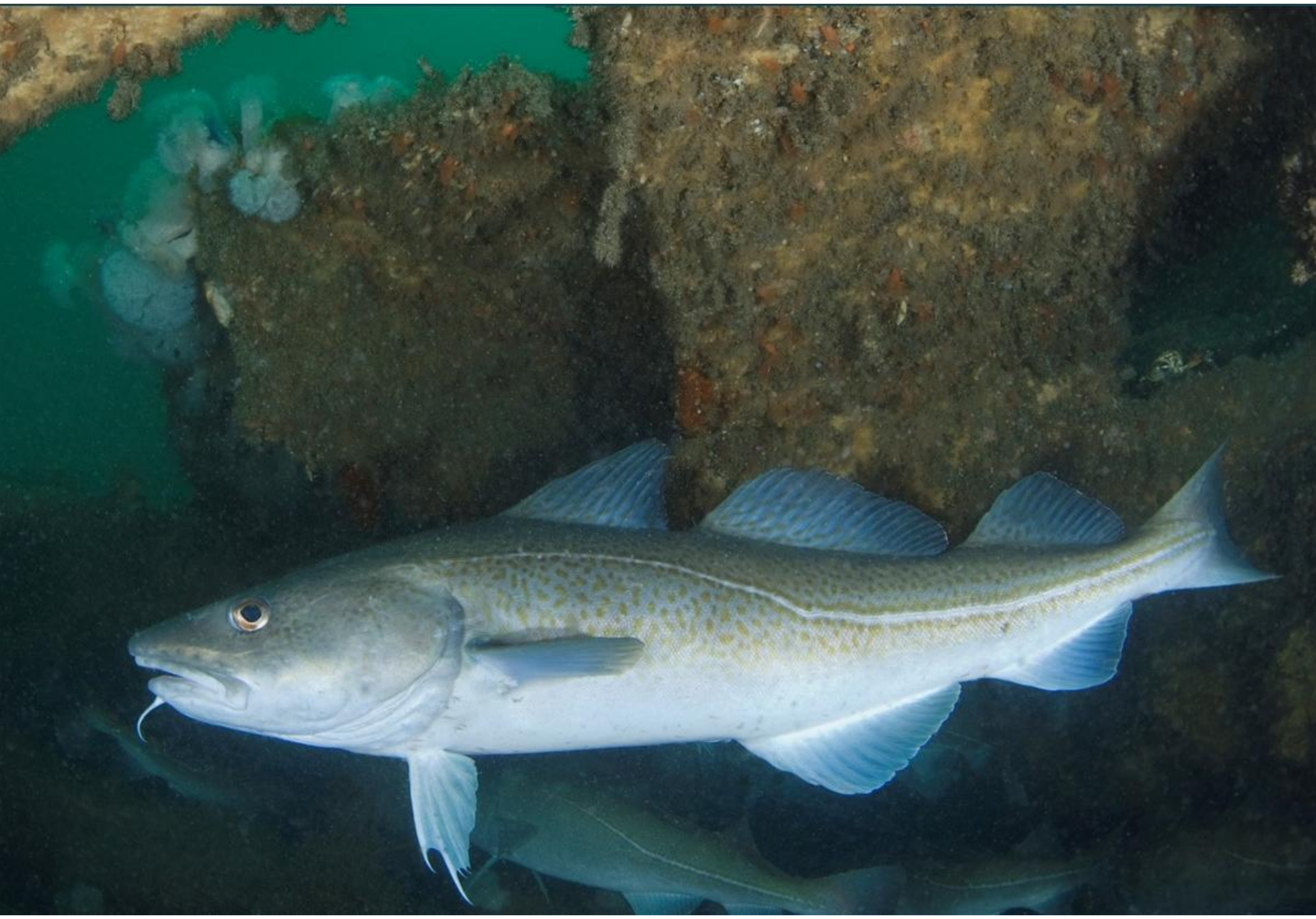

Quick scan interactive effects heat plumes

Final report

Rijkswaterstaat

11 March 2026

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SAMENVATTING - NEDERLANDSTALIG

Introductie

Nederland heeft ambitieuze doelen voor de ontwikkeling van Wind op Zee, waarbij in de toekomst ook waterstofproductie op zee kunnen plaatsvinden. Beide ontwikkelingen dienen te passen binnen de ecologische draagkracht van de Noordzee. Onder het HyOne project van de Gasunie is onder andere de haalbaarheid van een demonstratieproject van 450 MW binnen het windpark Ten Noorden van de Waddeneilanden (TNW) onderzocht. Hieruit zijn ecologische aandachtspunten en kennisleemtes gekomen. Zo is een belangrijk aandachtspunt de afgifte van koelwater wat nodig is tijdens de waterstofproductie. Een kennisleemte is of, en hoe deze warmtepluim, zou kunnen interacteren met veranderingen van hydrodynamische condities als gevolg van de aanwezigheid van turbinepalen, en de ecologische consequenties van dit gecombineerde effect.

Doel

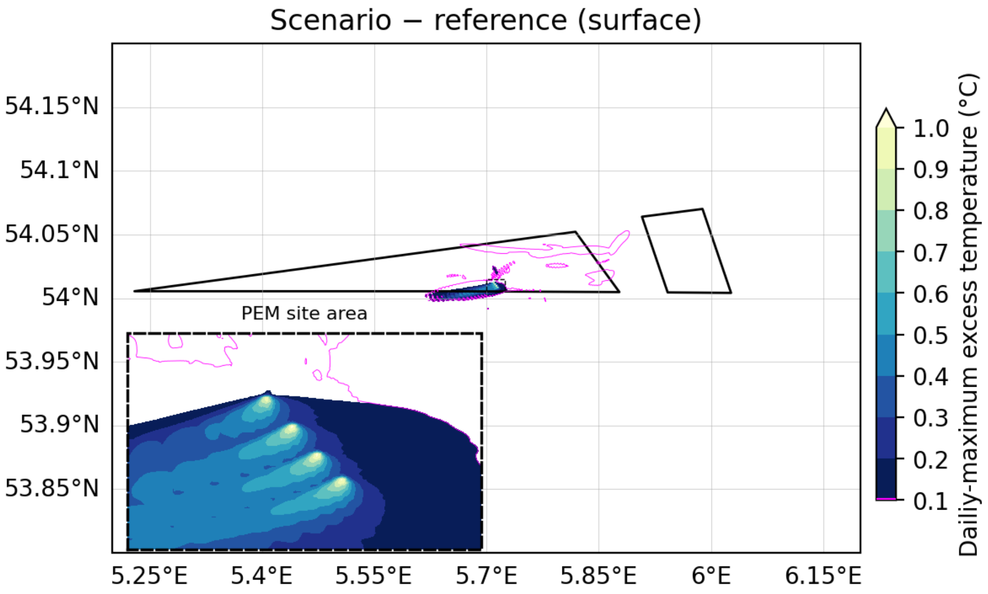
Het doel van deze studie is om een eerste inzicht te krijgen in hoe schaal van verandering veroorzaakt door warmtepluimen van offshore waterstof productie zich verhoudt met hydrodynamische veranderingen in windparken op zee. Hiermee wordt het begrip van hydrodynamische veranderingen, de mogelijke interactie tussen effecten en de doorvertaling naar ecologie, verbeterd, waardoor een weloverwogen keuze kan worden gemaakt voor vervolgonderzoek.

Scope en methode

Deze quickscan maakt gebruikt van uitgevoerde modelleringen, die oorspronkelijk voor verschillende doeleinden zijn ontwikkeld. Het onderzoek richt zich enkel om de hydrodynamische verandering i.c.m. de afgifte van koelwater van waterstofproductie, waarbij effecten van chemicaliën niet beschouwd zijn. De modeluitkomsten kunnen zonder aanpassingen van de modellen, niet worden geïntegreerd. Dit komt omdat bijvoorbeeld de celgrootte, de gemodelleerde ruimte en periode verschillen. Weergegeven scenario's zijn zo gekozen *worst-case* effecten inzichtelijk kunnen worden.

In voorliggend onderzoek zijn beide modeluitkomsten visueel en kwalitatief geanalyseerd voor de casus van 450 MW waterstofproductie in TNW, bestaande uit 4 waterstofproductieplatforms. De resultaten van beide modellen zijn vergeleken door deze zo veel mogelijk uniform weer te geven. Met een visuele analyse op basis van expert-judgement is onderzocht hoe effecten zich tot elkaar verhouden en is een inschatting gemaakt van de ecologische risico's.

Zomer scenario bij Δ15 °C met maximale temperatuursverandering van het wateroppervlak voor een gegeven dag. De maximale reikwijdte van de warmte pluim (als stijging van >0.1 °C) over de gehele modelperiode is gegeven in roze



Resultaten

Hieronder is een voorbeeld gegeven van de verspreiding van de warmtepluim, die zijn vergeleken met de resultaten van de Wozep modellering. Daarbij is het gehele windgebied TNW gegeven en een kader met daarin de vier waterstofproductieplatforms.

Modelresultaten

De lokale thermische pluimen van offshore waterstofproductie zijn sterk beperkt tot de directe omgeving van de PEM-platformen en verspreiden zich nauwelijks horizontaal of verticaal. Seizoensverschillen zijn duidelijk: in de winter stijgt de warme pluim snel naar het oppervlak, waardoor warmte snel wordt verspreid en afgegeven aan de omgeving, terwijl in de zomer pluimen, afhankelijk van temperatuurverschillen, deels onder het oppervlak kunnen blijven hangen. De effecten van offshore windparken hebben echter een veel grotere ruimtelijk schaal. Rond TNW resulteert dit in een algemene afname van de vertikale temperature gradient door menging, vooral in de zomer. Gezamenlijk lijken de effecten van beide activiteiten elkaar deels te compenseren: waterstofproductie verhoogt lokaal de vertikale temperatuur gradient, windparken verminderen deze juist over een groter gebied.

Ecologische analyse

Op basis van de huidige analyse lijken de warmtepluim niet of nauwelijks te interacteren met de hydrodynamische verandering rond turbinepalen. De warmtepluimen zorgen voor beperkte, lokaal geconcentreerde temperatuurverhogingen die vooral in de zomer relevant kunnen zijn voor temperatuurgevoelige soorten. Anderzijds hebben de turbines juist effecten op een grotere ruimtelijke schaal, met name door verticaal mengen, met als gevolg lokaal een verlaging in primaire productie in en ten oosten van TNW. Dit wijst op een laag tot matig ecologisch risico onder huidige (*worst-case)* casus van TNW.

Onzekerheden

- **opschaling van waterstofproductie is niet gemodelleerd:** bij een opschaling van meerdere gigawatts aan waterstofproductie zou dit kunnen leiden tot chronische warmtebelasting doordat veel kleine pluimen elkaar kunnen overlappen. De uiteindelijke ecologische impact hangt sterk van schaal, locatie (bijv. zoekgebied 6/7), platformindeling, en samenloop met andere drukfactoren. Hierbij is het van belang rekening te houden met realistische productiewaarden;
- **cocktail effecten van pekel, warmte en chemicaliën zijn niet onderzocht:** dit onderzoek richt zich op thermische effecten en gaat ervan uit dat veranderingen in zoutgehalte door lozing van pekel op deze schaal verwaarloosbaar zijn, waarbij de mogelijke ecologische risico's van een 'cocktail' aan chemische stoffen (die toegevoegd worden om aangroei in het koelsysteem te voorkomen) niet zijn meegenomen;
- **resultaten zijn gebaseerd op relatief korte tijdspan:** hierdoor zijn langetermijneffecten en cumulatie over tijd beperkt onderzocht;
- **directe effecten van thermische pluimen op primaire productie nog niet gemodelleerd:** De ecologische analyse is hoofdzakelijk gebaseerd op hydrodynamische veranderingen door windparken, terwijl directe effecten van thermische pluimen op primaire productie en soortensamenstelling niet expliciet zijn gemodelleerd en dus onzeker blijven.

Aanbevelingen voor vervolgonderzoek

De huidige resultaten voor TNW tonen dat er sprake is van een relatief laag ecologische risico als gevolg van de thermische pluim in combinatie met hydrodynamische veranderingen van windparken op zee. In paragraaf 5.4 zijn zes onderzoeksvragen voor vervolgonderzoek opgesteld. Daarnaast gelden de volgende aanbevelingen:

- **gericht vervolg onderzoek naar verschillende waterstofscenario's,** met nadruk op gecombineerde warmte-zout-chemicaliën effecten en lange termijn effecten op het ecosysteem;
- **parametrisering van effecten,** met behulp alternatieve en aanvullende modellering, bijvoorbeeld computational fluid dynamics (CFD);
- **opnemen van waterstofeffecten in cumulatieve effectstudies**, waarbij op basis van bovenstaande modelleringen wordt aangesloten aan bestaande Wozep-onderzoeken;
- **adaptief beheer en monitoring binnen toekomstige vergunningverlening**, zodat momenteel onvoorziene effecten vroegtijdig kunnen worden vastgesteld en bijgestuurd naarmate de uitrol toeneemt.

1

INTRODUCTION

1.1 Context

The Dutch government has set ambitious targets for offshore wind energy production. As more offshore wind farms (OWFs) are developed, further from the coast, new challenges arise. These include efficient long-distance energy transport, net congestion, unbalanced power production, and long-term power storage. Transforming wind power into hydrogen could reduce some of these challenges, as transmission losses may be lower, hydrogen can be stored for long periods, and it can be used by high-energy industries or as a resource for ammonium production.

Over the past few years, the Dutch government has investigated the possibilities and hurdles of offshore hydrogen production through several pilot projects and research programmes (e.g. HyOne). These include a scale demonstration project, Demo 1 (< 50 MW), a medium-scale project, Demo 2 (450 MW), and a strategic investigation into large-scale upscaling (up to 20 GW in total on the Dutch North Sea). While the technical feasibility of offshore wind and hydrogen systems is increasingly explored, understanding their environmental impacts remains critical.

Under the national research program Wind op Zee Ecologisch Programma (Wozep), the effects of the (Dutch) OWF developments are investigated. This includes research into ecological effects resulting from changes in hydrodynamic conditions caused by the presence of wind turbines (Van Duren et al., 2025; Zijl et al., 2021, 2024; Zijl, Laan, et al., 2023). This research provides insight in changes in hydrodynamic conditions and primary production in relation to OWFs. However, this does not consider other activities which may affect abiotic conditions within an OWF, such as offshore hydrogen production.

Uncertainties as identified in Demo 2

As part of these developments, Demo 2 resulted in a pre-FEED (pre Front-End Engineering Design) for offshore hydrogen production in the wind energy area Ten Noorden van de Waddeneilanden (TNW); see Figure 1.1. This project demonstrated the technical feasibility of offshore hydrogen production, but has also identified key uncertainties, including potential environmental effects. These effects arise from the offshore hydrogen production process and include:

- the use of seawater required for cooling of the electrolyser and hydrogen compressor;
- seawater intake for the cooling system and its potential impact on marine life;
- the release of warm water (thermal plumes) and their interaction with hydrodynamic changes caused by wind turbines, potentially impacting the marine ecosystem;
- the release of (anti-fouling) chemicals required to maintain a continuous cooling process and the potential impact on marine life;
- continuous underwater noise due to the use of pumps and/or compressors and its possible disturbance of marine life.

The scale and impact of these effects is largely unknown, both at the scale of 450 MW, as well as at larger scales. As of September 2025, the Demo projects have been temporarily put on hold. This pause provides the opportunity to better understand environmental effects and identify what critical knowledge is still missing to that end. This report further investigates the possible interaction between thermal plumes from hydrogen production and hydrodynamic changes resulting from the presence of offshore wind farms.

1.2 Current state of knowledge

This study is based on results of the following two investigations, (1) HyOne Demo 2 and (2) the Wozep study. Model results from these investigations are analysed and compared in this report. As starting information, key results from Demo 2 and the Wozep studies are presented here.

1.2.1 Results of Demo 2 (HyOne)

The engineering solutions of the Demo 2 project, initiated by Gasunie, provides a few important conclusions for this study (Cuevas et al., 2025[1]):

- to be able to produce 450 MW hydrogen, four PEM (Polymer Electrolyte Membrane) platforms are required, from where hydrogen is compressed on one separate compression platform and can be transported to land. One living quarters platform is assumed (Figure 1.1, right panel). The separate platforms are required, because 1) multiple foundations are needed for the required weight load of the different installations, 2) safety concerns (especially for the living quarters), 3) practical reasons, such of modularity and easier maintenance;
- a once-through cooling system using seawater is currently the most feasible option for cooling;
    - a closed cooling loop system on the seafloor is not sufficient effective, as marine fouling will hinder heat transfer, requiring > 10 km of cooling pipes per PEM-platform;
    - air cooling is not realistic, as it requires too much deck space and the weight increase of the system is too high (note that optimisation with a hybrid system air and water cooling may be expected);
- brine, produced as a byproduct of hydrogen production, is discharged in directly into the seawater, where it quickly dilutes. At maximal production, practical salinity increase less than 0.01 PSU at 100 m from the discharge location, remaining well within the natural variability at the TNW wind energy area. Furthermore, this small change does not form a detectable salinity plume in the far field and higher brine concentrations are kept within the near field. For this reason, this study only presents changes in seawater temperature, neglecting those in salinity;
    - it should be noted that other studies, such as Christiansen et al., (2025), indicate that at higher production rates (order of 500 MW from a single platform), salinity increases of up to 0.04 PSU can occur within a radius of approximately 50 m. These changes are small and not considered substantial.

As the Demo 2 project was a pre-FEED study, it is likely that further engineering may result in different design solution or optimisations. This may include a cooling system with a different impact on the environment.

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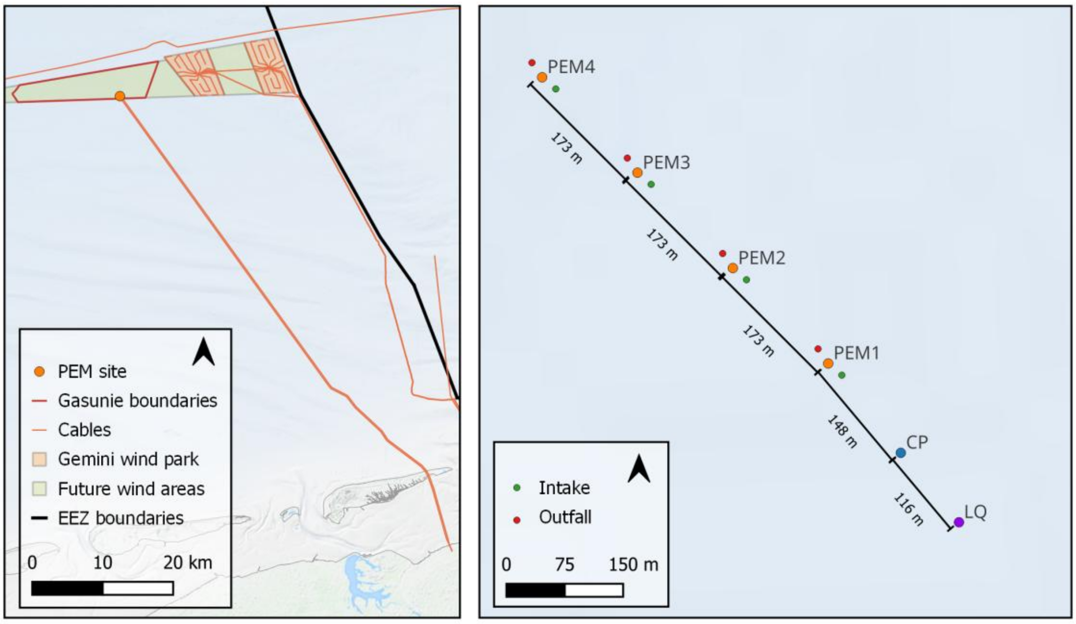
[1] Report is not publicly available. Outcomes of Cuevas et al. (2025) are presented in this study.

Figure 1.1 Left panel: project location for the PEM Platforms (orange dot, corresponds to PEM 1 platform). Right panel: location of the PEM platforms, the compression platform (CP), and living quarters (LQ) based on the DEMO-2 cluster layout (Cuevas et al., 2025), aligned to reduce the overlap among SCW plumes for the dominant flow currents



1.2.2 Results of Wozep study

The Wozep work has concluded a few important aspects for this study (Van Duren et al., 2025; Zijl et al., 2021, 2024; Zijl, Laan, et al., 2023):

- large-scale offshore wind farms can measurably alter North Sea ecosystems, primarily through changes in hydrodynamics, vertical mixing, and fine-sediment dynamics, which in turn affect light availability and nutrient supply;
- primary production responds differently by region: in shallow, well-mixed coastal areas (e.g. Holland coast, German Bight) production generally decreases due to increased turbidity and light limitation, while in deeper, seasonally stratified areas production can increase due to enhanced nutrient mixing;
- consistent reductions in fine-sediment transport along the Dutch coast (~5 to 10 %) are modelled, including reduced mud fluxes towards the Wadden Sea, driven by cumulative hydrodynamic changes from multiple wind farms;
- ecosystem effects are spatially heterogeneous but of potentially large local magnitude (up to ±40–60 % changes in primary production within or near wind-farm areas), while North Sea-wide averages are more moderate due to compensating processes;
- uncertainty remains high, particularly regarding small-scale turbulence, sediment processes, and longer-term food-web impacts; impacts of mussel colonisation on turbine foundations appear secondary compared with hydrodynamic and sediment effects but this requires further validation.

1.3 Project scope

This study aims to provide an initial analysis of how the magnitude of thermal plumes effects from seawater cooling discharges during offshore hydrogen production compares to the hydrodynamic changes caused by the presence of offshore wind turbines located near the PEM platforms. Building on this assessment, the study explores potential interactive effects arising from these processes and consider how such combined impacts may translate into ecological consequences.

For this quick scan, **existing model outcomes** are utilized. This includes (1) the **HyOne modelling,** with the layout of the Demo 2 cluster, which consists of four PEM platforms, and (2) the **Wozep modelling,** with the layout of the wind farms projected until 2040. The numerical model employed is the D-HYDRO Suite three-dimensional (3D) Dutch Continental Shelf Model (DCSM) (Zijl, Zijlker, et al., 2023). The scopes of the two previous studies are outlined in the subsections 1.3.1 and 1.3.2.

These modelling studies were conducted with different objectives and focus on different time scales and spatial resolutions (see Section 2.1.1). The results cannot be directly combined and therefore they are compared only visually and qualitatively. Moreover, the scenarios analysed herein are selected for their plausible highest impact to change the existing natural conditions, e.g. seasonal stratification. Expert judgement is applied to indicate further potential implications.

1.3.1 HyOne modelling scope

The scope of the HyOne modelling was to quantify and assesses the far-field dynamics of sea cooling water (SCW) effluent from the Demo 2 PEM platform cluster under varying ambient and operational conditions. This provides input for future ecological assessments and permit applications by evaluating potential impacts from elevated temperature, salinity, and antifouling chemicals.

The following parameters were considered in the HyOne modelling:
- time periods: Winter (14th February to 4th March) and summer (1st July to 19th July) in 2013;
- excess heat production of PEM-platform is 60 MW per platform, total 240 MW;
- excess temperature of the SCW effluent: +5 °C and +15 °C;
- SCW plume source terms: derived from a near-field assessment (with CORMIX);
- cooling discharge of 12 m^3/s is assumed for the 4 PEM-platforms;
- cooling required for compression platform is not considered in this study[1].

1.3.2 Wozep modelling scope

Main scope of the Wozep modelling scope was (Van Duren et al., 2025; Zijl et al., 2021, 2024; Zijl, Laan, et al., 2023):
- to reduce key knowledge gaps on the potential negative environmental effects of large-scale offshore wind farms on the North Sea ecosystem by means of integrated, system-scale modelling;
- to assess cumulative ecosystem effects of present and future offshore wind scenarios, focusing on changes in hydrodynamics, stratification, fine-sediment dynamics, light climate, nutrient availability, and primary production;
- to apply a bottom-up modelling approach, using a fully coupled hydrodynamic–sediment–water quality–ecological model, complemented within Wozep by a separate top-down line addressing vulnerable species such as birds and marine mammals;
- to evaluate realistic and upscaled future wind-farm scenarios (towards ~2040 and beyond) in order to identify at which level of offshore wind expansion ecosystem-level risks may arise;
- to provide policy-relevant insight for Dutch and North Sea offshore wind planning by identifying spatial patterns, regional sensitivities, and remaining uncertainties that require monitoring or further research.

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[1] The excess heat production of the compressor is 22-35 MW depending on compression method, accounting for an additional <15 %. Thermal plume of the compression platform was not modelled in Cuevas et al. (2025) and therefore cannot be included in this study.

1.4 Project objective

The objective of this study is get a first understanding on how the scale of thermal plume effects from offshore hydrogen production relates to the scale of hydrodynamic changes caused by nearby OWFs. Building on this understanding, the study will explore how these effects may interact or combined and what such interactive dynamics could mean for ecological functioning. Depending on the outcome of this study, a follow-up research process may be initiated.

Research questions

Main research question
To what extent do the thermal plumes from offshore hydrogen production relate to and interact with the hydrodynamic changes caused by nearby offshore wind turbines, and what could these combined effects imply for ecological functioning?

Sub questions

- how do thermal plumes from hydrogen production impact vertical and horizontal temperature structure and stratification in the receiving waters?
- how do offshore wind turbine foundations (monopiles/transition pieces) alter local hydrodynamics, and what is the consequent effect on temperature distribution and stratification?
- are interactions between thermal plumes and turbine-induced hydrodynamic changes expected to be additive, synergistic, or antagonistic?
- what ecological effects may arise from these potential interactions?
- what are the key sources of uncertainty in estimating ecological effects from thermal plumes and monopile foundation-induced hydrodynamics?
- which specific field measurements, laboratory experiments, or modelling developments are required to reduce the most important uncertainties?
- based on current knowledge and the identified uncertainties, how urgent is targeted follow-up research on thermal plumes needed to inform permitting and management decisions?

1.5 Abbreviations and acronyms

Table 1.1 Abbreviation and their description

Abbreviation	Description
CFD	computational fluid dynamics
CP	compression platform
DCSM	Dutch continental shelf model
LQ	living quarters
OWF	offshore wind farm
PEM	polymer electrolyte membrane
Pre-FEED	preliminary front-end engineering design
PP	primary production
SCW	sea cooling water
SST	sea surface temperature
TNW	Ten Noorden van de Waddeneilanden
Wozep	Wind op zee ecologisch programma

1.6 Reading guide

Chapter 2 contains the method description, with its approach and scenarios, split into the HyOne modelling and Wozep modelling. Additionally, the method of the analysis, including ecological analysis, is provided. In chapter 3 the results per scenario is given, followed by the ecological analysis. In chapter 4, the modelling outcomes are synthesised and compared, resulting in an ecological risk assessment. Chapter 5 discusses the results, including possible effects of upscaling of offshore hydrogen production. From there, an overview of key uncertainties and recommendations for follow-up research are provided. References can be found in chapter 6.

2

METHODS

2.1 Model description

This study uses model outcomes from already executed projects. The thermal plume modelling was done under the HyOne project, as requested by the Gasunie (Cuevas et al., 2025). The ‘partial revision’ scenario study (Zijl et al., 2024) is part of the Wozep program, as requested by Rijkswaterstaat. Both these studies use the Dutch Continental Shelf Model – Flexible Mesh (DCSM-FM) as the core hydrodynamic engine, described in subsection 2.1.1. Some elements of their setups differ because of their objectives (see 2.1.2 and 2.1.3 for more details).

2.1.1 D-HYDRO model

The three-dimensional Dutch Continental Shelf Model – Flexible Mesh (3D DCSM-FM) is a sixth-generation hydrodynamic model developed by Deltares for Rijkswaterstaat. It covers the Northwest European Shelf, including the North Sea and adjacent Dutch estuaries such as the Wadden Sea, the Ems-Dollard, and the Western and Eastern Scheldt (Zijl, Zijlker, et al., 2023). This model is built within the D-HYDRO Suite, which allows the use of unstructured grids for greater flexibility and accuracy.

Both the Wozep modelling (Zijl et al., 2024) and the HyOne modelling study share a common model foundation, using the same core modelling system, DCSM-FM, developed within the D-HYDRO Suite and apply it to the Northwest European Shelf, covering the area between 15°W and 13°E and 43°N to 64°N. Both aim to represent tides, surge, stratification, and residual transport accurately, and both have been validated against observations of water levels and temperature.

In both cases, the horizontal grid is based on a flexible mesh with approximately 630,000 cells, refined to about 0.5 nautical miles near the coasts and coarser offshore. Note that additional refinements were made for the thermal modelling approach (see subsection 2.1.2). Both models rely on EMODnet bathymetry combined with Dutch Baseline data for national waters and apply ERA5 meteorological forcing for wind, pressure, and heat fluxes. These models also use CMEMS data for temperature and salinity at open boundaries and E-HYPE climatology for river discharges, supplemented by gauged flows for major rivers. Turbulence closure in both configurations is based on a k–ε scheme.

Despite their similarities, the two configurations differ in several important aspects, as outlined in Table 2.1. Given these differences in model version, vertical and horizontal grid discretisation, boundary forcing, numerical settings, coupled models, and simulated periods, it is not good modelling practice to combine the HyOne and Wozep results into a single model output. The results of each model are thus presented separately and then compared qualitatively.

Table 2.1 Key differences between the model configurations used for HyOne modelling and Wozep modelling

	HyOne modelling	Wozep modelling
3D-DCSM-FM version	dflowfm3d-noordzee_0_5nm-j22_6-v1a	dflowfm3d-noordzee_0_5nm-j17_6-v1
Vertical grid	hybrid z–sigma vertical grid with up to 50 layers: - enhancing the simulation of thermoclines and baroclinic processes	sigma vertical grid with 20 equidistant layers: - good resolution in shallow areas; - limited representation of deep-water stratification
Horizontal grid	additional refinements required near PEM platform area (see subsection 2.1.2)	
Open boundary	new features: - advective velocities at open boundaries; - reduces the relative wind effect to 50 %; - applies pseudo-wind corrections for air density.	
Tidal forcing	- 39 constituents from FES2014, GTSMv4, and EOT20; - applies a uniform mean-level offset to improve coastal water level accuracy	- 31 constituents from FES2012; - surge added via an inverse barometer correction
River salinity	standardized to 0.2 PSU	not specified
Numerical parameters	explicit turbulence and viscosity values and applies a Smagorinsky horizontal viscosity scheme	not specified
Coupled-models	focuses solely on hydrodynamics and provides extensive multi-year validation across the shelf, including improvements in tide, surge, and stratification representation	coupled with wave, fine-sediment, and ecological models
Simulated periods	winter (14th February to 4th March) and summer (1st July to 19th July) in 2013	2007 (for this study specific months of 2007 were extracted)

2.1.2 HyOne modelling approach

The HyOne modelling approach consisted of two consecutive modelling steps, namely near-field and far-field modelling. The near-field analysis describes the behaviour of the warm cooling water plume in the immediate vicinity of the discharge point. The near-field modelling methodology and results are described in detail in Cuevas et al. (2025). The far-field modelling study examines the dispersion and mixing of the thermal plume with the surrounding marine environment over larger spatial scales and longer time periods. To simulate this process in the HyOne study, key outputs from near-field analysis were used, including the plume thickness, width, distance from the outfall, and dilution. The present study is based on the results of the far-field model only, which are supported by a precedent near-field study.

Implementation of the far-field modelling in the 3D DCSM-FM model requires several modifications, including local grid refinement, incorporation of PEM platform intakes and outfalls, and the schematisation of near-field results within the far-field framework. These modifications are described in the subsections below.

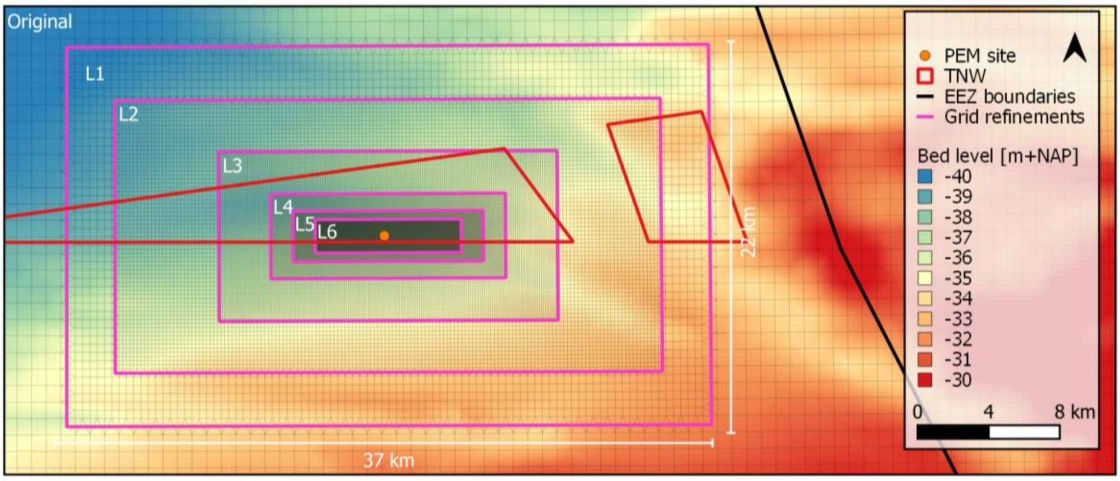
Grid refinement

The area around the discharge platforms is modelled on a computational grid that becomes finer near the platforms to capture plume behaviour in detail. This optimized approach allows for both investigating large scale effects (far from the project area), as well as detailed plume behaviour. The grid sizes at each refinement level are listed in Table 2.2, and the grid refinements are shown in Figure 2.1.

Table 2.2 Cell size at sequential grid refinements

Refinement	Original	L1	L2	L3	L4	L5	L6
E-W direction	820 m	410 m	205 m	102.5 m	51.2 m	25.6 m	12.8 m
N-S direction	925 m	462.5 m	231.2 m	115.6 m	57.8 m	28.9 m	14.5 m
cell area	758,500 m²	189,625 m²	47,396 m²	11,849 m²	2,959 m²	740 m²	186 m²

Figure 2.1 Sequential grid refinements in the project area (magenta lines)



PEM platform intakes and outfalls

For each of the four PEM platforms, the cooling-water intakes are located at a depth of 25 meters below the sea surface (-25 m NAP), and the outfalls at a depth of 5 meters (-5 m NAP). The location of the intakes and outfalls are displayed in Figure 1.1.

Schematization of near-field input

Water withdrawals at the cooling-water intakes are represented in the model as sinks (removal points). The effluent, is schematized with the Distributed Entrainment Sink Approach (DESA) (Choi & Lee, 2007) to capture near-field behaviour. DESA combines two ideas: (a) sinks simulate how water is entrained or pulled into the jet as it moves, and (b) sources represent the actual cooling-water discharge. In practice, this means the model accounts for how the jet mixes with seawater along its path and how much dilution occurs. The DESA method is designed to conserve mass, include near-field dilution, and account for background concentrations.

2.1.3 Wozep modelling approach

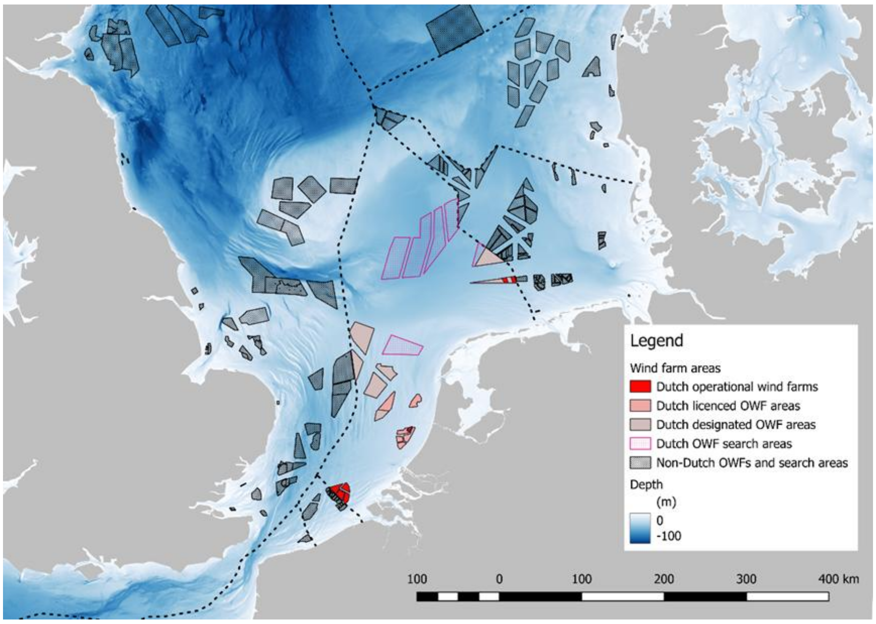
The Wozep modelling uses the 3D DCSM-FM model as a research tool for scenario analysis of offshore wind farm impacts. In this modelling framework, offshore wind farms are represented through sub-grid parameterizations that include momentum sinks to simulate turbine-induced drag, based on pile density and monopile diameter. In addition, a simplified 10 % reduction of wind speed within wind-farm polygons is applied in order to reflect the first-order effects of turbine wake interactions (Zijl et al., 2021, 2024; Zijl, Laan, et al., 2023).

The reference scenario is the North Sea area without the presence of wind farms, similar to the earlier reports on ecosystem effects. The Wozep scenario 1 represents a scenario derived from the officially designated offshore wind farm zones in the North Sea Programme 2022–2027, updated governmental capacity assumptions per wind farm, and current planning constraints. Several areas or sub-areas are excluded due to spatial conflicts—such as sand extraction concessions, military exercise areas, and shipping safety corridors. When combined, the selected areas in this scenario result in a total projected offshore wind capacity of approximately 50.2 GW (Zijl et al., 2024).

In the 2024 Wozep study, the turbine specifications and their model representation follow the established parameterization principles from earlier Wozep modelling efforts (Zijl et al., 2024), but incorporate updated values that reflect the current understanding of Dutch and international offshore wind development (Zijl et al., 2024). Wind farms constructed before 2020 are represented using a pile density of 3.15 monopiles per square kilometre, corresponding to earlier turbine generations for which individual turbine capacities were considerably lower than modern installations. In contrast, wind farms constructed after 2020 are modelled with a reduced pile density of 0.85 monopiles per square kilometre. For all future Dutch offshore wind farms included in the scenario horizon towards 2030–2040, the modelling approach assumes 15 MW turbines. Wind farms located outside the Dutch Exclusive Economic Zone are schematized using the same 12-metre monopile diameter, but with a standardized density of 0.67 monopiles per square kilometre, ensuring consistent representation across national boundaries in the coupled hydrodynamic and ecological model.

As illustrated in Figure 2.2, scenarios consist of large, clustered wind-farm areas, enabling assessment of cumulative impacts on hydrodynamics, sediment dynamics, and ecosystem processes at North Sea scale. Layout effects are represented through enhanced drag and turbulence from monopiles and a prescribed wind-speed reduction over wind-farm areas, ensuring consistency across scenarios while focusing on ecosystem-scale responses.

Figure 2.2 Layout used for the Wozep modelling on large upscaling scenarios (Zijl et al., 2024)



2.2 Scenario description

2.2.1 HyOne modelling scenario

The simulation scenarios analysed in this study are selected to evaluate the impact of PEM platforms under different seasonal and operational conditions. The scenarios are divided in three distinct sea cooling water (SCW) discharge conditions, none of which includes the effects of OWFs:

1. reference (no PEM platforms): This scenario represents background conditions without SCW discharge and serves as a baseline. It is used to determine ambient temperature conditions and to isolate the thermal impact of SCW discharges by subtracting background temperatures from the scenarios with excess discharge temperatures;
2. constant maximum discharge at ΔT + 5 °C: This scenario simulates thermal plume dispersion resulting from PEM platforms operating at maximum duty (and discharge capacity) with an excess cooling water temperature of +5 °C;
3. constant maximum discharge at ΔT + 15 °C: This scenario evaluates thermal plume dispersion under maximum duty (and discharge capacity) with an excess temperature of +15 °C.

The far-field thermal plume assessment comprises the three output scenarios mentioned above which differ only in season and excess temperature (ΔT). Each scenario applies the corresponding near-field plume characteristics as summarised in Table 2.3.

Note that to maintain a constant heat flux and port exit velocity, the SCW discharge flow rate and port area are adjusted with excess temperature. Consequently, higher excess temperatures correspond to proportionally lower discharge flow rates.

Table 2.3 HyOne modelling scenarios

	Operational conditions			Near-field plume characteristics used in far-field model			
scenario	**duty [MW]**	**duty [%]**	**discharge [m3/s]**	**Dilution [-]**	**Distance [m]**	**Thickness [m]**	**Width [m]**
reference	-	-	-	-	-	-	-
winter Δ5ºC	60	100	3 (max)	6.8	35	10	20
summer Δ5ºC	60	100	3 (max)	6.8	35	10	20
summer Δ15ºC	60	100	1 (max)	8.2	20	6	13

2.2.2 Wozep modelling scenario

Model results were derived from a single long-term Wozep model simulation, from which two representative output periods were extracted and referred to as “winter” and “summer” scenarios. These scenarios do not constitute separate model runs, but rather seasonal subsets of the same simulation. For the winter scenario, February 2007 was selected to best approximate the period used in the HyOne modelling (14 February–4 March 2013). For the summer scenario, July 2007 was extracted to closely match the HyOne modelling period of 1–19 July 2013.

2.3 Analysis

2.3.1 Time and space

For both the HyOne modelling and the Wozep modelling, previously generated model output was used to produce the figures presented in this report. No new model simulations were performed; instead, relevant variables were extracted from existing model datasets and analysed consistently across both studies. Model output was analysed for the following variables: surface water temperature (defined as 1 m below the water surface), bottom water temperature, and the difference between surface and bottom temperature (vertical temperature gradient). The vertical temperature gradient, and any chances in that due to the activities taking place, is used as an indicator for trends and shifts in water column stratification. In addition, primary production at the surface layer was analysed for the Wozep model output only. Within the geographical domain bounded by longitudes 5.2° to 6.2° and latitudes 53.8° to 54.2°.

Temporal subsets of the model results were selected to represent winter and summer conditions for both studies. For the HyOne modelling, the winter period covered 14 February–4 March 2013, while the summer period spanned 1–19 July 2013. Corresponding periods for the Wozep model output were selected to allow seasonal comparability: February 2007 for winter conditions and July 2007 for summer conditions.

2.3.2 Qualitative and visual assessment

A qualitative and visual assessment was conducted on the model output from both the HyOne modelling and the Wozep modelling. This assessment aimed to facilitate a direct comparison between the two modelling approaches and to evaluate spatial patterns and relative changes across scenarios.

For each seasonal scenario and variable (surface temperature, bottom temperature and vertical temperature gradient), the visual assessment was presented using a structured layout consisting of six or nine panels (2 × 3 or 3 x 3). The rows represent the different model outputs, with the HyOne modelling shown in the firsts rows, followed by the Wozep modelling. The three columns represent: (i) the reference situation, (ii) the scenario with SCW, and (iii) the relative change between the scenario and the reference. This standardized layout was applied consistently across all analysed variables to ensure comparability between models, seasons, and scenarios.

For the Wozep model also the effects on primary production are assessed to come to a first insight into the effects on the ecosystem.

3

RESULTS

3.1 Qualitative and visual comparison winter Δ5°C

Thermal plumes

In winter the effects of thermal plumes on temperature, surface, bottom and vertical gradient, are confined to the vicinity of the PEM platform outfalls (~200 m radius) and are limited to the TNW area (Table 3.1-3.3). The warmer effluent (Δ5°C) rises to the sea surface because the surrounding water is colder, producing a local increase in surface temperature that is strongest close to the discharge points (Figure 3.1 and Table 3.1). Bottom temperatures remain unchanged beneath the plume, as the buoyant plume reaches the surface (Table 3.2). The vertical gradient is only enhanced within the plume area itself and does not extend beyond this zone (Table 3.3).

Wind energy area

In winter the effects of the wind energy area Ten Noorden van de Waddeneilanden on temperature, surface, bottom and vertical gradient, are minimal (Table 3.1-3.3). There is a slight difference, at both the surface and the bottom temperature, with no clear pattern in lower or higher temperatures arising from the presence or absence of the wind energy area (Table 3.1-3.2). The vertical temperature gradient, as well as stratification, is relatively low in this area in wintertime, the difference between a scenario with or without wind energy areas is also relatively small. There is, however, a minimal increase in vertical temperature gradient in the eastern part of the wind energy area as well as east of the wind energy area (~ +0.1 °C) (Table 3.3).

Figure 3.1 Scenario winter Δ5 °C: The colour bar indicates the spatial distribution of the **daily-maximum excess temperature** at the surface layer on 27 February 2013, i.e. results from this specific day only. The magenta contour indicates the maximum extend or the area in which an increase ≥ 0.1 °C **daily-maximum excess temperature** threshold at the surface at any time during the entire simulation period for the. This area is indicative for the maximum extend of the thermal plume. Dashed box indicates the PEM site area

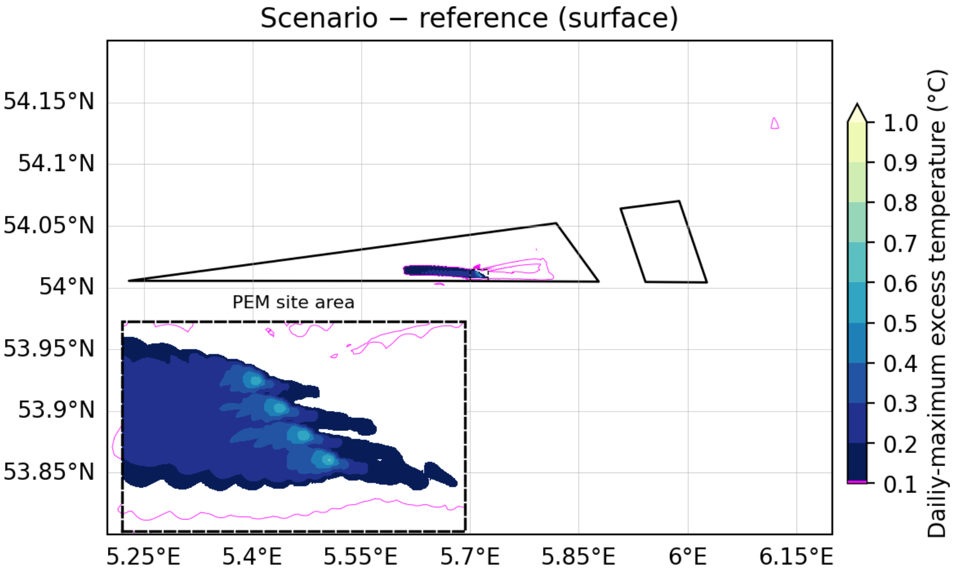


Table 3.1 Scenario **winter Δ5°C** results: Sea Surface Temperature (SST) in winter (–1 m below sea surface). The HyOne modelling shows **average temperatures** in the period of 14 February - 4 March 2013. Wozep modelling shows **average winter temperatures**, calculated as the mean of February 2007

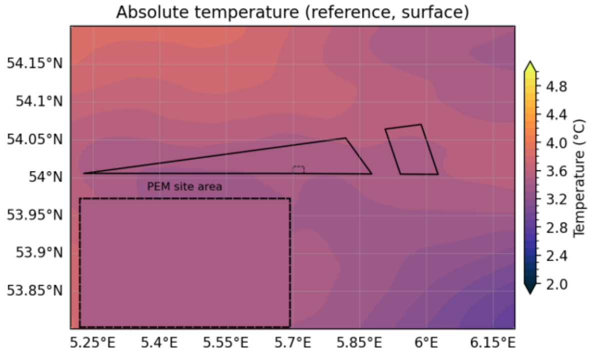
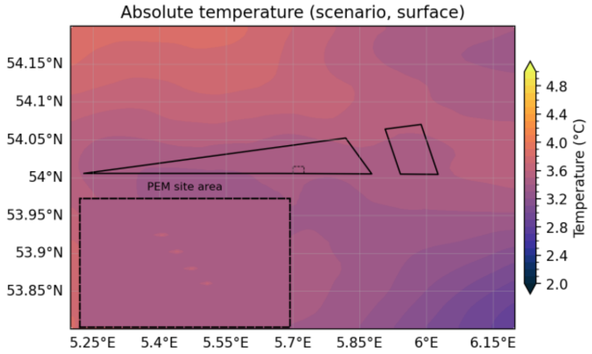
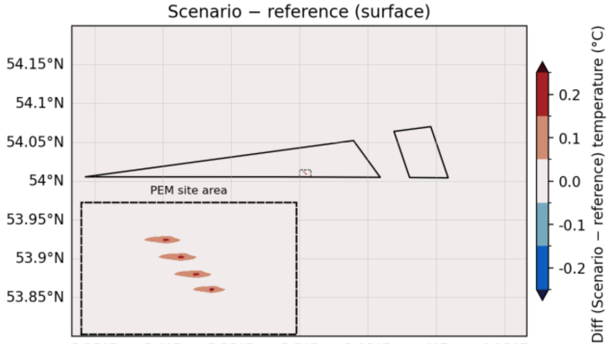
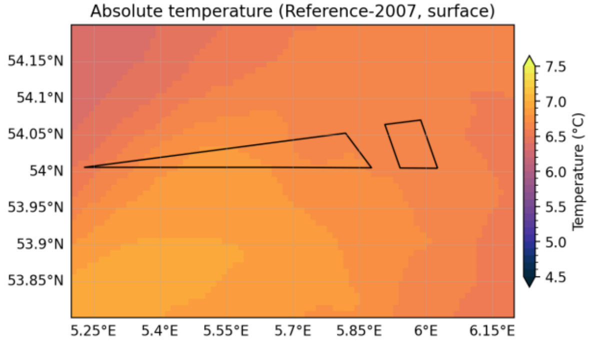
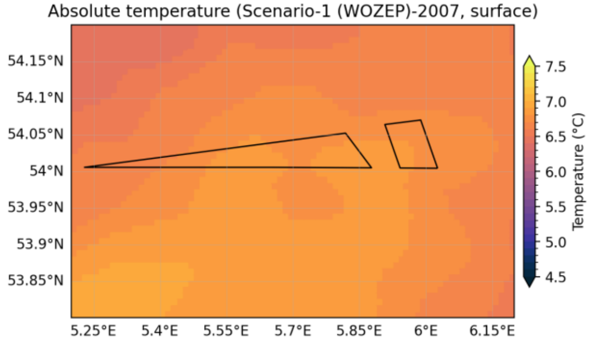
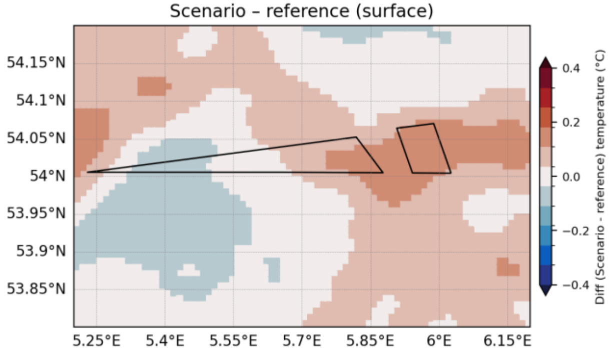
	Reference (absolute SST)	Scenario (absolute SST)	Scenario minus Reference (change in SST)
HyOne modelling			
Wozep modelling			

Table 3.2 Scenario **winter Δ5ºC** results: Bottom temperature in winter (layer 20 - deepest layer). The HyOne modelling model shows **average temperatures** in the period of 14 February - 4 March 2013. Wozep modelling shows **average winter temperatures**, calculated as the mean of February 2007

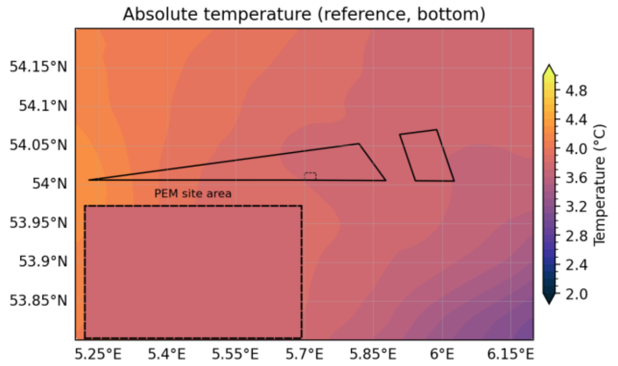
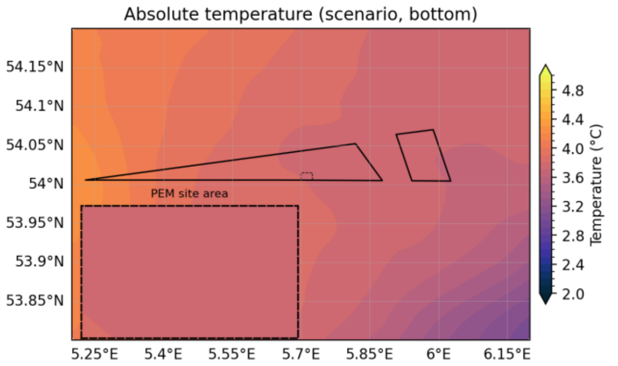
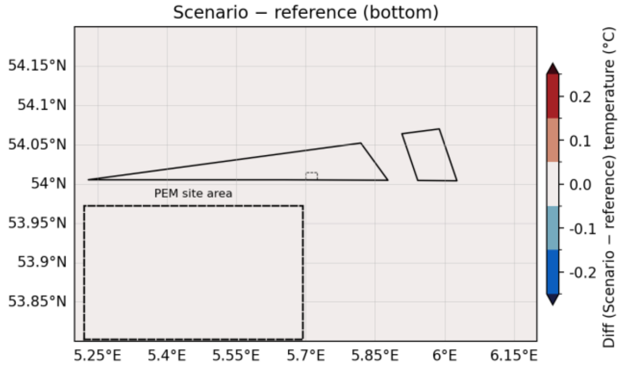
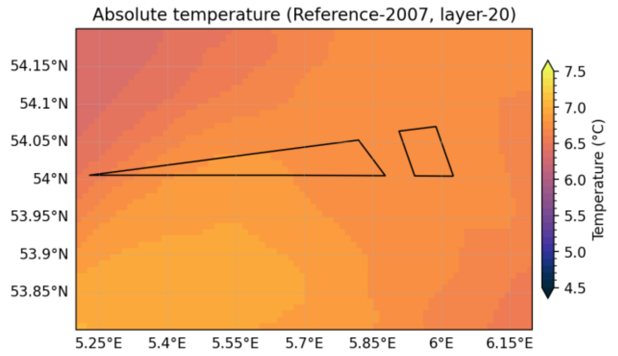
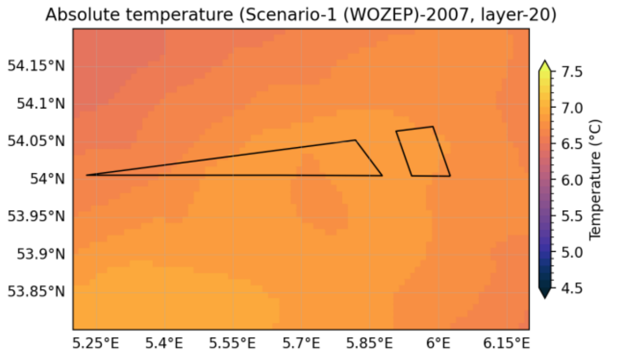
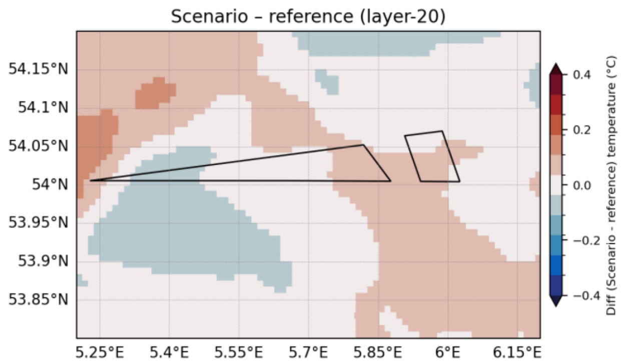
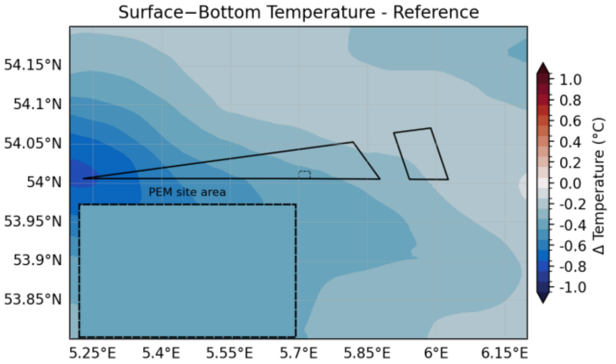
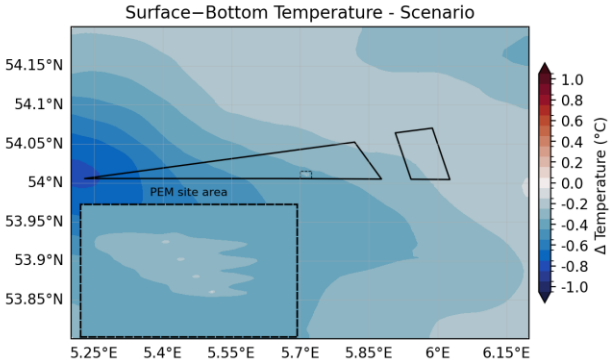
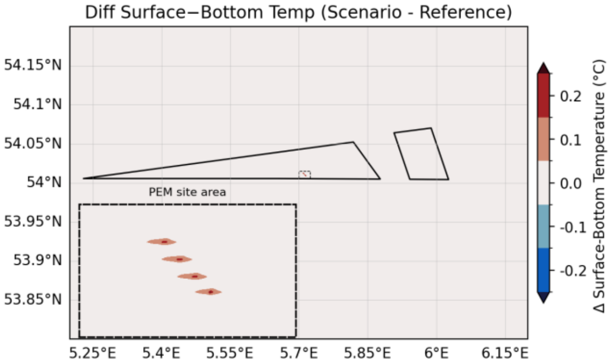
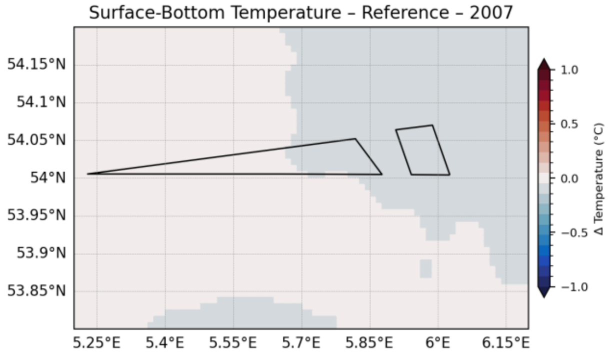
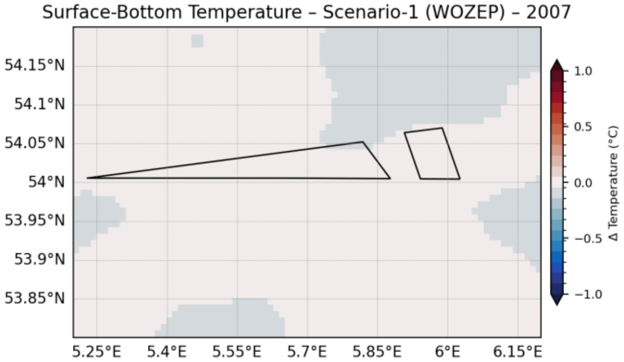
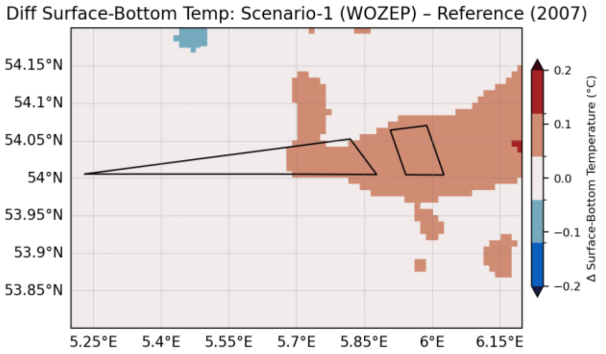
	Reference (absolute bottom temperature)	**Scenario (absolute bottom temperature)**	**Scenario minus Reference (change in bottom temperature)**
HyOne modelling			
Wozep modelling			

Table 3.3 Scenario **winter Δ5ºC** results: Difference in surface and bottom temperature (vertical temperature gradient) in winter. The HyOne modelling shows the differences in **average temperatures** in the period of 14 February - 4 March 2013. Wozep modelling shows differences in **average winter temperatures**, calculated as the mean of February 2007. Surface is –1 m below sea surface and bottom is layer 20 (deepest layer)

	Reference (absolute vertical temperature gradient)	**Scenario (absolute vertical temperature gradient)**	**Scenario minus Reference (change in vertical temperature gradient)**
HyOne modelling			
Wozep modelling			

3.2 Qualitative and visual comparison summer Δ5ºC and Δ15ºC

Thermal plumes

In summer the effects of thermal plumes on temperature, surface, bottom and vertical gradient, differ from winter primarily because of the warmer ambient surface waters (Table 3.4). For the effluent (Δ5°C), which in winter would rise to the surface, the plume can instead become trapped within the water column during summer due to smaller density differences relative to the ambient waters (Figure 3.2 and Table 3.4). This is visible in Figure 3.2, where the plume is seen surfacing north-east of the PEM platform area. Likely meaning that the plume was initially trapped between the outfall layer and the surface layer. By contrast, an effluent with a higher temperature (Δ15°C), the plume still rises to the surface because of the greater buoyancy of the effluent (Figure 3.3 and Table 3.4). Otherwise, the effects on bottom temperature and vertical temperature gradient are similar to the winter situation (Table 3.5-3.6), bottom temperatures remain unchanged beneath the plume, and the increase in vertical gradient is restricted to the relatively small plume area.

Wind energy area

In the summer period the effects of the wind energy area Ten Noorden van de Waddeneilanden on temperature become more pronounced, especially east of the area (in the direction of the main current (Table 3.4 -3.6). The cause of these differences between the situation with and without wind turbines lies in the increase mixing of waters. The surface temperatures become colder when offshore wind areas are rolled out (around –0.1 to –0.2 °C; Table 3.4), whereas the bottom temperature become warmer (~ +0.1 °C; Table 3.5). This indicates an increase in the mixing of different water layers. In a situation without offshore wind this mixing is less likely to happen, as indicated by the large vertical temperature gradient (Table 3.6). The difference in this vertical temperature gradient, and thus likely also in stratification, between the situation with and without wind farms is therefore also most pronounced in the eastern part as well as east of the wind energy area (between –0.1 and –0.2 °C).

Figure 3.2 Scenario summer Δ5 °C: The colour bar indicates the spatial distribution of the **daily-maximum excess temperature** at the surface layer on 27 February 2013, i.e. results from this specific day only. The magenta contour indicates the maximum extend or the area in which an increase ≥ 0.1 °C **daily-maximum excess temperature** threshold at the surface at any time during the entire simulation period for the. This area is indicative for the maximum extend of the thermal plume. Dashed box indicates the PEM site area. Note that the surface plumes are located away from the outfall area as this specific scenario presented a trapped plume

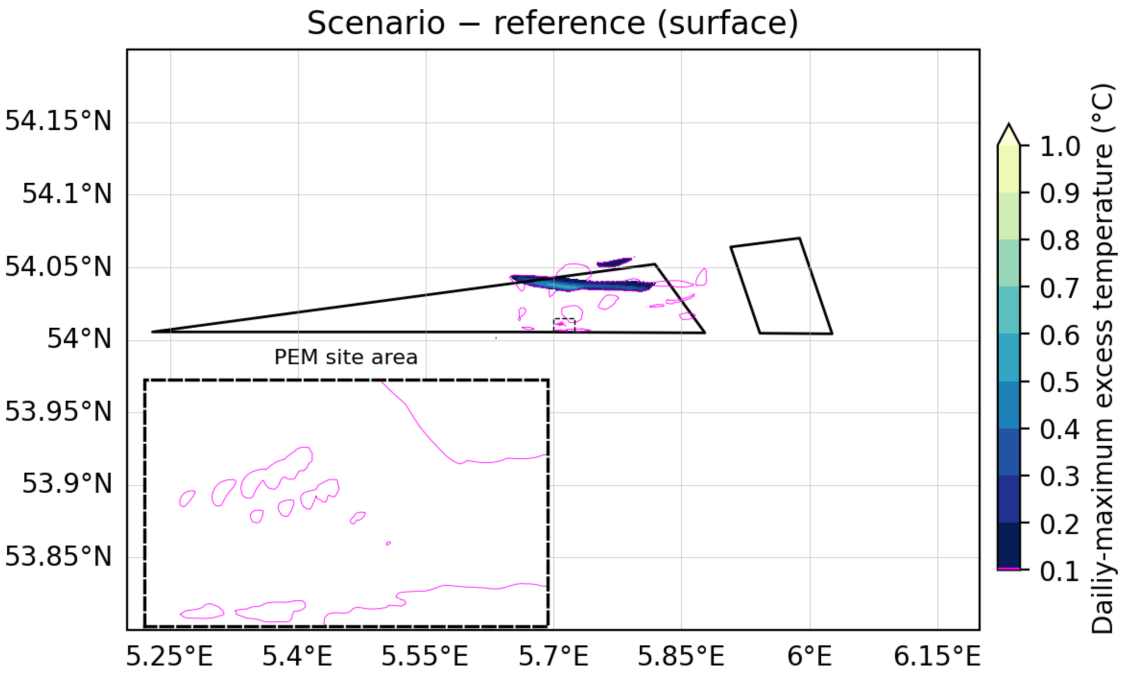


Figure 3.3 Scenario summer Δ15 °C: The colour bar indicates the spatial distribution of the **daily-maximum excess temperature** at the surface layer on 27 February 2013, i.e. results from this specific day only. The magenta contour indicates the maximum extend or the area in which an increase ≥ 0.1 °C **daily-maximum excess temperature** threshold at the surface at any time during the entire simulation period for the. This area is indicative for the maximum extend of the thermal plume. Dashed box indicates the PEM site area

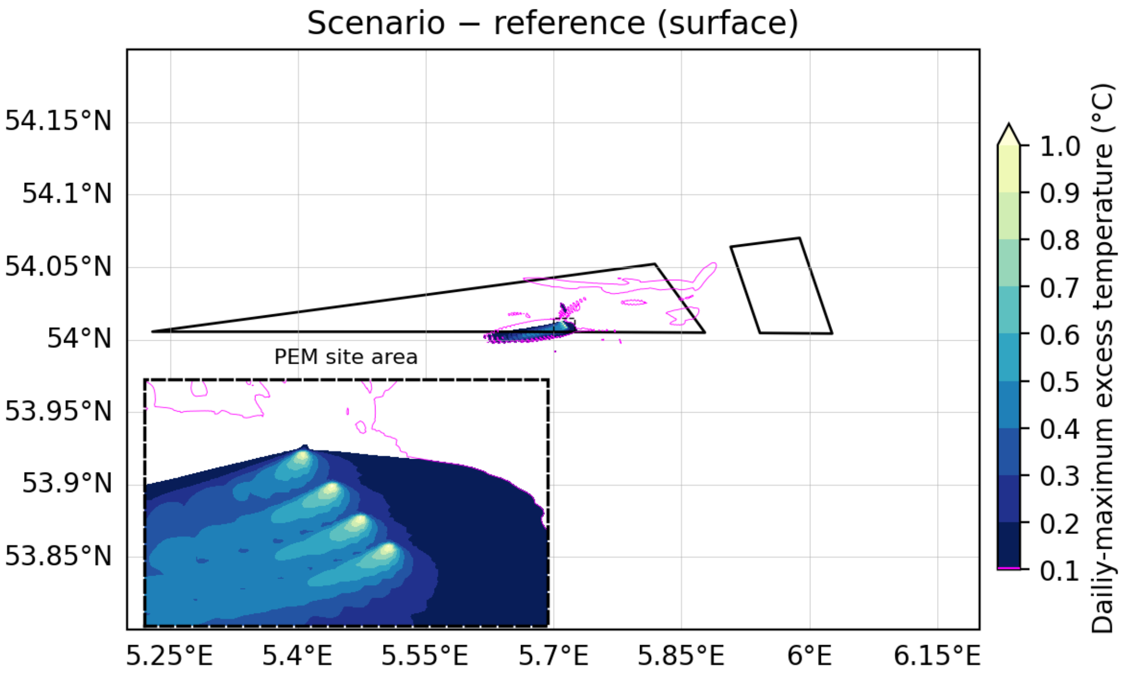


Table 3.4 Scenario **summer Δ5°C** and **summer Δ15°C** results: Surface temperature in summer (–1 m below sea surface). The HyOne modelling shows **average temperatures** in the period of 1 - 19 July 2013. Wozep modelling shows **average summer temperatures**, calculated as the mean of July 2007

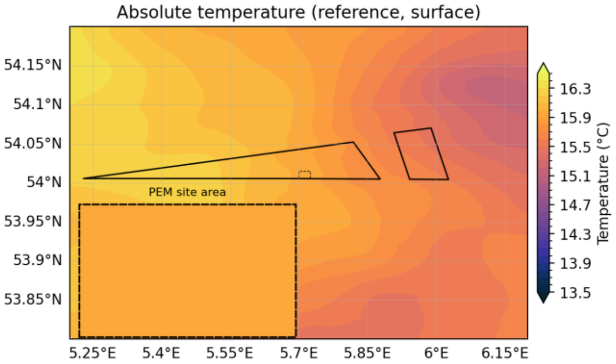
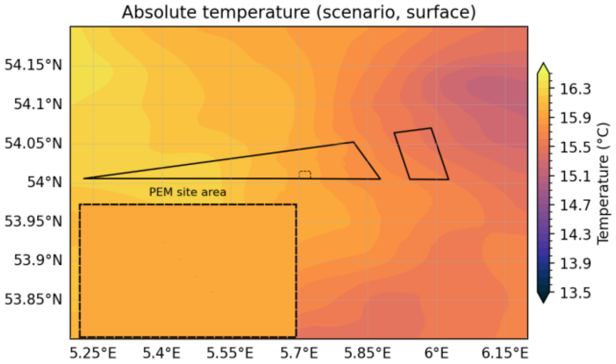
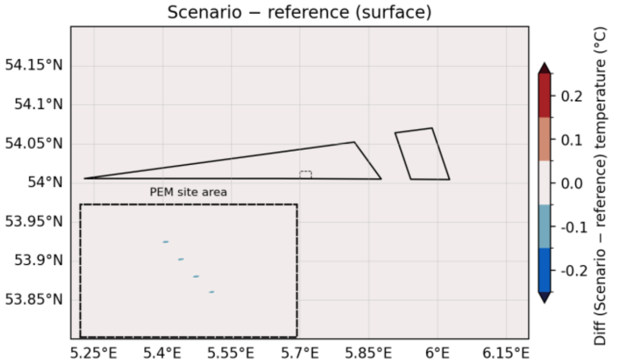
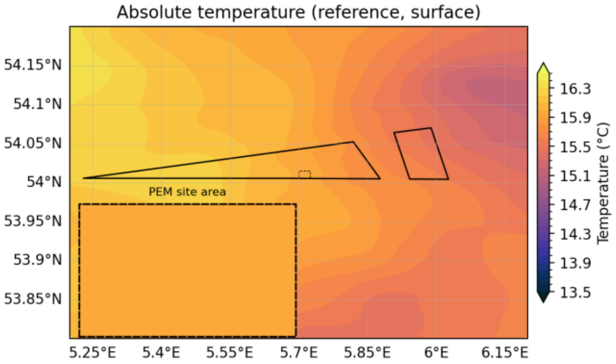
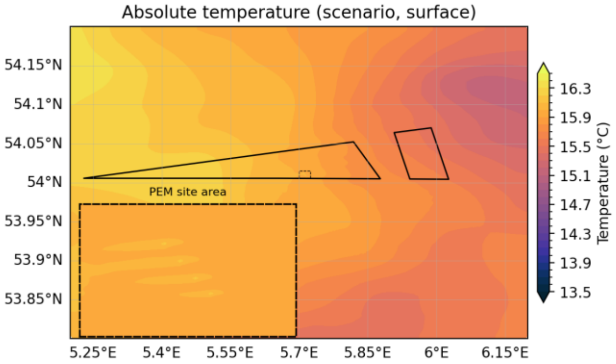
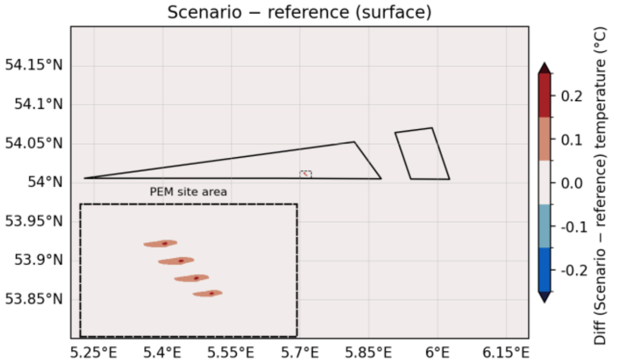
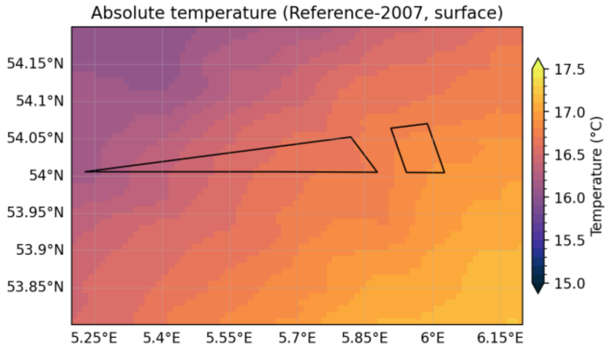
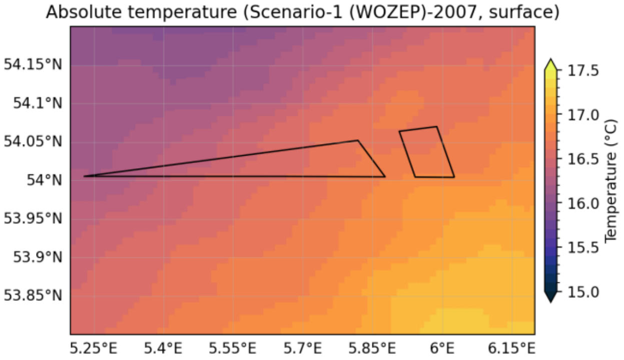
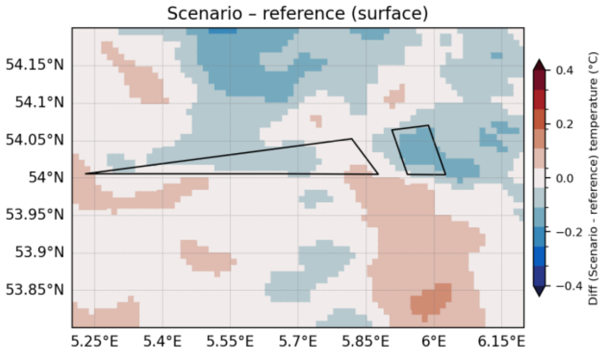
	Reference (absolute SST)	Scenario (absolute SST)	Scenario minus Reference (change in SST)
HyOne modelling Δ5°C			
HyOne modelling Δ15°C			
Wozep modelling			

Table 3.5 Scenario **summer Δ5°C** and **summer Δ15°C** results: Bottom temperature in summer (layer 20 - deepest layer). The HyOne modelling shows **average temperatures** in the period of 1 - 19 July 2013. Wozep modelling shows **average summer temperatures**, calculated as the mean of July 2007

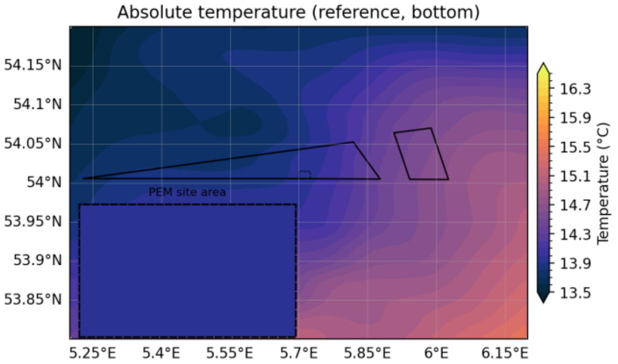
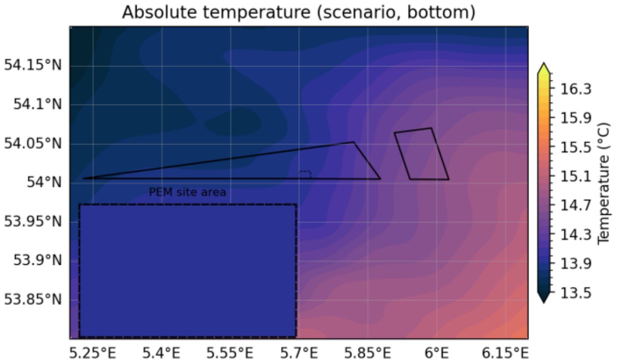
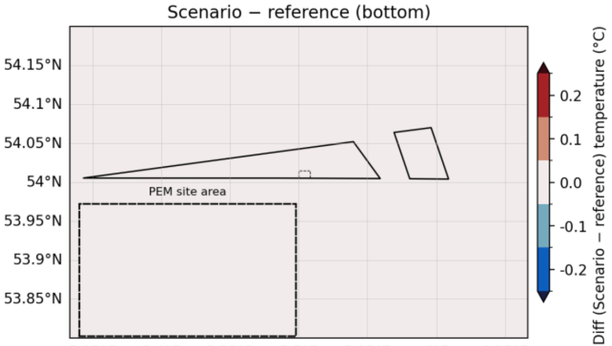
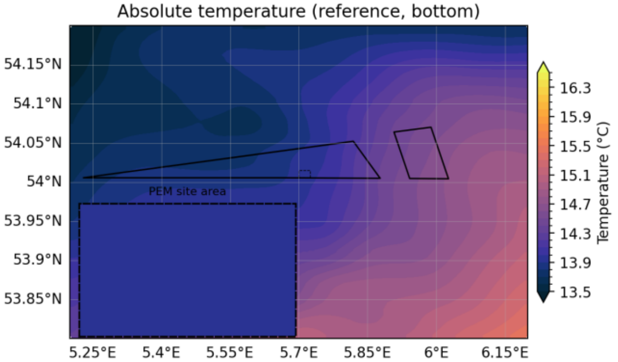
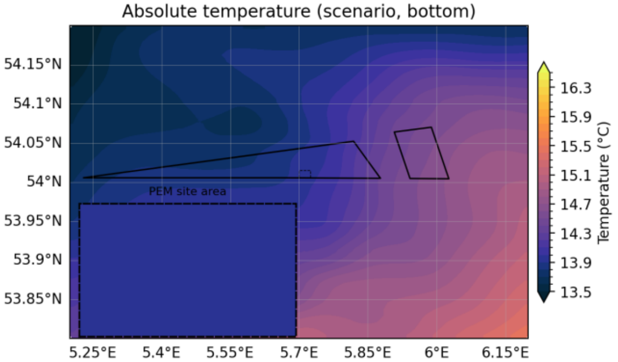
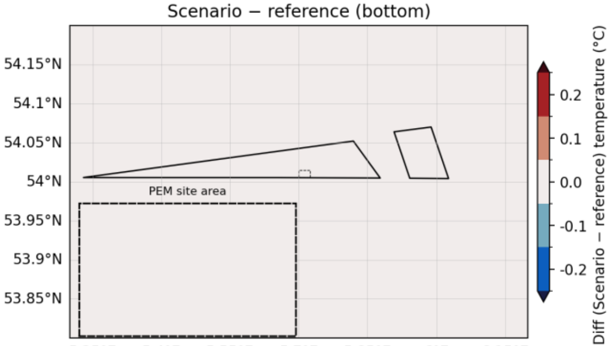
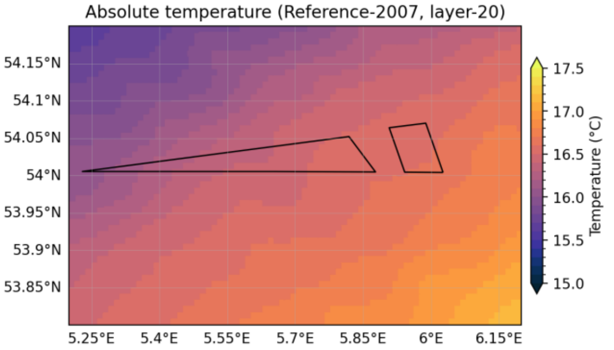
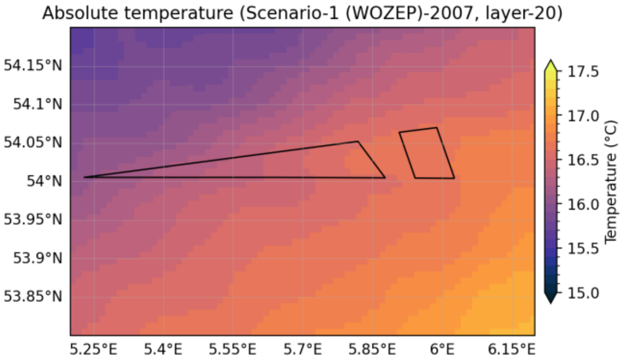
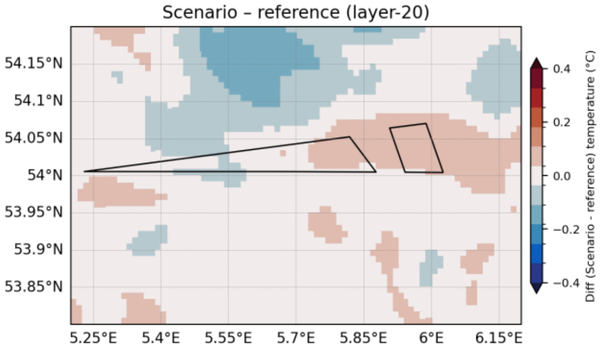
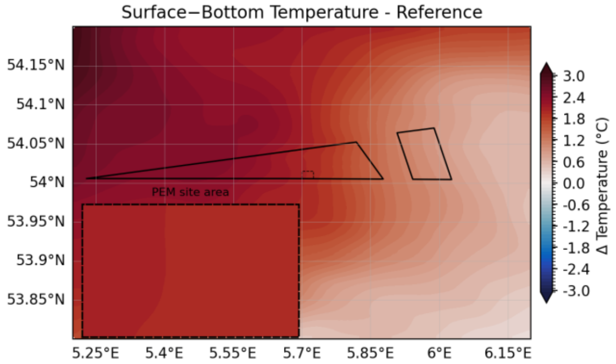
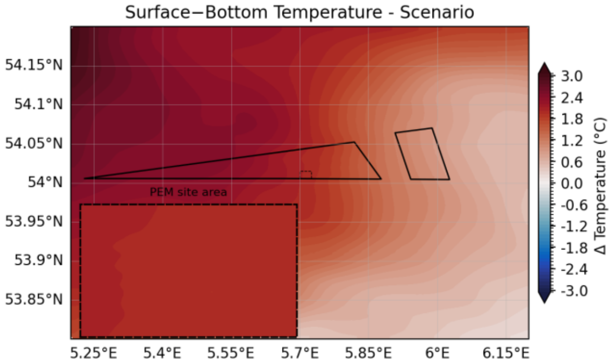
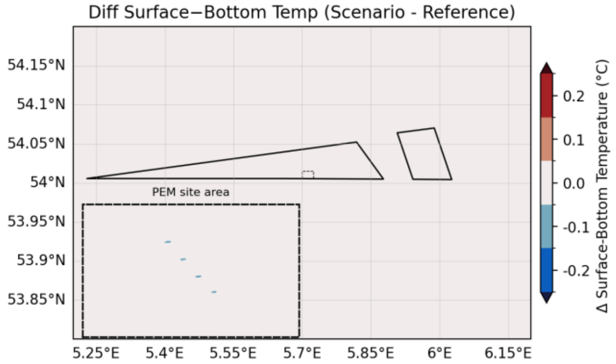
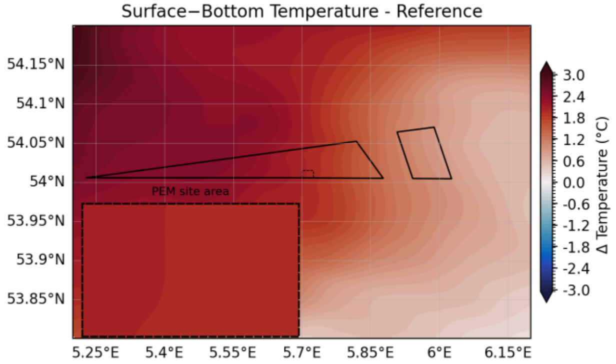
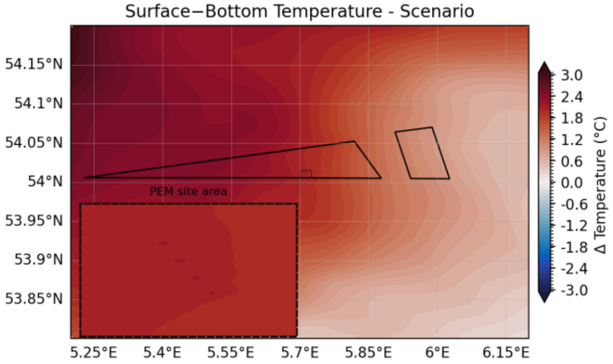
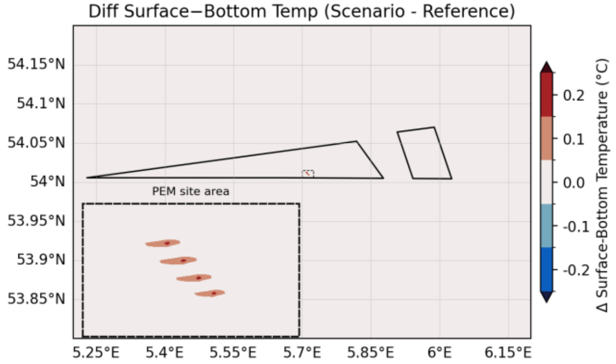
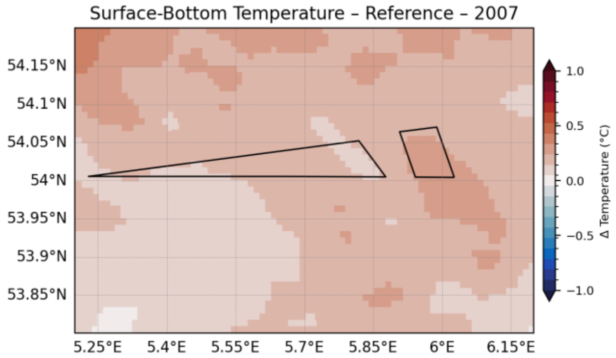
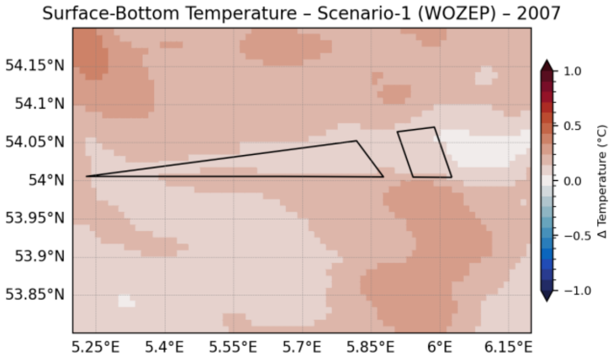
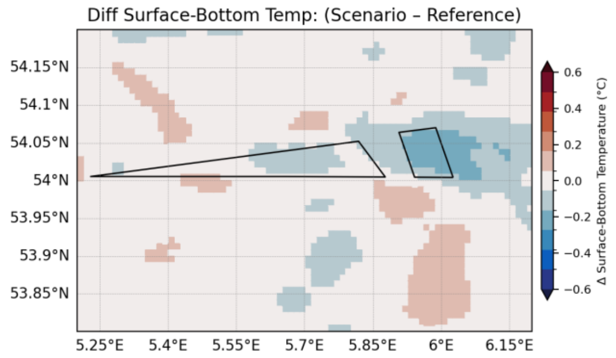
	Reference (absolute bottom temperature)	Scenario (absolute bottom temperature)	Scenario minus Reference (change in bottom temperature)
HyOne modelling Δ5°C			
HyOne modelling Δ15°C			
Wozep modelling			

Table 3.6 Scenario **summer Δ5°C** and **summer Δ15°C** results: Difference in surface and bottom temperature (vertical temperature gradient) in summer. The HyOne modelling shows the differences in **average temperatures** in the period of 1 - 19 July 2013. Wozep modelling shows differences in **average summer temperatures**, calculated as the mean of July 2007. Surface is –1 m below sea surface and bottom is layer 20 (deepest layer)

	Reference (absolute vertical temperature gradient)	Scenario (absolute vertical temperature gradient)	Scenario minus Reference (change in vertical temperature gradient)
HyOne modelling Δ5°C	 Surface−Bottom Temperature - Reference 	 Surface−Bottom Temperature - Scenario 	 Diff Surface−Bottom Temp (Scenario - Reference)
HyOne modelling Δ15°C	 Surface−Bottom Temperature - Reference 	 Surface−Bottom Temperature - Scenario 	 Diff Surface−Bottom Temp (Scenario - Reference)
Wozep modelling	 Surface-Bottom Temperature – Reference – 2007 	 Surface-Bottom Temperature – Scenario-1 (WOZEP) – 2007 	 Diff Surface-Bottom Temp: (Scenario – Reference)

3.3 Ecological impacts: primary production

Primary production

For the assessment of ecological impacts, springtime values of primary production (PP) are considered most relevant (Zijl, Laan et al 2023). Figure 3.4 presents the spring (March–May) PP for the reference scenario and the Wozep scenario, as well as the spatial differences between these scenarios, for the detailed TNW case study area.

In both the reference and Wozep scenarios, spring PP values generally range between approximately 0.6 and 1.2 gC m^{-2} day^{-1} across most of the study area (Figure 3.4). However, a pronounced spatial variation is observed east of the TNW wind farm area. In this region, the OWF scenario demonstrates substantially lower PP values, on the order of 0.3 to 0.6 gC m^{-2} day^{-1} (Figure 3.4). The reduced primary production east of TNW is associated with reduced vertical temperature gradient (or enhanced mixing) in this area, which transport more silt particles into the surface layer during spring. This mixing effect leads to a clear and spatially coherent decrease in PP relative to surrounding regions (Figure 3.5). As already indicated in an earlier study primary production in TNW-east might be reduced by ~60 % (van Duren et al., 2025).

Figure 3.4 Average primary production (in gC m-2 day-1) for spring 2007 (March, April and May) for the reference run (left) and the OWF scenario run (right)

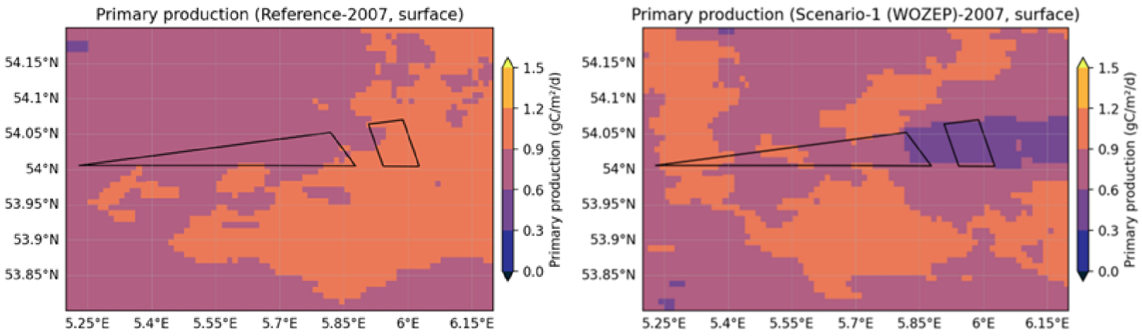
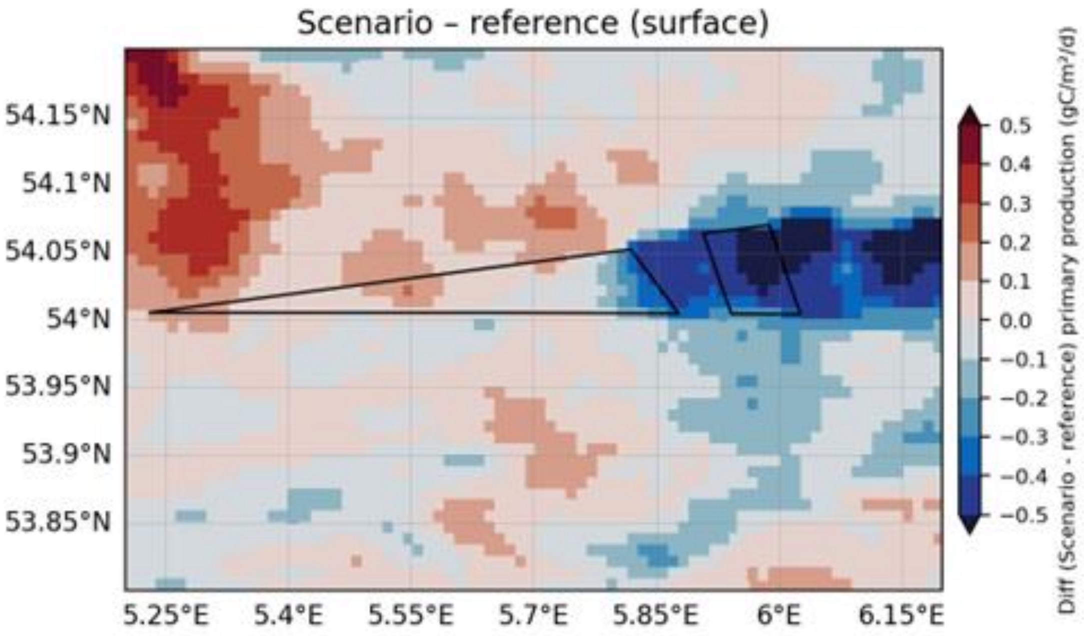


Figure 3.5 Difference between average primary production (in gC m-2 day-1) between the reference run (left) and the scenario run (right) for spring 2007 (March, April and May)



4

SYNTHESIS OF MODEL RESULTS

4.1 Main results

Local thermal plume characteristics of offshore hydrogen production

The simulated thermal plumes associated with offshore hydrogen production are highly localized and remain largely confined to the direct vicinity of the PEM platforms. Both horizontally and vertically, temperature gradients are restricted to the near-field and do not propagate into the wider water column during either winter or summer conditions. This finding is consistent with previous high-resolution modelling work, which demonstrated that waste heat from offshore hydrogen production primarily affects the upper tens of meters and rapidly dilutes due to tidal mixing, resulting in negligible far-field effects compared to other offshore energy infrastructures (Christiansen et al., 2025).

Seasonal differences in plume behaviour reflect the background stratification regime. During winter, weak ambient stratification and enhanced vertical mixing cause thermal plumes to remain positively buoyant and rise rapidly to the sea surface, where excess heat is efficiently dissipated through air–sea exchange. As a result, no measurable warming occurs near the seabed, and changes in vertical temperature gradient are limited to the immediate plume area. Similar winter conditions were shown by Christiansen et al. (2025) to suppress vertical density gradients, thereby effectively limiting the ecological relevance of hydrogen-induced heating during this period.

In summer, plume dynamics depend strongly on the temperature differential between effluent and ambient seawater. For high effluent temperature anomalies ($\Delta T \approx 15$ °C), buoyant plumes consistently reach the surface, in agreement with earlier findings that discharged heat dominates plume density despite concurrent saline discharge. For lower temperature anomalies ($\Delta T \approx 5$ °C), plumes may become trapped beneath the surface mixed layer, forming subsurface temperature maxima. Here, there is a time delay before heat can be exchanged with the air at the sea surface, and heat is exchanged further away from the platform. From an ecological perspective, effects with a longer impact in time and space are less desirable than small scale effects. However, given the change in temperature (below 0.1–0.2 °C), it is unlikely that such plume behaviour will have a detectable effect on ecology. This behaviour aligns with previous simulations showing that moderate heat release can interact with seasonal stratification to locally enhance density gradients without affecting bottom waters (Christiansen et al., 2025). In all cases, temperature changes remain confined to the plume footprint and do not extend to the benthic layer.

Spatial extent of temperature anomalies

While instantaneous maximum excess temperatures are concentrated near PEM platforms, daily maximum temperature anomalies of approximately 0.1 °C can extend further downstream under favourable hydrodynamic conditions. Nevertheless, these anomalies remain confined to the TNW zone and its nearby surroundings, and rapidly decrease with distance from the source. Averaged temperature changes are even more limited, indicating that ecologically relevant warming occurs predominantly within tens to hundreds of meters of the discharge location.

These results align with earlier model-based estimates showing that, for production capacities up to ~1 GW, annual mean sea surface temperature increases remain below 0.1–0.2 °C outside the immediate vicinity of hydrogen plants, and that large-scale effects are negligible when compared to those induced by offshore wind farms (Christiansen et al., 2025).

Comparison with offshore wind farm–induced stratification changes

Wozep modelling shows that offshore wind farms systematically alter temperature and stratification patterns in the direction of the prevailing current, east of the wind farm area in the case of TNW. In winter, background stratification is minimal and wind-farm-induced mixing results only in a small increase in surface temperature, leading to a marginal enhancement of stratification downstream. The addition of offshore wind farms therefore does not fundamentally change wintertime vertical structure, a conclusion consistent with previous North Sea simulations (Zijl et al., 2021, 2024; Zijl, Laan, et al., 2023).

In summer, however, offshore wind farms exert a markedly different influence. Monopile-induced turbulence disrupts the seasonal thermocline, leading to a reduction of stratification both within and downstream of the wind farm. This destratification effect has been repeatedly documented and shown to exceed the magnitude of stratification changes caused by offshore hydrogen production (Christiansen et al., 2025).

Combined effects and potential interactions

When considering both activities simultaneously, visual assessment suggest an apparent balancing of effects on vertical temperature gradients, though not necessarily at the same location. Offshore hydrogen production causes a localized increase in vertical temperature gradient in summer due to near-surface heating, whereas offshore wind farms induce enhanced mixing that reduces the vertical temperature gradient (stratification) over a much larger area. Consequently, the net effect appears distributed spatially, resulting in a compensation over a broader region rather than a direct cancellation at the source.

In winter, both activities tend to slightly increase the vertical temperature gradient, leading to an additive effect. However, this occurs during a season characterized by strong natural mixing driven by wind and tides. Such background conditions likely mask these small anthropogenic signals, since water is typically well mixed (Van Leeuwen et al., 2015; Zijl, Laan, et al., 2023), raising uncertainty as to whether this additive effect would be observable in practice.

Hydrodynamic interactions and implications

Potential interactions between offshore wind farms and hydrogen thermal plumes are most relevant in summer. The enhanced turbulence generated by the dense array of monopile foundations may increase dilution rates of hydrogen-induced thermal plumes. Given that hydrogen-related temperature anomalies are vertically shallow and spatially confined, additional mixing could disperse these plumes more rapidly, reducing peak temperature anomalies but extending their footprint slightly.

This interaction is in line with conclusions from Christiansen et al. (2025), who noted that monopile-induced turbulence can dominate local stratification dynamics and substantially overshadow the hydrographic footprint of hydrogen production beyond the near-field. As a result, offshore wind farms are expected to remain the primary driver of anthropogenic changes in stratification at the scale of wind farm clusters, while offshore hydrogen production contributes localized, short-range thermal disturbances.

4.2 Similarities and differences between model results

Both modelling approaches indicate that for TNW the impact on temperature and vertical temperature gradient is distinctly seasonal, with effects being considerably weaker in winter than in summer. This similarity is primarily explained by background hydrographic conditions: during winter, natural stratification is generally weak, and the water column is strongly mixed by wind and tides, limiting the persistence and detectability of anthropogenic influences. As a result, both the HyOne modelling and the Wozep modelling show only minor wintertime changes. In summer, when stratification is well developed, both models indicate temperature changes of a similar order of magnitude.

Differences in temperature between surface and bottom increases up to approximately 0.2 °C. This indicates that, under stratified conditions, both offshore hydrogen production and offshore wind farm development can locally influence the thermal structure of the water column.

At the same time, clear differences exist in the spatial scale, direction and nature of the impacts. The thermal plume associated with hydrogen production affects the vertical temperature only in the immediate vicinity of the production platforms and extends mainly in the direction of the prevailing current. In contrast, the Wozep modelling shows that offshore wind farms influence vertical temperature gradients across a much larger area, both within the wind farm boundaries and downstream. In absolute terms, the spatial extent of wind farm-induced changes is therefore substantially larger than that of the hydrogen thermal plume. Another key distinction is the sign of the impact: hydrogen production generally leads to a local increase in the vertical temperature gradient due to buoyant surface heating, whereas offshore wind farms tend to reduce the vertical temperature gradient as a result of enhanced vertical mixing caused by turbine foundations. Finally, differences between the results are also partly attributable to methodological aspects, including the use of different numerical models and the simulation of different years and time periods. While this limits direct quantitative comparison, the overall conclusion is robust: offshore hydrogen production results in small-scale, localized changes, whereas offshore wind farms are the dominant driver of vertical temperature gradient changes at the scale relevant for policy and spatial planning.

4.3 Ecological risk assessment

This study constitutes a quick scan intended to provide a first, qualitative indication of potential ecological risks associated with the interaction between offshore hydrogen production and offshore wind farms. No full ecological impact assessment has been performed, and the conclusions presented here should therefore be interpreted as screening-level insights, aimed at identifying whether further, more detailed investigation is required.

The visual analysis of the modelling results show that the two anthropogenic pressures considered in this study operate at clearly different spatial scales. Offshore hydrogen production results in small-scale, localized thermal disturbances, confined to the direct vicinity of production platforms. Offshore wind farms, by contrast, are the dominant driver of changes in vertical temperature gradients (or even stratification) and vertical mixing at the scale of wind farm areas and beyond. This distinction forms the basis for the qualitative ecological risk screening presented below.

Indicative ecological effects of hydrogen-related thermal plumes

Hydrogen-related thermal plumes may locally elevate water temperatures near discharge points, particularly in the surface layer. Daily-maximum temperature increases >0.4 °C are confined close to the outfall (0-50 m). Daily-maximum temperature increases of around 0.1-0.2 °C can extend over several hundred metres reaching ~6 km, and daily-average temperature increases of that order remain confined to the vicinity of the platforms (~200 m radius from outfalls).

On a screening level, such localized warming could bring temperatures closer to physiological tolerance limits for temperature-sensitive organisms (e.g. plankton, early life stages of fish, benthic larvae), increase metabolic rates and oxygen demand, and favour warm-adapted or opportunistic species (Dussauze et al., 2026; Li et al., 2011; Moyano et al., 2020; Zhang et al., 2022).

These potential effects are expected to be most relevant during summer, when background temperatures and stratification make ecosystems more sensitive to additional thermal stress. Mobile species may respond behaviourally through avoidance or local aggregation at plume boundaries, potentially leading to minor, localized redistribution of organisms (Dussauze et al., 2026). Based on the present modelling, direct impacts on benthic communities and far-field ecological effects are not expected under currently anticipated production (450 MW) capacities.

Ecological effects associated with offshore wind farms

In contrast, offshore wind farms are associated with systematic, spatially extensive changes in stratification, driven by monopile-induced turbulence and wind-field attenuation over wind farm areas. These processes lead to a weakening of seasonal stratification, particularly in deeper offshore regions.

The ecological consequences of reduced stratification are potentially substantial. Enhanced vertical mixing facilitates the earlier and more frequent transport of nutrients from below the thermocline into the photic zone (Van Duren et al., 2025; Zijl et al., 2021, 2024; Zijl, Laan, et al., 2023). In nutrient-limited offshore areas, this generally stimulates phytoplankton production and may even counteract periods of increased suspended particulate matter, as stratification often re-establishes before the onset of the spring bloom.

Responses differ by region. In deep, seasonally stratified offshore areas, increased mixing can lead to higher primary production through enhanced nutrient supply (Van Duren et al., 2025; Zijl et al., 2021; Zijl, Laan, et al., 2023). In contrast, in shallow or weakly stratified regions, increased mixing may resuspend sediments, reduce light availability, and thereby suppress primary production.

Changes in stratification also affect the timing of the spring bloom, which is closely linked to the establishment of stable water column structure (Van Duren et al., 2025; Zijl et al., 2021; Zijl, Laan, et al., 2023). Wind-farm-induced mixing can delay stratification onset, potentially shifting the timing of blooms. Such changes may propagate through the food web, affecting zooplankton and fish larvae that depend on synchrony between bloom development and life-cycle stages.

Precautionary principle and associated ecological risk

Within the precautionary-principle framework, the potential interactive ecological effects identified in this quick scan can be positioned qualitatively rather than quantitatively. The analysis of the results suggest that interactions between hydrogen-related thermal plumes and wind farm-induced vertical temperature gradient changes are weak, non-additive, or partly compensating, particularly with respect to the vertical temperature gradient (or even stratification).

Importantly, uncertainty increases when considering long-term ecosystem responses and food-web-level effects, especially under future upscaling scenarios. While no indication of high ecological risk emerges from this quick scan, the combination of dominant wind farm effects, localized thermal anomalies, and remaining knowledge gaps means that combined ecological effects cannot be classified as negligible a priori. As substantial uncertainties remain, future efforts should focus to support responsible upscaling and adaptive management to mitigated consequences of currently unforeseen effects.

5

DISCUSSION AND FOLLOW-UP

5.1 Main conclusions

This quick scan provides a first analysis of how the magnitude of effects of thermal discharges from offshore hydrogen production compares to hydrodynamic changes induced by offshore wind farms (OWFs) in the Dutch North Sea, with a focus on the Ten Noorden van de Waddeneilanden (TNW) area. This first indication is followed by an exploration of how these could potentially result in a combined effect, both on hydrodynamics as well as the ecology. For this objective the following can be concluded:

- **Thermal plumes remain largely confined to the near-field**, both horizontally and vertically;
    - temperature anomalies are limited to the TNW zone. Higher (daily-maximum) temperatures (>0.4 °C) are confined to the near-field area (~50 m radius);
    - average temperature increases outside the immediate vicinity of the platforms (~200 m radius from outfalls) remain in the order of ≤0.1–0.2 °C;
    - **in winter**, mixing prevents the persistence of **a strong vertical temperature gradient**, and causes thermal plumes to rise to the surface, where heat is efficiently dissipated;
    - **in summer**, plume effects remain spatially restricted as well, plumes behave differently depending on discharge temperature:
        - **Δ15 °C:** plumes are buoyant and reach the surface swiftly, where heat is efficiently dissipated;
        - **Δ5 °C:** plumes may remain temporarily trapped below the surface. This temporary effect causes the plume the reach the water surface further away from the platform, but it is unlikely that this will result in a different ecological impact.

- **Offshore wind farms induce large-scale and spatially coherent changes,** in hydrodynamics and stratification through monopile-induced turbulence and wind-field attenuation;
    - **In winter,** OWFs reduce **the vertical temperature gradient** downstream, but as stratification is naturally limited, the change caused by OWFs is relatively small;
    - **In summer**, OWFs reduce the vertical temperature gradient (and in this case stratification) over extensive areas downstream.

- **Potential ecological effects are assessed as low in magnitude and localized,** based on the precautionary principle;
    - visual assessment of model results suggest a limited interaction between thermal plumes from hydrogen production and hydrodynamic changes induced by OWF;
    - as effects remain localized, they are not additive, resulting in a relatively low ecological risk;
    - however, uncertainty remains regarding long-term ecosystem responses, food-web interactions, and cumulative impacts under large-scale deployment;
    - additionally, upscaling or regional differences are not considered, limit the applicability of this analysis to the case of TNW only.

- **Main research question**: *To what extent do the thermal plumes from offshore hydrogen production relate to and interact with the hydrodynamic changes caused by nearby offshore wind turbines, and what could these combined effects imply for ecological functioning?*
    - for the case of TNW, interaction with regard to hydrodynamic changes are, based on visual assessment and expert-judgment, expected to be limited, resulting a low ecological risk. However, considering the level of detail of this study, substantial uncertainties remain, especially in relation to upscaling and regional differences (see below).

5.2 Upscaling of hydrogen production

Upscaling offshore hydrogen production from pilot-scale or demonstration projects to multi-gigawatt systems is a stated long-term ambition for the Dutch North Sea. The results of this study provide several insights relevant to such upscaling.

At the level assessed here (four PEM platforms supporting a 450 MW cluster), thermal impacts remain localized and minor relative to OWF-induced effects. However, upscaling fundamentally changes the context, primarily through an increase in the number, density, and spatial distribution of discharge points, rather than through a proportional increase in plume size from individual platforms.

Key considerations for upscaling include:

- **Different spatial effects and aggregation of sources:** large-scale hydrogen production may involve multiple clusters within a single wind farm or across several wind farms. While individual plumes remain small, overlapping near-field effects could increase the area exposed to persistent, low-level thermal anomalies. Moreover, this study has focused on the TNW area, where stratification seems mainly temperature driven, however the cause of stratification in the area is complex. A study by van Leeuwen et al. (2015) indicated this area to, over time, switch between seasonally, intermittently and ROFI stratified regimes, also linked to different driving factors. A study by Zijl & Laan (2022) indicated temperature as the main driving factor for stratification in this area, with a much smaller influence of salinity (and thus freshwater, e.g. Rhine ROFI). Other possible locations for upscaling of offshore hydrogen production, such as search area 6/7, are more clearly determined as seasonally or intermittently stratified (Van Leeuwen et al., 2015) and which is clearly temperature driven (Zijl & Laan, 2022);

- **Temporal persistence:** continuous, year-round hydrogen production implies chronic exposure rather than intermittent thermal disturbance. Over long-time scales, even small anomalies may influence biological processes sensitive to cumulative stress, such as metabolic rates, species competition, or phenology. To explore this effect, realistic production scenarios should be considered;

- **Changing balance with OWF-induced mixing:** at larger scales, enhanced mixing by OWFs may increasingly dominate temperature and stratification dynamics, potentially mitigating hydrogen-related heating. However, this compensation cannot be assumed a priori, as the balance depends on platform layout, discharge depth, ambient stratification, and future turbine designs;

- **Interaction with other pressures:** in an upscaled energy system, thermal plumes may co-occur with other pressures, such as salinity increases from brine discharge, chemical additives, underwater noise, and habitat alteration. Even if each pressure is small in isolation, their combined effect may become ecologically relevant.

Consequently, while current results are broadly reassuring, the ecological relevance of hydrogen production is expected to increase with scale, especially when considering cumulative effects over decades and across multiple developments. Upscaling therefore calls for a transition from a quick scan-level toward integrated, scenario-based evaluation.

5.3 Key uncertainties

This quick scan has deliberately focused on a limited set of interactions and relies on existing model output. Therefore, several key uncertainties remain and should be explicitly acknowledged:

- **Separate modelling effort and comparison of independent model outputs:** this quick scan relies on two pre-existing modelling efforts (HyOne and Wozep), which differ substantially in their schematisation, simulated periods, grid resolution, boundary conditions and software version (refer to 2.1.1.). Because these models were developed independently and for different purposes, their outputs cannot be directly combined into a single model result. Instead, results are compared only visually and qualitatively. Given the methodological differences, merging the outputs would not align with good modelling practice. As a result, uncertainties arise from the lack of harmonized modelling framework;

- **Combined 'cocktail' effects of brine discharge and chemicals:** this study primarily assesses thermal effects and assumes that salinity changes from brine discharge are negligible at the assessed scale. Moreover, discharge of chemicals, which may be required as antifouling, antiscalant, desalination or other processes for offshore hydrogen production, are not considered. This 'cocktail' effect may pose additional ecological risks. To a large extent, this effect is related to ecotoxicology, rather than hydrodynamics. Regarding hydrodynamics, other studies indicate that at higher production rates, salinity plumes may persist over larger distances, particularly at depth. The combined effect of warm, saline discharges on density stratification - especially under summer conditions - remains uncertain at higher production rates;

- **Cumulative impacts over long time scales and with large-scale deployment**: the assessment is based on relatively short, representative time windows and a small hydrogen cluster (although assumed a maximal production rate). For example, intra-annual variability of the impact of cluster platforms has not been considered in this study. Long-term effects, such as gradual shifts in stratification patterns, cumulative exposure of ecosystems, or delayed food-web responses, are not resolved. These uncertainties become more important under sustained, large-scale hydrogen production;

- **Ecological interactions and primary production responses**: the ecological analysis primarily draws on Wozep modelling related to hydrodynamic changes from OWFs. Direct ecological effects of thermal plumes, such as impacts on phytoplankton growth rates, respiration, microbial activity, or thermal tolerance thresholds, are not explicitly investigated. The extent to which localized warming may modify primary production, species composition, or trophic transfer therefore remains uncertain, particularly in stratified summer conditions.

These uncertainties do not invalidate the conclusions of this quick scan, but they do limit its predictive power for future, upscaled scenarios, regional differences or effects from hydrogen production not considered in this study (see *Uncertainties as identified in Demo 2* from chapter 1) .

5.4 Possible follow-up questions and recommendations

Suggested follow-up questions

To reduce uncertainty and support informed decision-making on offshore hydrogen production, the following research questions are recommended:

- how do combined thermal, salinity and (antifouling) chemical discharges influence hydrodynamic conditions, water quality, and cause related ecological effects?
- how would realistic production rates (accounting for wind availability and energy demand and seasonality) influence hydrodynamic conditions, and cause related ecological effects?
  - at what production scale and platform architecture (density and clustering) do cumulative thermal plumes begin to overlap in a way that is ecologically relevant?
- how do chronic, low-level temperature anomalies influence primary production, species composition, and bloom timing in stratified offshore regions?

- to what extent does OWF-induced turbulence mitigate or redistribute thermal and salinity plumes under future wind farm locations and layouts?
- which ecological indicators are most sensitive to long-term cumulative exposure and therefore suitable for targeted monitoring?
- through which design adaptation can ecological effects be mitigated?

Recommendations based on ecological urgency

No immediate ecological constraints are identified for pilot-scale or moderate hydrogen production within OWFs, provided current design assumptions hold. However, in accordance with the precautionary principle and the current findings, the following recommendations are made:

1. **incorporate hydrogen-production scenarios** (including both thermal and brine plumes) with targeted follow-up studies, considering upscaling and the specific project location, are recommended before large-scale implementation. Considering upscaling and the specific project location as well as, focusing on combined heat-salinity-chemicals effects and long-term ecosystem responses is recommended. Here, a two-step approach to reach a compromise between spatial resolution and simulation period is proposed:
    1) detailed thermal plume modelling of targeted scenarios and hydrogen production developments, in a similar way as it was done in HyOne project;
    2) slight grid refinement of the DCSM-FM model at the location of PEM platforms would be applied, together with plume characteristics defined based on the detailed simulations.

    The first step serves to know the main characteristics of thermal plumes under different ambient conditions and effluent characteristics; the second enables a more accurate representation of plumes in the large-scale model over longer periods of time;

2. **improve parameterization of the effects with computational fluid dynamics (CFD) modelling**, as an alternative or complementary approach. In parallel, further development of mechanistic understanding, such as formulations for turbidity and stratification, could enhance future model robustness;

3. **Incorporate these individual, or combined, effort into cumulative ecosystem modelling,** a follow-up step of any the above mentioned activities (recommendation #1 and #2). These individual or combined efforts could be incorporated into a cumulative model, thus modelling the interaction between thermal/brine plumes coming from hydrogen production and turbulence effects coming from windfarms. This could be done by imposing average temperature or salinity changes can be imposed on Wozep-compatible grids (coming from recommendation #1 which provides more detailed plume dynamics), which also offer stronger validation potential. An iterative workflow between CFD (recommendation #2) and large-scale models can also help ensure realistic representation across scales. The resulting hydrodynamic and water-quality outputs can then be translated into ecological implications using response curves, ecological pathway modelling, or habitat-suitability approaches, allowing estimation of potential impacts on higher trophic levels;

4. **adaptive management and monitoring** should be considered as part of future permitting, enabling early detection of unexpected effects as deployment scales increase.

Additionally, we recommend investigating ecotoxicological effects resulting from chemical discharge, in combination with temperature and salinity increases. We denote this recommendation separately, as chemical discharge was not considered explicitly in this study.

In conclusion, offshore hydrogen production appears environmentally feasible with regard to hydrodynamic effects resulting from the seawater cooling system at current scales. However, responsible upscaling, in other regions of the North Sea, requires proactive reduction of key uncertainties and integration into cumulative North Sea ecosystem assessments.

6

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