directions/next steps in research to fill in knowledge gaps identified within the time frames A, B and C on the following topic areas:

1. What can happen: piling schedules
2. When (if): probability of exposure, subpopulations, movement ecology
3. For how long: duration of disturbance
4. What happens after: energetic pathway and other pathways
5. Model extensions
6. Monitoring
7. Other
8. Testing the current model

Key messages summarized from the large number of suggestions are (see Annex 3 for an extended summary):

- Make better use of existing monitoring and research datasets. Many model assumptions—movement, energetics, reproduction, disturbance responses—require updated, long-term, and spatially explicit data. There is also a need to improve access to developer and industry data to better represent real-world construction scenarios.
- Improve the understanding of disturbance, recovery, and energetic consequences.
- Strengthen the link between field observations, health indicators, and model development.
- Models must be tested against real observations—strandings, tagging, PAM, drone data, prey dynamics, and demographic indicators.
- Understanding of the population structure, including subpopulations, site fidelity/movement patterns and regional differences.

[9] PEDROW: Porpoise Effective Deterrence Ranges and Dose-Response functions for pile-driving of Offshore Wind.

5 General discussion and outlook

5.1 To DEB or not to DEB

At the end of the workshop all participants were (again) asked how they would value the two iPCoD versions (EE versus DEB) in a 100-point split and were asked to argue why they weighted the models in such a way. On the average, there was a 61,1% preference for the DEB version of the model, although most saw value in combining elements of both approaches (see Appendix 2.2 for results). Participants generally viewed DEB as the more promising long-term framework because of its mechanistic, energy-based, and data-driven nature. However, confidence in DEB remains conditional on further validation and model refinement. Many respondents favoured a hybrid approach, retaining EE's ability to capture non-energetic and expert-informed effects while using DEB as the primary modelling framework. A summary of the arguments for choosing for one of the two models is given below.

Strong points of iPCoD DEB:

- Preference for empirical, mechanistic approaches
  - Many participants expressed greater confidence in a model grounded in data, mechanisms, and energetic processes rather than expert judgment alone.
  - iPCoD DEB was viewed as more objective, scientifically rigorous, and easier to validate because its predictions arise from explicit biological mechanisms.
- Importance of energetics
  - Respondents consistently emphasized that energetics are central to harbour porpoise ecology and therefore provide a strong common currency for assessing impacts.
  - Several considered energetics the only pathway currently supported by a clear evidence base.
- Flexibility and transparency of iPCoD DEB
  - iPCoD DEB was seen as more flexible for testing scenarios, modifying assumptions, conducting sensitivity analyses, and identifying influential parameters.
  - Participants appreciated that iPCoD DEB is less dependent on subjective user input and expert opinion.

Concerns about iPCoD DEB:

- Need for validation and testing
  - Uncertainty about whether DEB is sufficiently mature for full adoption.
  - Respondents called for further evaluation, sensitivity analyses, bug fixes, and testing against real-world scenarios before making a definitive choice.

Strong points of iPCoD EE:

  - Despite a general preference for DEB, many respondents highlighted that EE could incorporate non-energetic pathways, expert knowledge, and ecological nuances that are currently absent from DEB.
  - These broader considerations were viewed as important and should ideally be retained or integrated into future model development.

Concerns about iPCoD EE:

- Several participants felt EE outputs exhibited high variance and limited transparency, making it difficult to assess assumptions, conduct sensitivity analyses, or determine the drivers of results.
- The reliance on expert judgment was seen as both a strength and a potential weakness, given that experts can be wrong and human perspectives may introduce bias.

5.2 Outlook

5.2.1 Research on harbour porpoises at Utrecht University

At Utrecht University, with funding from the Ministry of LVVN, Wozep and Ecowende, various studies are being carried out providing relevant data for the improvement of the models:

- Spatiotemporal and demographic variability in body condition of North Sea harbour porpoises (recently published as: Schotanus et al. 2026).
- Evaluation of the applicability of 'age-at-independence' determination (expected results in 2027).
- Determination of the reproductive cycle of harbour porpoises in the southern North Sea, including conception, gestation, calving, and lactation periods (expected results in 2027).
- Characterization of body condition in relation to life-history stage and seasonality in adult female harbour porpoises (expected results in 2027/2028).
- A study on demographic structure of porpoises in Dutch coastal waters, by evaluating and comparing body length distributions obtained from aerial surveys with those obtained from necropsied animals (expected results in early 2027).
- Also, a study will be carried out by a MSc student if the presence of Wischnewski spots could be a reliable indicator for emaciation (expected preliminary results in early 2027).

5.2.2 Model development

In a separate study, related to the Ecowende/Wozep workshop, and commissioned by Rijkswaterstaat/Wozep Chudzinska et al. (2026) compared and analysed the two versions of the iPCoD model (to be published on Noordzeeloket.nl). Preliminary results were presented at the workshop (see Section 4.4).

Based on the findings of the study, recommendations and considerations were included on the following topics:

- The assessment of metrics for quantifying populations effects: choice of percentile for the Dutch ecological standard, choice of time window for assessing the population effect (average over 6 years after disturbance ends in iPCoD EE is not suitable for iPCoD DEB);
- The inclusion of density dependence and environmental stochasticity;
- Disturbance duration (fixed 6 hours vs. distribution around – lower – mean);
- Temporal distribution of piling activity.

In the roadmap for further model development and testing Chudzinska et al. (2026) proposed to focus on:

- **Model parametrisation**
  The current parameterisation in iPCoD DEB results in a population that increases slightly over time in the absence of any type of disturbance (~1% per year). Future work could explore alternative parameterisations that produce more stable long-term population dynamics, which may better reflect equilibrium conditions where density-dependent mechanisms more strongly regulate population growth. Re-parameterisation may also be warranted if new empirical data on harbour porpoise energetics, behaviour or demography become available, for example from ongoing projects such as the Ecowende initiative and the Wozep programme. Suggested parameters are energy expenditure and different demographic rates. As shown reducing parameter uncertainty through empirical research on harbour porpoise energetics could substantially narrow the range of predicted outcomes, potentially leading to more robust and defensible population assessments. This task would not require any code modifications, but it would require a large number of simulations.
- **Revisiting disturbance duration**
  The default assumption of 6 hours of foraging cessation per disturbance event has remained unchanged since the second expert elicitation in 2018 (van Beest et al. 2018, Booth et al. 2019). Our sensitivity analysis demonstrates that disturbance duration has the largest influence on predicted population impacts of all parameters tested. Given the importance of this parameter, a systematic review of recent empirical data on harbour porpoise behavioural responses to pile-driving noise is recommended to determine whether updated estimates of disturbance duration are warranted. This task would not require any code modifications in iPCoD DEB, as the option of changing duration is already available in the code. To modify this in iPCoD EE e new expert elicitation would be necessary.
- **Seasonal timing of disturbance**
  The sensitivity analysis performed for iPCoD DEB could not isolate the effect of avoiding piling in specific months, because the algorithms used to redistribute piling across the remainder of the year introduced new annual peaks in that confounded the seasonal signal. A dedicated analysis — using simplified or hypothetical schedules in which the total number of harbour porpoise disturbance days is held constant while seasonal distribution is varied — would be required to address this question directly. This was not attempted in the current work because it would not inform KEC 6.0, which is built around multi-project scenarios; however, it would be valuable for informing project-level mitigation measures and for understanding how the energetic cycle of harbour porpoises relates to population-level vulnerability. This task would not require any code modifications in iPCoD DEB (seasonal timing of disturbance does not affect iPCoD EE outcomes).

5.2.3 Framework for Assessing Ecological and Cumulative Effects (KEC)

The KEC is continuously refined and supplemented with the latest insights. There is a new version approximately every two years. In addition to the most recent insights from new research, each new version also includes calculations of the cumulative effects of a new

wind farm scenario. Assumptions that were made earlier are continually refined by new insights, documented in 'Updates of the knowledge base'. The most recent version of the KEC, KEC 5.0, dates from April 2025 and the knowledge base for the KEC 6.0 report on Underwater Noise from June 2026.

TNO & HWE are currently working on the KEC 6.0 report, which will be published at the end of 2026. For this report, the cumulative impact of a new (inter)national scenario for windfarm development on marine mammal populations will be estimated, using the most recent maps on the distribution of harbour porpoises and seals. Both iPCoD EE and iPCoD DEB models will be used to get an indication of the cumulative impact on the harbour porpoise population of the North Sea. The insights gained during the Ecowende/Wozep workshop and the study by Chudzinska et al. (2026) will be used to interpret the results.

5.2.4 Other ongoing and planned research in the Netherlands

Wozep Ecological Programme

- Effect of vibropiling in an experimental setup. A study is carried out at the Fjord&Baelt research facility to assess behavioural- and TTS- thresholds by exposing three porpoises held in captivity to playbacks of different vibropiling signals (VISSKA, SIMPLE III). Final report expected in October 2026.
- Since 2023, a pilot project has been running that aims to catch, tag and release porpoises in the wild. During four field campaigns (May 2024-March 2026), a total of five porpoises were equipped with a satellite transmitter, enabling the monitoring of individual porpoises for the first time in the Dutch North Sea. This will provide a better understanding of movements, behaviour and use of the North Sea and adjacent waters by porpoises.
- Passive Acoustic Monitoring (PAM):
    - Borssele windfarm, which is located in a very busy area of the Southern North Sea (see Figure 5-1): data were collected at 14 locations in and around the windfarm for a period of five years (2021 – 2026). These data will be analysed in the coming period.
    - Ecowende windfarm: see below
    - Future Doordewind windfarm: a PAM-network is installed in January 2026 in the area where the windfarm will be built. Measurements will be collected at six locations in this area over the next three years to gain insight into underwater noise levels and the presence of cetaceans.

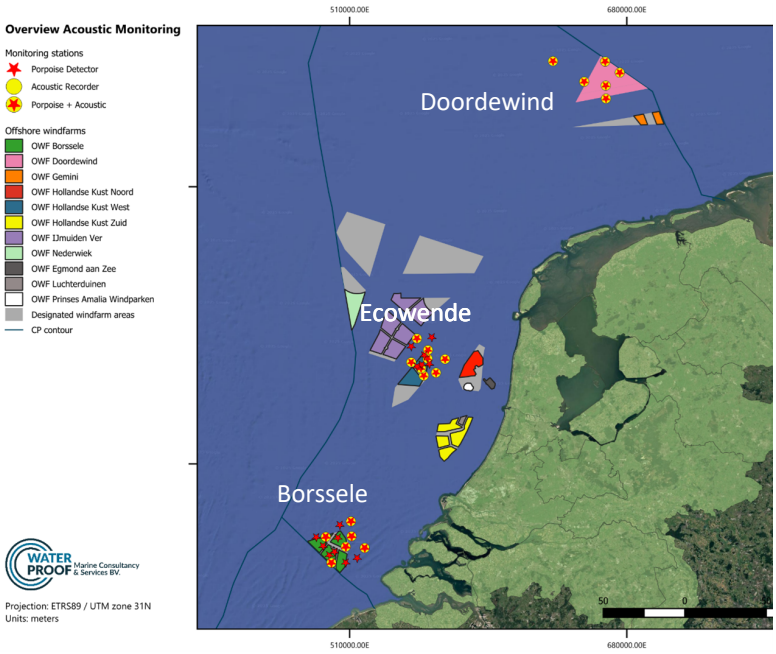


Figure 5-1 Locations of acoustic measurement networks in present or future windfarms in the Dutch North Sea.

MONS Programme (Monitoring and Research Programme for Nature Enhancement and Species Protection)

On going research:

- Drones for condition assessment: research carried out by Ecowende and Utrecht University (see also below) to explore the potential for practical drone use for the determination of the condition of porpoises. Largely determined by volume as proxy for condition. Furthermore, other external characteristics that can be used as an indicator for condition parameters are examined.
- Bycatch in gill-net fishing: bycatch of porpoises and its potential impact on the population.

In preparation:

- Integration of spatial data: Integrating existing monitoring datasets to fill gaps in cetacean and seal distribution over time and reduce uncertainty.
- Masking: Desk study into masking effects of sound sources relevant for the North Sea on porpoises. This investigation should take a step in the process of gathering enough information to be supplemented to the MSFD descriptor on continuous noise.
- Drift models (MONS/ Wozep): Incorporate an option into the already used drift model of RWS aiming at the determination of the most likely origin or stranding location of marine mammals at sea.

Planned:

- Genetic research: Research into the genetic diversity of porpoises (stranded or bycaught) along the Dutch coast to determine the existence of sub-populations.

- AI acoustic monitoring: AI analysis of monitoring data of porpoises but especially exploration of other cetaceans as well as AI analysis of available public databases of whale sounds relevant for the North Sea.
- Digital area survey: Exploring the possibility of using High-Definition cameras to replace the current marine mammal monitoring without (or with a known trend break), as well as the automated analysis of the data produced.

Ecowende – Hollandse Kust West VI (HKW VI)
Ecowende, in collaboration with Waterproof and TNO will carry out several studies aimed at improving the technical assumptions within KEC:

- Waterproof is working on a noise characterisation of various noise mitigation methods (near-field and far-field, incl. bubble curtains) and innovative installation techniques such as vibropiling and vibrojetting. This study is a basic analysis to attain insight into the (spectral) characteristics of the emitted sound and applied mitigation measures during the installation of turbine foundations at Hollandse Kust West VI windfarm. The report is expected to be made publicly available at the end of 2026.
- For HKW VI, TNO will compare their modelled underwater sound predictions (prior to windfarm construction) with the measured underwater sound levels for impact piling, vibro-piling, and vibrojetting. The comparison will include the measured effectiveness of the applied noise mitigation systems, including dBBC (double Big Bubble Curtain) and the AdBm noise mitigation system. Including a short interpretation of discrepancies between measured sound and predictions based in the KEC method. The report is expected in 2027.
- Various studies aimed at addressing the knowledge gaps in determining the noise dose to which animals are exposed during construction and verifying related technical assumptions (e.g. influence of the state of the water surface, influence of sound transmission through the seabed) in the KEC. The report(s) is/are expected in 2027.

Furthermore, in collaboration with Waterproof and Seamarco, several studies will contribute to improving the biological assumptions within KEC, and more generally the impact of offshore wind on harbour porpoises:

- Seamarco studies:
  - Masking effect: Critical bandwidth of a Harbour Porpoise (at 4 kHz) (in prep.)
  - Effect of Duty Cycle Composition of Intermittent Sound on Temporary Hearing Threshold Shift in a Harbor Porpoise (*Phocoena phocoena*) (Kastelein et al., 2026)
  - Temporary Hearing Threshold Shift and Testing the Equal-Energy Hypothesis in a Harbor Porpoise (*Phocoena phocoena*) after Exposure to Continuous Noise Bands at 8 kHz, and a revised TTS onset function (Kastelein et al., 2024)
- Investigation into the applicability of using drones (or aerial) surveys to study health of wild harbour porpoises (partially within Utrecht University project; Eva Schotanus' PhD). A recent meeting between Ecowende, Utrecht University and BioConsult identified possible health indicators that can already be extracted from aerial surveys.
- MSc student at Waterproof investigating the link between PAM (F-POD) data and aerial survey data from the HKW VI area.

- Pilotting of an innovative monitoring method, Harbour Porpoise Tracking Station, allowing for 3D tracking of wild individual harbour porpoises.
- Noise measurement campaign during the operational phase of the windfarm, characterising the emitted sound from a Service Operation Vessel (SOV).
- Continuation of Ecowende's PAM network until 2031, studying the presence of harbour porpoises before, during and after construction of HKW VI. These data are also used by WaterProof to establish the dose-response relationship between piling sound exposure and harbour porpoise response during Ecowende installations.

6 References

Baier-Stegmaier, S., C. Gundlach, M. Chriél, M.S. Hansen, C. Vedel-Smith, C.V. Hansen, D.K. Johansson, L.B. Henriksen, M. Wahlberg, C.B. Thøstesen et al. (2023). Computed Tomography as a Method for Age Determination of Carnivora and Odontocetes with Validation from Individuals with Known Age. Animals 2023, 13, 1783. https://doi.org/10.3390/ani13111783.

Barratclough A, R. Sanz-Requena, L. Marti-Bonmati, T.L. Schmitt, E. Jensen & D. Garcíía-Párraga (2019). Radiographic assessment of pectoral Flipper bone maturation in bottlenose dolphins (Tursiops truncatus), as a novel technique to accurately estimate chronological age. PLoS ONE 14(9): e0222722. https://doi.org/10.1371/journal. pone.0222722.

Bakkeren, M., M. Ladageaard, K.A. Hansen, M. Wahlberg, P.T Madsen & L. Rojano-Doñate (2023). Visual deprivation induces a stronger dive response in harbor porpoise. iScience 26, 106204. https://doi.org/10.1016/j.isci.2023.106204.

Booth, C. & F. Heinis, 2018. Updating the Interim PCoD Model: Workshop Report – New transfer functions for the effects of permanent threshold shifts on vital rates in marine mammal species. Code SMRUC-UOA-2018-006.

Booth, C., F. Heinis & J. Harwood, 2019. Updating the Interim PCoD Model: Workshop Report – New transfer functions for the effects of disturbance on vital rates in marine mammal species. Report Code SMRUC-BEI-2018-011.

Booth, C.G., M. Ryder, M. Chudzinska, E. Jacobson, J. Harwoord, V. Hin, M. Quinn & L. Thomas (2026). Marine Species Monitoring for the Population Consequences of Disturbance (MSM4PCoD): an integrated Approach to robustly monitoring marine mammal populations – Final Report to Living Marine Resources. Report number SMRUC-LMR-2026-007 (unpublished).

Brennecke, D., U Siebert, L. Kindt-Larsen, H.S. Midtiby, H.D. Egemosse, S. Torres Ortiz, K. Knickmeier & M. Wahlberg (2022). The fine-scale behavior of harbor porpoises towards pingers. Fish. Res. 255:106437. https://doi.org/10.1016/j.fishres.2022.106437.

Chudzinska M., Klemntisova, K., Booth, C. & Harwood, J. (2023). Combining bioenergetics and movement models to improve understanding of the population consequences of disturbance. Oikos 2023: e10123. doi: 10.1111/oik.10123.

Chudzinska, M., N.M. Risser, C.A.F de Jong & F. Heinis (2026). DEB or not to DEB, this is a question: comparison and analysis of the two opulation consequences of disturbance models: iPCoD EE and iPCoD DEB. SMRUC-RJK-2026-003.

Costa, D.P., Hückstädt, L.A., Schwartz, L.K., Friedlaender A.S. et al. (2016). Assessing the exposure of animals to acoustic disturbance: Towards an understanding of the population consequences of disturbance. Proceedings of Meetings on Acoustics, Vol. 27, 010027.

Derous et al. (2020) Toward New Ecologically Relevant Markers of Health for Cetaceans. Front. Mar. Sci. doi:10.3389/fmars.2020.00367.

Derous et al (2021) Comparative genomics of cetartiodactyla: energy metabolism underpins the transition to an aquatic lifestyle, Conservation Physiology, Volume 9, Issue 1, 2021, coaa136.

Derous, D., A. Kebke, P.A. Fair, M. Styczynski, G.D. Bossart, A. Douglas & D. Lusseau (2022). Untargeted plasma metabolomic analysis of wild bottle nose dolphins (*Tursiops truncatus*) indicate protein degradation when in poorer health et al. 2022. Comp. Biochem, Physiol. – Part D: Genomics and Proteomics 42. https://doi.org/10.1016/j.cbd.2022.100991.

Derous, D., N.J. Dacison & A. Brownlow (2026). Proteomic Insights into Liver Pathology and Stratified Blubber Biology in a Stranded Adult-Juvenile Cetacean Pair: A Proof-of-Concept Study. Marine Mammal Science, 42e:70229. https://onlinelibrary.wiley.com/doi/10.1111/mms.70229.

Elmegaard, S.L., J. Teilmann, L. Rojano-Doñate, D. Brennecke, L. Mikkelsen, J.D. Balle, U. Gosewinkel, L.A. Kyhn, P. Tønnesen, M. Wahlberg, A. Ruser, U. Siebert & P.T. Madsen (2023).

Wild harbour porpoises startle and flee at low received levels from acoustic harassment device. Scientific Reports 13:16691. https://doi.org/10.1038/s41598-023-43453-8.

Filatova, O.A., I.D. Fedutin, F. Jakobsen, L. Kindt-Larsen & M. Wahlberg (2024). Harbor porpoise displacement by a solitary bottlenose dolphin in the Baltic Sea. Mar. Mam. Sci. https://doi.org/10.1111/mms.13164.

Gilles, A., N. Ramirez-Martinez, D. Nachtsheim & U. Siebert, 2020. Update of distribution maps of harbour porpoises in the North Sea. Commissioned by Rijkswaterstaat. University of Veterinary Medicine, Institute for Terrestrial and Aquatic Wildlife Research (ITAW).

Gilles, A., Authier, M., Ramirez-Martinez, N., Araújo, H., Blanchard, A., Carlström, J., . . . Hammond, P. (2023). Estimates of cetacean abundance in European Atlantic waters in summer 2022 from the SCANS-IV aerial and shipboard surveys. Final report published 29 September 2023.

Graham, I.M., N.D. Merchant, A. Farcas, T.R. Barton, B. Cheney, S. Bono, P.M. Thompson, 2019, Harbour porpoise responses to pile-driving diminish over time. R. Soc. Open sci. 6: 190335. http://dx.doi.org/10.1098/rsos.190335.

Hamel, H., S. Torres Ortiz & M. Wahlberg (2024). Long-term observations reveal short-term mother-calf affiliation in wild harbour porpoises. Animal Behaviour 219: 122992. https://doi.org/10.1016/j.anbehav.2024.10.006

Hanninger, E-M., F., K.J. Peters, L. Gerbe, A. Barratclough, E.L.Betty, E.I.Palmer, S. Horvath & K.A. Stockin 2025. Dental Ageing Offers New Insights into the First Epigenetic Clock for Common Dolphins (Delphinud delphis). Ecology and Eveolution. https://doi.org/10.1002/ece3.72424.

Hao, X., H. Hamel, C. Hagerup Grandjean, I. Fedutin, M. Wahlberg, C.K. Frankish & J. nabe-Nielsen (2024). Harbour pospoise respond to recreational boats by speeding up and moving away from the boat path. Ecology and Evolutio, 2024;14:e11433. https://doi.org/10.1002/ece3.11433.

Harwood J., M. Chudzinska, V. Hin, F. Wilder, E, Marwood & C. Booth, 2023. Adapting the iPCoD Framework for Harbour Porpoises to Utilise a Dynamic Energy Budget Model in Modelling the Effects of Disturbance – Final Report. Report number SMRUC-MSS-2024-006. Prepared for Offshore Wind Directorate and Marine Directorate, May 2024.

Harwood, J., S. King, R. Schick, C. Donovan & C. Booth, 2013. A protocol for implementing the interim population consequences of disturbance (PCOD) approach: quantifying and assessing the effects of UK offshore renewable energy developments on marine mammal populations. Report SMRUL-TCE-2013-014. Scottish Marine and Freshwater Science 5(2).

Henriksen, L.B., C.B. Thøstesen, A.K. Olsen Alstrup, H.L Larsen, M. Wahlberg, U. Siebert & S. Pagh (2024). A New Simple Method for Age Determination of Harbour Porpoises (*Phocoena phocoena*). Aquatic Mammals 50: 30-38. DOI 10.1578/AM.50.1.2024.30.

Hin, V., J. Harwood, and A. M. de Roos (2019). Bio-energetic modeling of medium-sized cetaceans shows high sensitivity to disturbance in seasons of low resource supply. Ecological Applications **29**:e01903.

Houser et al (2021) Metabolic response of dolphins to short-term fasting reveals physiological changes that differ from the traditional fasting model. J Exp Bio; 224 (9): jeb238915. doi: https://doi.org/10.1242/jeb.238915

IJsseldijk L.L., M.F. Leopold, L. Begeman, M.J.L. Kik, L. Wiersma, M. Morell, E.L. Bravo Rebolledo, T. Jauniaux, H. Heesterbeek & A. Gröne (2022). Pathological findings in stranded harbor porpoises (*Phocoena phocoena*) with special focus on anthropogenic causes. Front. Mar. Sci. 9:997388. doi: 10.3389/fmars.2022.997388.

IJsseldijk, L.L, S. Hessing, A. Mairo, M.T.I. ten Doeschate, J. Treep, J. van den Broek, G.O. Keijl, U. Siebert, H. Heesterbeek, A. Gröne & M.F. Leopold, 2021. Nutritional status and prey density govern reproductive success in a small cetacean. *Sci Rep* 11, 19201. https://doi.org/10.1038/s41598-021-98629-x

IJsseldijk, L.L. (2021). Living on a knife-edge – Unravelling harbour porpoise health through multidisciplinary and cross-border approaches. PhD thesis, Utrecht University.

IJsseldijk, L.L., & ten Doeschate, M.T.I., Brownlow, A., Davison, N.J., Deaville, R., Galatius, A., Gilles, A., Haelters, J., Jepson, P.D., Keijl, G.O., Kinze, C.C., Olsen, M.T., Siebert, U., Bie Thøstesen, C., van den Broek, J., Gröne, A., & Heesterbeek, H. (2020a). Spatiotemporal mortality and demographic trends in a small cetacean: Strandings to inform conservation management. Biological Conservation 249: 108733.

IJsseldijk, L.L., Scheidat, M., Siemensma, M.L., Couperus, B., Leopold, M.F., Morell, M., Gröne, A., & Kik, M.J.L. (2020b). Challenges in the Assessment of Bycatch: Postmortem findings in Harbor Porpoises (*Phocoena phocoena*) retrieved from gillnets. Veterinary Pathology, 58(2), 405–415. https://doi.org/10.1177/0300985820972454

Irschick D.J., J.Martin, U.Siebert, J.H.Kristensen, P.T. Madsen & F. Christiansen (2020). Creation of accurate 3D models of Harbor porpoises (*Phocoena phocoena*) using 3D photogrammetry. Mar. Mam. Sci. 2020: 1-10. DOI: 10.1111/mms.12759.

Jakobsen, F., Sveegaard S., Slusarczyk, H. Kaarsted, T. Thybo, M. & Wajlberg, M. (2025). Fine-scale distribution and seasonality of harbour porpoises (*Phocoena phocoena*) investigated with citizen science. J. Cetacean Res. Mange. 26: 77 – 86. https://doi.org/10.47536/jcrm.v26i1.959

Kastelein, R.A. (1998). Food consumption and growth of marine mammals. PhD thesis.

Kastelein, R. A., L. Helder-Hoek, & N. Jennings, 2018. Seasonal changes in Food consumption, respiration rate, and body condition of a male harbor porpoise (*Phocoena phocoena*). Aquatic Mammals, 44, 76–91.

Kastelein, R.A., Helder-Hoek, L., Jennings, N., van Kester, R. & Huisman, R. (2019a). Reduction in body mass and blubber thickness of harbor porpoises (*Phocoena phocoena*) due to fasting for 24 hours in four seasons. Aquatic Mammals, 45 37-47. DOI 10.1578/AM.45.1.2019.37.

Kastelein, R.A., Helder-Hoek, L., Booth, C., Jennings, N. and Leopold, M. (2019b). High levels of food intake in harbor porpoises (*Phocoena phocoena*): Insight into recovery from disturbance. Aquatic Mammals 45(4), 380-388, DOI 10.1578/AM.45.4.2019.380.

Kastelein, R.A., L.A.E. Huijser, S. Cornelisse, L. Helder-Hoek, N. Jennings, & C.A.F. de Jong, (2019c). Effect of Pile-Driving Playback Sound Level on Fish-Catching Efficiency in Harbor Porpoises (*Phocoena phocoena*). Aquatic Mammals 45: 398 – 410, DOI 10.1578/AM.45.4.2019.398.

Kastelein, R.A., L. Helder-Hoel, L. van Acoleyen, L.N. Defillet & J. Terhune (2024). Temporary Hearing Threshold Shift and Testing the Equal-Energy Hypothesis in a Harbor Porpoise (*Phocoena phocoena*) after Exposure to Continuous Noise Bands at 8 kHz, and a revised TTS-onset function. Aquatic Mammals 50(5) 445-459. DOI https://doi.org/10.1578/AM.50.5.2024.445

Kasteleien, R.A., L. van Acoleyen, K. Tuytens, J.M. Terhune, A.M. von Benda-Becskmann & E. Jansen (2026). Effect of Duty Cycle Composition of Intermittent Sound on Temporary Hearing Threshold Shift in a Harbor Porpoise (*Phocoena phocoena*). Aquatic Mammals 52($), 334-344. https://doi.org/10.1578/AM.52.4.2026.334

Kershaw, J., C. Ramp, R. Sears, A. Hall & D. Derous (2024). Proteome profiling reveals opportunities to investigate responses in blubber biopsies from free-ranging baleen whales. Conservation Physiology 12. 10.1093/conphys/coae059.

Khudyakov J.I., K.N. Allen2 D.E. Crocker, N.S. Trost, A.H. Roberts, L. Pirard, C. Debier, E.R. Piotrowski and J.P. Vázquez-Medina (2022). Comprehensive molecular and morphological resolution of blubber stratification in a deep-diving, fasting-adapted seal. Front. Physiol. 13:1057721. doi: 10.3389/fphys.2022.1057721.

Lockyer, C. & C. Kinze (2003). Status, ecology and life history of harbour porpoise (*Phocoena phocoena*), in Danish waters. NAMMCO Scientific Publications, Volume 5: 143 – 175.

Mitchell, S.E., C. Delville, P. Konstantopedos, D. Derous1, C.L. Green, L. Chen, J.-D. J. Han, Y. Wang, D.E.L. Promislow, A. Douglas, D. Lusseau & J.R. Speakman (2015). The effects of graded levels of calorie restriction: III. Impact of short term calorie and protein restriction on mean daily body temperature and torpor use in the C57BL/6 mouse. Oncotarget, Vol. 6, No. 21. 18314 – 18337.

Murphy, S., Barber, J. L., Learmonth, J. A., Read, F. L., Deaville, R., Perkins, M. W., ... & Jepson, P. D. (2015). Reproductive failure in UK harbour porpoises *Phocoena phocoena*: legacy of pollutant exposure? PLoS One, 10(7), e0131085.

Nabe-Nielsen, J & J. Harwood (2016). Comparison of the iPCoD and DEPONS models for modelling population consequences of noise on harbour porpoises. Aarhus University, DCE – Danish Centre for Environment and Energy, 22 pp. Scientific Report from DCE – Danish Centre for Environment and Energy No. 186. http://dce2.au.dk/pub/SR186.pdf

Nielsen, N.H., J. Teilmann, S. Sveegaard, R.G. Hansen, M-H.S. Sinding, R. Dietz & M.P. Heide-Jørgensen, 2018.Oceanic movements, site fidelity and deep diving in harbour porpoises from Greenland show limited similarities to animals from the North Sea.Mar. Ecol. Prog. Ser. 597, 259 – 272.

Osiecka, A.N., O. Jones & M. Wahlberg (2020). The diel patters in harbour porpoises clicking behaviour is not a response to prey activity. Scientific Reports 10:14876. https://doi.org/10.1038/s41598-020-71957-0.

Pirotta, E, C.G. Booth, D.P. Costa, E. Fleishmann, S.D. Kraus, D. Lusseau, D. Moretti, L.F. New, R.S. Schick, L.K. Schwarz, S.E. Simmons, L. Thomas, P.L. Tyack, M.J. Weise, R.S. Wells & J. Harwood, 2018. Understanding the population consequences of disturbance. Ecol Evol. 8: 9934 – 9946. *https://doi.org/10.1002/ece3.4458*

Read, A. J., & Westgate, A. J. (1997). *Monitoring the movements of harbour porpoises (Phocoena phocoena) with satellite telemetry*. Marine Biology, 130(2), 315–322

Read, A.J., Wiepkema, P.R. & Nachtigall, P.E., eds. (1997). The biology of the harbour porpoise. De Spil publiskers.

Rojano-Doñate,L., B.I. McDonald, D.M. Wisniewska, M. Johnson, J. Teilmann, M. Wahlberg, J. Højer-Kristensen & P.T. Madsen (2018). High field metabolic rates of wild harbour porpoises. Journal of Experimental Biology (2018) 221, jeb185827. doi:10.1242/jeb.185827.

Rojano-Doñate, L., J. Teilmann, D.M. Wisniewska, F.H. Jensen, U. Siebert6, B.I. McDonald, S.L. Elmegaard, S. Sveegaard, R. Dietz, Mark Johnson & P.T. Madsen (2024). Low hunting costs in an expensive marine mammal predator. Sci. Adv. 10, eadj7132.

Scheidat, M., J. Vrooman, J. Teilmann, J. Baltzer, C.B. Thøstesen, B. Diederichs, R. Dietz, S.C.V. Geelhoed, A. Gilles, L.L. IJsseldijk, G.O. Keijl, J. Nabe-Nielsen, A. Ruser, J. Schnitzler, S. Sveegaard & U. Siebert (2024). Harbour porpoise (*Phocoena phocoena*) in the Wadden Sea World Heritage Site and requirements for trilateral monitoring. Marine Biodiversity 54:42. https://doi.org/10.1007/s12526-024-01428-6.

Schotanus, E.T., ten Doeschate, M.T.I., Brownlow, A.C., Dabin, W., Deaville, R., Gröne, A., Haelters, J., Heesterbeek, H., Jauniaux, T., Jensen, T.K., Kristensen, N.M., Lennon, R.L., Leopold, M.F., Peltier, H., Thøstesen, C.B., Williams, R.S. & L.L. IJsseldijk (2026). Spatiotemporal and demographic variability in body condition of North Sea harbour porpoises. Global Ecology and Conservation, 69, e04275.

Siebert et al., (2022). Variation of blubber thickness for three marine mammal species in the southern Baltic Sea. *Frontiers in Physiology*, *13*, 880465. https://doi.org/10.3389/fphys.2022.880465

Sinclair, R., J. Harwood, and C. Sparling (2020). Review of demographic parameters and sensitivity analysis to inform inputs and outputs of population consequences of disturbance assessments for marine mammals. Scottish Marine and Freshwater Science **11**:74.

Stepien et al., (2023). Determination of growth, mass, and body mass index of harbour porpoises (Phocoena phocoena): Implications for conservational status assessment of populations. *Global Ecology and Conservation*, *42*, e02384. https://doi.org/10.1016/j.gecco.2023.e02384

Sveegaard, S., J. Teilmann, J. Tougaard, R. Dietz, K.N. Mouritsen, G. Desportes & U Siebert (2011). High-density areas for harbor porpoises (Phocoena Phocoena) identified by satellite tagging. Mar. Mamm. Sci. 27: 230-246.

Taylor, B.L., M. Martinez, T. Gerrodette, J. Barlow & Y. Hrovat (2007). Lessons from monitoring trends in abundance of marine mammals. Mar. Mam. Sci. 23: 157 – 175. DOI: 10.1111/j.1748-7692.2006.00092.x.

Teilmann, J., Sveegaard, S., Dietz, R., Petersen, I. K., Berggren, P., & Desportes, G. (2008). *High density areas for harbour porpoises in Danish waters* (NERI Technical Report No. 657). National Environmental Research Institute, Aarhus University.

Tougaard, J., A.J. Wright & P.T. Madsen, 2015. Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. Marine Pollution Bulletin 90: 196–208.

Tougaard, J., Breedholm, K. & Madsen P. (2022). Thresholds for noise induced hearing loss in harbor porpoises and phocid seals. J. Acoust. Soc. Am. 151: 4252 – 4263. https://doi.org/10.1121/10.0011560.

Van den Heuvel-Greve, M.J., A. M. van den Brink, M.J.J. Kotterman, C.J.A.F. Kwadijk, S.C.V. Geelhoed, S. Murphy, J. van den Broek, Hans Heesterbeek, A. Gröne & L.L. IJsseldijk (2021). Polluted porpoises: Generational transfer of organic contaminants in harbour porpoises from the southern North Sea. Science of the Total Environment 796 (2021) 148936. https://doi.org/10.1016/j.scitotenv.2021.148936.

Wahlberg, M, Delgado-García, L & Kristensen, J.H. (2017). Precocious hearing in harbour porpoise neonates. J. Comp. Physiol. 203: 121 – 132.

Wisniewska, D.M., M. Johnson, J. Teilmann, ..., L.A. Miller, U. Siebert & P.T. Madsen (2016). Ultra-High Foraging Rates of Harbor Porpoises Make Them Vulnerable to Anthropogenic Disturbance. Current Biology 26, 1441–1446. http://dx.doi.org/10.1016/j.cub.2016.03.069.

ANNEXES

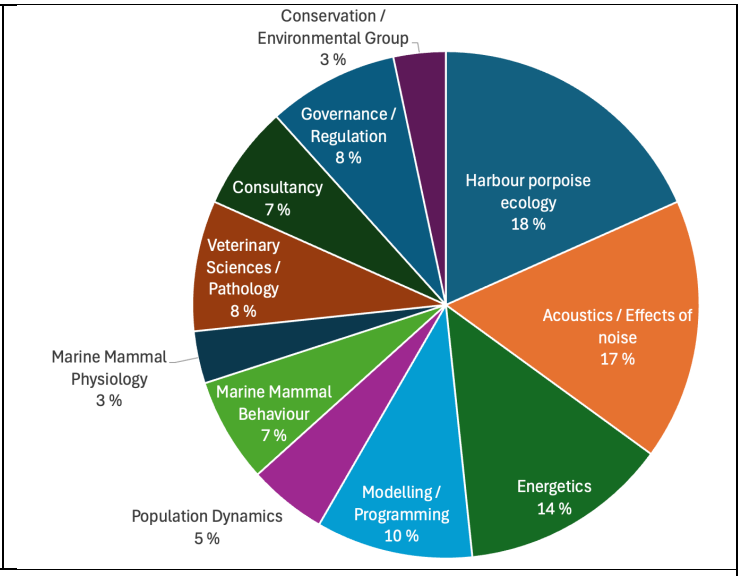
Annex 1 Workshop participants

Name	Organisation
Aleksija Neimane	Swedish Veterinary Agency
Andrea Gröne	Utrecht University
Andrew Brownlow	University of Glasgow / SMASS
Anna Roos	Stockholm Natural History Museum
Aylin Erkman	Rijkswaterstaat
Cara Gallagher	Aarhus University
Christ de Jong	TNO
Cormac Booth	SMRU Consulting
Davina Derous	University of Aberdeen
Eva Schotanus	Utrecht University
Floor Heinis	HWE Ecology
Frans-Peter Lam	TNO
Hans Heesterbeek	Utrecht University
Irna Huisjes	Waterproof B.V.
Laia Rojano Doñate	Aarhus University / Stanford University
Lonneke IJsseldijk	Utrecht University
Magda Chudzinska	SMRU Consulting
Magnus Wahlberg	University of Southern Denmark
Marije Siemensma	Marine Science & Communication commissioned by RWS
Meik Verdonk	Rijkswaterstaat
Nolwenn Risser	TNO
Pauline Roos	Ecowende
Rens Cronau	Rijkswaterstaat
Rob Deaville	Zoological Society of London / CSIP
Ron Kastelein	SeaMarco B.V.
Sander von Benda-Beckman	TNO
Sanne Hessing	SOS Dolfijn / Utrecht University
Verna de Groes	Ministry of Agriculture, Fisheries, Food Security and Nature
Vincent Hin	Wageningen Marine Research

Annex 2 Results of polls

Annex 2.1 Answers to questions sent in advance of workshop

Expertise

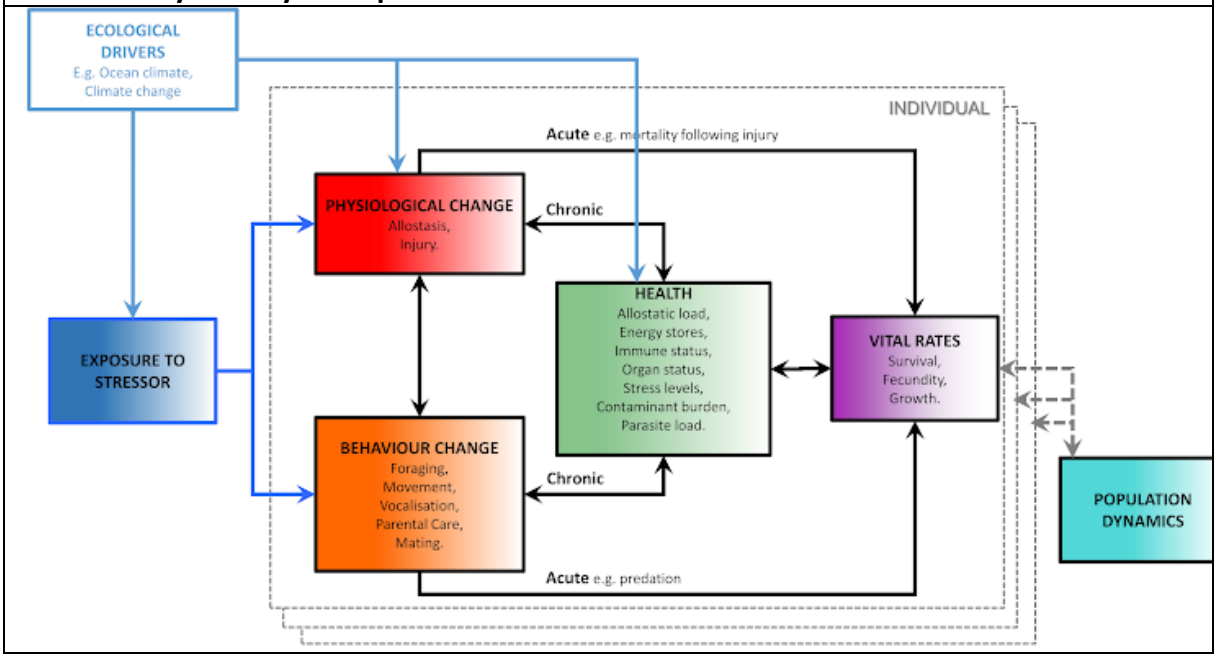


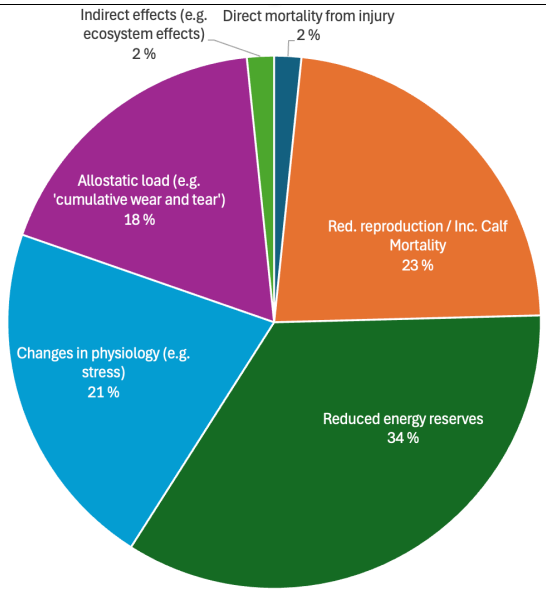
Impact pathways

The PCoD framework has many pathways by which behavioural (orange box) or physiological (red box) change can impact health and vital rates (which is what the expert elicitation transfer functions covered). Which of the following pathways, do you think are the most likely to be impacting vital rates as a result of porpoises being disturbed via exposure to noise from offshore wind construction?

(We recognise that there are potentially interactions between factors - but these are challenging to disentangle with the current state of knowledge).

You can only select your top 3.



• Direct mortality from injury • Increased risk of predation • Reduced reproduction / increased risk of calf mortality (e.g. mother-calf separation) • Reduction in energy reserves due to reduced foraging or increased energetic costs • Changes in physiological condition (e.g. stress hormones, contaminant burden, parasitic load, organ or immune status) • Allostatic load (i.e. 'cumulative wear and tear from chronic stresses' potentially leading to physiological dysregulation and increased risk of disease) • Other	

Annex 2.2 To DEB or not to DEB

	iPCoD EE	iPCoD DEB	I weighted the models in such a way, because
1	0	100	I have more trust in a data driven approach
2	60	40	I'm not entirely sure about the demographic parameters in DEB.
3	35	65	I don't really have a good reason, but basing something on more empirical data than EE seems logical to me
4	20	80	Experts can be wrong
5	30	70	More weight to more mechanistic model. Include ipcod+ee to estimate contribution of effects other than energetics
6	50	50	Comparison with previous KECs is important
7	30	70	Energetics play an extremely important rolel in Hp ecology
8	27	73	I think the energetic model is more well documented so think it has greater utility. But I also think there are other pathways that aren't considered but are likely considered by experts in the EE version.
9	30	70	Because of the power of an shared currency but the need for some details until the DEB has integrated them to satisfaction.
10	50	50	It needs more evaluation and testing to decide after the bug has been fixed.
11	20	80	EE variance appears to be too high to be useful, and cannot easily lend itself to sensitivity analysis or modifying assumptions. However elements of iEE, such as the ability to consider and integrate factors which are not energetic, are vital to consider in any impact model
12	50	50	I dont know… Good if they could be tested and compared in a "real" scenario
13	50	50	For me the choice depends on the outcomes of the model sensitivity studies
14	60	40	I am still not sure to be honest.
15	30	70	Common sense
16	40	60	I think that the DEB model has more possibilities for changing the effect of different parameters and getting at which as the sensitive parameter we need to pay more attention to. However, I also believe that the EE model has value because it is capable of accounting for nuances that the DEB is not parametrized to consider
17	50	50	DEB appears to be a better model, but needs more testing to use it with more confidence
18	20	80	i feel this is the only plausible pathway where we have a clear evidence base with porpoises.
19	40	60	I think there is great values in the 'other' (beside energy budget) in the EE model, but the DEB is more flexible at the moment to be able to include some of the discussion points brought up at the workshop. In general, I also support using energy as a common currency to model effects
20	20	80	EE may be more comprehensive in theory but we have no benchmark to assess whether it is more accurate. DEB generates predictions that are rooted in mechanism and so it can to understand why the results are obtained and has more avenues for validation.
21	30	70	In my understanding of the models. The DEB takes into account more energetic energy restraints and has more parameters. For real life scenarios this may be better suited and a more stable (less uncertainty?) then the EE model?
22	60	40	the EE version is more mature, the DEB version looks promising but I am not yet convinced that it has a stable output.
23	40	60	The DEB model is more 'objective' but the energetic part has still a lot of guesses and simplification and probably missing parts but it improves everytime. Also less dependent to user input which is a good thing. It is also more flexible on what you test without having to have a new expert elicitation. The EE version uses broader knowledge of people working with these animals so broad is good but it also depends on humain perspective.
24	30	70	I's say the DEB version is more complex but more scientifically aligned
	34,9	**61,1**	

Annex 3 Ideas for future work

3.1 Short term priorities

Category	Topic	Proposed Action / Research Need
1. What can happen?	Piling schedules	Assess how long pile driving is expected to remain part of offshore wind farm construction through a desk study.
	Piling scenarios	Improve pile-driving scenarios by incorporating knowledge from industry developers and expert elicitation with engineers.
2. When (if)?	Probability of exposure, subpopulations and movement ecology	Identify key knowledge gaps related to exposure probabilities, population structure, and movement ecology of harbour porpoises.
3. For how long?	Duration of disturbance	Improve understanding of the duration of disturbance effects and recovery processes.
	Recovery from disturbance	Quantify the time required for individuals to resume foraging behaviour (time to first buzz) as a function of individual context and condition.
4. What happens after?	Energetic consequences	Use the existing model to assess the significance of acute liver pathology by incorporating estimated prevalence and calf mortality rates.
	Growth and compensation	Reanalyse existing food consumption and body-weight datasets with a focus on weight gain and compensatory processes following disturbance.
	Weight dynamics	Analyse rates of weight loss in compromised animals and weight gain in recovering animals.
5. Model extensions	Environmental conditions	Incorporate spatial variation in temperature into PCOD simulations and investigate limits for maintaining blubber reserves.
	Thermoregulation	Implement energetic costs of thermoregulation as a function of blubber thickness and water temperature.
	Reproduction	Introduce a pregnancy decision point within the harbour porpoise energetics model.
	Energetics model refinement	Refine the energetics model using data from animals under human care.

6. Monitoring	Health and life stages	Collect additional data on animals from different life stages and health conditions.
	Data integration	Compile and integrate existing datasets, including aerial surveys, PAM, tagging data, and PEDROW data.
7. Other	Blubber thickness measurements	Measure blubber thickness during tagging activities to establish healthy reference values.
	Temporal resolution	Explore the use of finer model time steps, as disturbances and animal responses occur on shorter timescales than one day.
8. Testing the current model	Energetics model validation	Further refine and test the energetics model using data from animals under human care.
	Alternative hypotheses	Broaden the focus beyond underwater noise and evaluate other potential explanatory mechanisms.
	Fertility scenarios	Test model performance using alternative fertility-rate assumptions and subpopulation scenarios.
	Sensitivity analysis	Conduct a comprehensive sensitivity analysis of the current model framework.
	Uncertainty quantification	Quantify uncertainty in iPCOD model outputs through systematic assessment of parameter sensitivity and parameter distributions.

3.2 Medium term priorities (until end of 2027)

4. Category	Topic	Proposed Action / Research Need
1. What can happen?	Industry data sharing	Improve access to developer and industry data to better represent real-world construction scenarios and operational practices.
	Industry involvement	Strengthen collaboration with industry stakeholders and establish mechanisms for mandatory data sharing where appropriate.
2. When (if)?	Site fidelity	Determine site fidelity patterns in harbour porpoises using both short-term and long-term tagging approaches in relation to reproductive cycles.
	Movement ecology	Quantify annual and lifetime movement ranges of harbour porpoises using long-term telemetry data.
	Movement modelling	Improve movement assumptions in iPCOD models by accounting for both residential and nomadic behaviour.
	Regional modelling	Investigate region-specific differences and develop spatially explicit modelling approaches where supported by evidence.
	Agent-based modelling	Use individual-based models (IBMs) to better quantify cumulative noise exposure.
	DEPONS application	Use DEPONS outputs to estimate probabilities of repeated disturbance exposures.
	Exposure studies	Explore the use of D-tags to monitor behavioural responses immediately before and after disturbance events.
	Habitat use	Improve understanding of habitat use in the southern North Sea through genetics and photo-identification studies.
	Population structure	Assess whether distinct subpopulations should be represented in future models.
	Subpopulation assessment	Determine population sub-structuring through tagging, genetics and morphometric analyses.
	Calving areas	Identify areas that are particularly important for calving and calf occurrence.
	Feeding-ground displacement	Improve understanding of displacement from feeding grounds and return behaviour following disturbance.
	Drone monitoring	Use drone observations to monitor population changes and post-disturbance recovery of feeding behaviour.
	Management units	Explore future approaches for defining and managing potential management units within the North Sea.

	Model comparison	Compare movement and population assumptions across iPCOD and DEPONS-type models.
3. For how long?	Foraging success	Determine whether disturbance affects foraging efficiency and prey capture success.
	Behavioural response	Use tag data to improve understanding of behavioural responses following disturbance.
	Response severity	Improve methods for quantifying response severity and energy loss associated with behavioural disturbance.
	Integrated monitoring	Combine tagging, visual observations and PAM data to improve estimates of disturbance impacts.
	Prey competition	Assess whether displaced animals experience lower feeding efficiency because of increased competition for prey.
4. What happens after?	Age at independence	Determine the age at which calves become nutritionally independent using necropsy and diet studies.
	Mother-calf dynamics	Investigate risks of mother-calf separation and reunion processes during and after disturbance.
	Demography	Improve understanding of age structure and potential lifetime reproductive output.
	Energy budgets	Develop quantitative energy budgets across life stages.
	Demographic validation	Validate demographic parameters using both strandings and field observations.
	Lactation costs	Quantify energetic costs of lactation and changes in milk composition over time.
	Body condition	Develop field-based measures of body condition using drones and stranded animals.
	Recovery of feeding	Combine PAM and drone observations to assess the time required to resume feeding after disturbance.
	Energy intake	Improve and test assumptions related to energy intake in current models.
	Prey quality	Assess seasonal variation in prey energy density and nutritional value.
	Age-specific energetics	Quantify energy acquisition across age classes and identify thresholds for independence.
	Model comparison	Compare iPCOD outcomes with alternative energetic models such as DEPONS.
	Health and reproduction	Investigate relationships between health status, reproduction and vital rates.

5. Model extensions	Temperature effects	Incorporate sea-surface temperature effects on body condition, prey consumption and health.
	Fisheries and prey dynamics	Assess impacts of climate change on prey distribution, abundance and nutritional value.
	Acute metabolic failure	Develop model structures capable of representing acute metabolic collapse.
	Disturbance distributions	Investigate how different assumptions regarding disturbance affect model outcomes.
	Individual variability	Incorporate inter-individual variation in growth, condition and physiological response.
	Toxicology integration	Integrate energetics models with toxicant (PBTK) models.
	Diurnal processes	Represent sub-daily biological and behavioural processes within future model versions.
6. Monitoring	Health indicators	Develop harmonised indicators for nutritional status, reproduction and disease burden.
	Biomarkers	Identify robust biomarkers for health and nutritional status.
	Population structure	Develop methods to estimate immature-to-adult ratios at population scale.
	OWF benefits	Assess potential positive effects of offshore wind farm development, including reef effects and fisheries exclusion.
	North Sea strategy	Develop a coordinated North Sea-wide strategy for population assessment.
	Prey modelling	Improve prey-distribution and abundance models.
	Energy metabolism	Identify physiological indicators of catabolism and energy metabolism.
	Mortality rates	Develop mortality estimates that better represent the free-ranging population.
	Pregnancy rates	Quantify variability in pregnancy rates across regions and years.
	Habitat-use monitoring	Improve monitoring through tagging and photo-identification programmes.
7. Other	Prey-field dynamics	Investigate long-term changes in prey availability and predator-prey dynamics.
	Noise characteristics	Determine which acoustic properties trigger behavioural responses.
	Contaminants	Assess seasonal contaminant dynamics linked to blubber reserves.
	Research coordination	Improve communication and coordination regarding future monitoring activities.
	Expert network	Continue interdisciplinary expert meetings and knowledge exchange.

	Hindcasting	Conduct hindcasting studies to evaluate model performance against historical data.
	Disease interactions	Investigate interactions between disease and anthropogenic disturbance.
	Health biomarkers	Develop improved biomarkers for cumulative stress and health effects.
	Stranding network improvements	Improve protocols and reporting systems for strandings.
	International collaboration	Facilitate international collaboration and data exchange.
8. Testing the current model	Age determination	Improve ageing techniques for older individuals.
	KEC validation	Compare monitoring data during OWF construction with KEC predictions.
	Pregnancy assessments	Develop baseline pregnancy estimates using necropsies, hormones and biopsies.
	Multiple stressors	Evaluate the importance of cumulative and interacting stressors.
	PCOD validation	Compare PCOD outputs with measurable population indicators such as calf ratios and age structure.
	Disturbance validation	Compare observed disturbance distributions with KEC assumptions.
	Model-real world linkage	Relate state variables within energetics models to measurable biological characteristics.
	Feeding-rate variation	Quantify variation in feeding rates using tagged animals.
	Energetics model comparison	Compare different energetics models under identical disturbance scenarios.
	Vital-rate validation	Compare observed vital rates with predicted reproduction and survival outputs.

3.2 Long term priorities (after 2027)

Category	Topic	Proposed Action / Research Need
2. When (if)?	Population structure	Investigate the potential existence of subpopulations using genetic analyses and skull morphology studies.
	Site fidelity	Expand long-term tagging programmes to better understand site fidelity and population structure.
	Integrated population assessment	Combine morphological and genetic datasets from across the North Sea to assess population structuring.
	Phenotypic variation	Investigate differences among harbour porpoise phenotypes, including potential epigenetic effects.
	Vulnerable populations	Quantify the size of potentially vulnerable subpopulations.
	Population dynamics	Develop a comprehensive understanding of North Sea harbour porpoise population dynamics and identify remaining knowledge gaps.
	Individual identification	Develop methods for identifying and tracking individual harbour porpoises over long periods.
	Habitat relationships	Assess relationships among habitat use, temperature, prey distribution, blubber thickness, fertility and population dynamics.
4. What happens after?	Sudden starvation pathways	Investigate biological pathways leading to sudden starvation in apparently healthy animals.
	Individual variation	Quantify variation in physiological responses, energetics and life-history strategies among individuals.
	Physiological effects	Assess whether physiological consequences of disturbance and health impacts can be quantified directly.
	Reproductive studies	Conduct detailed reproductive studies, including milk composition and calf growth dynamics.
	Condition benchmarks	Develop regional and seasonal benchmarks for body condition and health status.
	Alternative energy stores	Investigate physiological responses to fasting and the role of energy stores beyond blubber reserves.
	Behavioural development	Study behavioural development and prey-capture learning processes in young harbour porpoises.
	Exercise physiology	Quantify how ingested energy is partitioned between locomotion, thermoregulation and other physiological processes.
5. Model extensions	Multiple pressures	Develop approaches for integrating and weighting multiple anthropogenic and

		environmental pressures within model frameworks.
	Reproductive drivers	Improve understanding of the mechanisms that influence reproductive success.
	Construction techniques	Include different offshore wind farm construction methods (e.g. pile driving, vibro-piling, jetting) in model scenarios.
	Construction schedules	Incorporate alternative pile-driving schedules and timelines within disturbance analyses.
	Prey distribution	Improve long-term modelling of prey distribution through collaboration with fisheries scientists and isotope studies.
	Search efficiency	Use tagging datasets to estimate prey-search efficiency and parameterise functional responses in models.
	Sensitivity analyses	Conduct systematic sensitivity analyses of iPCOD and DEPONS models to identify key drivers and uncertainties.
	Computational performance	Collaborate with software developers and game designers to improve model speed and efficiency.
	Modular modelling	Develop modular model architectures capable of incorporating additional datasets and external stressors.
6. Monitoring	Population estimation	Improve abundance estimates and age-structure assessments using drones, aircraft, satellite imagery and automated detection systems.
	Pathology integration	Integrate pathology datasets across stranding networks to improve assessment of health and resilience.
	Prey-field monitoring	Improve monitoring of prey availability, fisheries competition and reef effects.
	Condition-demography links	Improve understanding of links between body condition and demographic outcomes.
	Energy resources	Monitor energy demand, prey resources, fisheries activity and bycatch across the North Sea.
	Survey harmonisation	Harmonise survey methodologies and increase survey frequency across seasons and years.
	Life-history monitoring	Assess long-term changes in reproduction, age structure and body size.
	Age determination	Improve ageing techniques and harmonise ageing methodologies among research groups.
	AI-assisted monitoring	Develop drone systems with AI-supported species recognition capabilities.
	Non-invasive ageing	Develop ageing techniques suitable for biopsies, scat samples and swabs.

	Calf-adult ratios	Establish long-term monitoring of calf-adult ratios and body condition using drones.
	Fish-stock monitoring	Initiate targeted programmes to monitor fish stocks important in harbour porpoise diets.
	Distribution and prey	Improve understanding of relationships between porpoise distribution and prey availability.
	Citizen science	Explore the use of offshore personnel as observers contributing harbour porpoise sightings.
	Technology development	Invest in advanced monitoring technologies including drones, acoustic tools and tagging systems.
	Baseline data	Improve ecological baselines before offshore wind farm development.
	Mother-calf monitoring	Determine monitoring effort and survey coverage required to estimate mother-calf ratios reliably.
	UXO impacts	Apply models to assess impacts of unexploded ordnance (UXO) disposal and improve mortality estimates.
	Fisheries displacement	Assess impacts of fisheries displacement resulting from expansion of renewable-energy developments.
	Pregnancy thresholds	Identify thresholds and stressors associated with declines in pregnancy rates.
	Environmental data needs	Determine the spatial and temporal resolution required for environmental and prey datasets in long-term models.
7. Other	Terminology harmonisation	Continue efforts to standardise terminology and definitions across disciplines.
	Energy transition	Explore societal pathways toward reducing overall energy consumption.
	Bycatch mitigation	Continue improving and implementing bycatch mitigation measures.
	Food-system impacts	Investigate broader changes in food systems and fisheries that may affect prey availability.
8. Testing the current model	Multiple disturbance sources	Assess impacts of concurrent disturbance sources under future large-scale offshore wind development scenarios.
	Hindcasting	Use historical construction and hammer-time data to evaluate model predictions retrospectively.
	Initial conditions	Enable models to account for different baseline population states and stress levels.
	Process validation	Test individual model processes against empirical datasets and develop testable predictions.
	Indirect impacts	Assess indirect effects of noise and fisheries on prey species and trophic interactions.