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Programme Area: Marine

Project: Tidal Modelling

Title: Interactions: Analysis and Conclusions Report

Abstract:

The Project develops and verifies a set of modelling tools, and performs an initial analysis of the impact of energy extraction at various potential tidal range and tidal stream energy extraction sites. This document describes the results of TRM modelling runs to determine if there are interactions between potential future Tidal Stream and Tidal Range schemes. It describes the Continental Shelf Model, the modelling scenarios and the interpretation of results. The report draws a number of significant conclusions which are at page 6 and proposes recommendations at page 7.

Context:

Launched in October 2011 this project involved Black & Veatch, in collaboration with HR Wallingford and the University of Edinburgh to develop a model of the UK Continental Shelf and North European Waters, 100 times more accurate than existing marine data. This has been used to assess the tidal energy potential around the UK (tidal range and tidal streams), to inform the design of energy harnessing schemes, to assess their interactions, and to evaluate their impact on European coasts. It can also be used to renew and inform flood defences, coastal erosion and aggregate extraction. Now completed, the project has been launched to market under the brand of SMARTtide. This is available to the marine industry under licence from HR Wallingford.

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Tidal Modelling
(Modelling Tidal Resource Interactions around the UK)

PM03.07

Interactions (analysis and conclusions report)

Implementation of Extraction Modelling Scenarios

24th August 2012

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Participant Lead – B&V
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CONTENTS

APPENDIX GUIDE

1 EXECUTIVE SUMMARY

The Energy Technologies Institute (ETI) has proposed the development of a *Continental Shelf Model* (CSM) of UK waters to assess the tidal energy potential around the UK, to inform the design of energy harnessing schemes and to evaluate their impact on European coasts. The CSM was delivered to, and signed off by, the ETI as part of Milestone 2 of this Tidal Resource Modelling (TRM) project.

This document is Deliverable 07 - Interactions (analysis and conclusions) report, which summarises the results from the energy extraction scenarios that were designed throughout the delivery of D01, D02, and D03 of the TRM project.

The TRM project is delivered by Black & Veatch (B&V) as Prime Contractor with HR Wallingford (HRW) and the University of Edinburgh (UoE) as Subcontractors.

The overall aim of the TRM scope of work is to answer the following fundamental questions:

1. How will the interactions between tidal range and tidal current systems positioned around the UK's waters combine to form an overall effect?
2. Will the extraction of tidal energy resource in one area impact the tidal energy resource at distant sites around the UK and Europe?
3. What constraints might these interactions place on the design, development and location of future systems?

This will be achieved through a series of work packages and, ultimately, 10 deliverables of which this report forms Deliverable 07 - Interactions (analysis and conclusions), which draws out these final conclusions.

The objective of the TRM project is to improve understanding of the possible interactions between tidal energy extraction schemes as they are deployed between now and 2050. The project has developed models that can be used to investigate how energy extraction at one site may affect the energy available elsewhere. A wide range of possible future tidal range and tidal current schemes and combinations, with differing technology possibilities, are represented in the models.

Project Design/Methodology

In this analysis, a series of tidal current and tidal range energy schemes have been defined and implemented in the DCSM that generally reflect realistic developments for different time horizons (2020, 2030, 2040 and 2050), dependent upon the available technology and political will (optimistic, medium or pessimistic). Extreme and special cases have also been included.

Tidal Range
Deliverables D01- Tidal resource characterisation, and D02 – Continental Shelf Model (CSM) requirements specification, extensively investigated potential locations and configurations for tidal range schemes (barrages and lagoons) with peak power output greater than 100 MW, in UK coastal waters. Ten (10) barrage and eleven (11) lagoon alignments were identified as suitable locations for tidal range schemes.

Three possible modes of operation have been considered for a tidal barrage or lagoon:
Ebb-only generation with conventional turbines;
Dual (ebb and flood) generation with conventional turbines; and
Dual generation with Rolls-Royce turbines.

Pumping and dredging scenarios have not been included in this project; however, the capability for incorporation of pumping and dredging to use in future specific site feasibility has been incorporated into the DCSM – note that we would not advise this in the CCSM (other than for testing this caveat) as the resolution is not fine enough to represent the enhanced hydrodynamic influences of pumping and dredging. The incorporation of actual pumping and dredging schemes requires specific parameterisation by the user.

D03 - Scenarios modelling, provides full details on the compilation of the tidal range schemes. The build order specified in D03 has been followed in the implementation of the scenarios.

Tidal Current
An automated methodology was developed to define tidal current schemes corresponding to different search (constraint) criteria for each tidal current (TC) scenario (see D03, Section 6 Table 29). The methodology is described in full in Appendix B of this Interactions Report (D07). The main goal of the methodology is to determine an appropriate deployment strategy to underpin scenario development. The automated methodology that was used mostly follows that described in D03 (Section 6.3.2), but it has been slightly adapted. Changes were made for optimisation purposes. The improvements have been agreed within the project team and include removal of two constraints previously defined in D03 Tables 44 – 50:

- Removal of the significant wave height constraint, as sites already under development do not meet the proposed constraint and also the data available from the Marine Energy Atlas is not sufficiently accurate to be used.
- Removal of maximum extraction limit. This was removed because the site extraction constraint resulted in low extraction levels (in particular, lower than leased sites in the Pentland Firth and Orkney Waters, from which all scenarios are initially built). As the overarching aim of the entire TRM project is to investigate interaction effects within and between proposed tidal range and tidal current schemes, including ‘extreme’ cases, discarding this constraint was clearly a more appropriate and conservative approach to understanding these interaction effects given sites that have already been leased and other proposals for tidal current development. If this constraint had been applied as initially proposed, it would not have been possible to draw conclusions on the interactions within and between currently proposed arrays, nor on the interactions between any significant level of tidal current developments and the tidal range developments.

Apart from these two aspects, the methodology previously specified for automated selection is used to generate the scenarios for consecutive decades and political will (for example, 2030 medium case). The installed capacity and site areas for each of these scenarios can be found in Appendix B and C.

Results - Energy extraction outputs

It is noted that the tidal current and tidal range developments were incremental (in keeping with D01 – Tidal resource characterisation, and D03 – Scenarios modelling) and therefore the optimistic cases have fed into the medium cases in the next decade (time horizon).

30 scenarios have been completed and there are multiple outputs per scenario which include colour contour maps of the entire CSM and regional areas (to show more detail) showing the change in tidal range (in absolute (m) and relative (%)) and velocity (relative (%)) and kinetic power density (kW/m^2), and time series data for the energy outputs.

The DCSM has proven, as expected, to be an extremely useful tool for the analysis of tidal characteristics on the UK’s continental shelf and, most importantly for this project, the energy extraction and interactions resulting from the development of schemes to harness these tidal characteristics, be they tidal range or tidal current schemes.

There are a number of clear conclusions that can be drawn from the results of the scenarios:

- That any credible tidal current development does not impact on the tidal range sites.
- That there is only a minimal impact of tidal range sites on tidal current sites, in the most extreme cases. In less extreme cases, there is essentially no impact.
- Extreme scenarios (22) suggest that the Severn Outer barrage has a significantly more severe far-field impact (on tidal current sites) in comparison with the combination of the Cardiff-Weston barrage and Bridgewater Bay lagoon.
- ‘Mega’ schemes with dual generation (Severn Outer, Solway Firth) do not work as intended, and effectively cannot move the water away fast enough, impeding generation.
- Noticeable benefits in using Rolls-Royce turbines in dual-mode schemes were observed for the Solway Firth, Mersey, and the Wash as there are reduced impacts on downstream tidal range than equivalent dual schemes.
- Large reduction in downstream tidal range for major barrages/lagoons in estuaries (Bridgwater Bay, Cardiff-Weston, Mersey, Thames, Wash, Humber) reduces their energy output compared to 0D modelling, as expected.
- Much less effect on downstream tidal range for lagoons on open coastlines (Rye, Dymchurch, Cumbria, Wigtown) or smaller lagoons, suggesting these may be worth further investigation.
- The increased tidal range which is visible, in particular in the Irish Sea and surroundings, when there is large scale deployment of tidal range schemes in that area, is unlikely to be acceptable in terms of environmental (and safety) impacts.
- Significant interactions (i.e. a negative effect on tidal range and potential energy) within the Severn – e.g. the Cardiff-Weston barrage reduces energy output for lagoons downstream.
- Almost no interaction between tidal range schemes in Irish Sea, despite the impacts on increased tidal range discussed earlier.
- In UK waters, large scale utilisation of the tidal resource requires significant optimisation to avoid potentially unacceptable cumulative impacts and to ensure the most energy can be extracted from the resource (potentially at least cost, with least impact on the grid etc.).

From the time series analysis, tidal range deployment around the UK is all essentially in phase if dual mode generation is used, reducing the options for power smoothing. With ebb-only generation the options for power smoothing are improved. The tidal current sites, although they are generally all in phase with each other, are out of phase with the tidal range schemes. Therefore it is possible to develop a combination of range and current schemes to contribute to power smoothing, and scenario 10 represents the best scenario investigated to date. However, although the 24 hour cycle can be ‘smoothed’ significantly through judicious selection of the combination of tidal range and tidal current sites, the spring-neap cycle of course cannot be ‘smoothed’ in the same way and the maximum power at spring tide is still c. 2-3 times that available at neap tide. The only way that this spring-neap factor could be reduced would be to reduce the installed capacities of the schemes so that the capacity factor would naturally increase.

10 critical factors for optimising tidal power systems have been identified and 5 optimisation outcomes have been identified. Optimisation of a tidal power project could be driven by a number of outcomes, singly or in combination. We believe the best single optimisation would be based on maximising energy generation within CoE thresholds/constraints as it would ultimately be possible to incorporate all critical factors (and other optimisation outcomes) as a relative cost. Alternatively, it is possible, that optimisation could focus on maximum power generation unconstrained by CoE thresholds/constraints, minimising environmental impacts, maximising power smoothing or minimising impacts on the available grid network.

Conclusions and recommendations

The aim of the TRM scope of work is to address the following fundamental questions:

1. How will the impacts of tidal range and tidal current energy schemes positioned around the UK combine to form an overall effect?
    - The 30 scenarios that have been run and are summarised in this report provide a good representation of possible tidal deployments through to 2050. From these scenarios, we have summarised the implications on the overall near-field and far-field effects.
    - In general, the extraction of tidal current energy has been shown to have a severe near-field effect when extraction is unlimited and therefore extraction requires close management of the resource both within and between nearby projects to ensure that the resource is not over exploited (which could potentially cause detrimental economic and environmental effects). However, there is no far-field effect that impacts any tidal range locations (as specified in this report).
    - The extraction of tidal range energy in UK waters has been shown to have wide-scale and significant effects in the extreme cases. The combination of all schemes on the west coast causes tidal range changes which we believe would be unacceptable.

Therefore, optimisation for environmental/human impact, energy output, economics or power smoothing is needed if the overall tidal resource is to be exploited to its full potential.

2. Will the extraction of tidal energy resources in one area affect the tidal energy resources at distant sites around the UK and Europe?
    - The results of the scenario runs completed using the DCSM give the most in-depth and accurate assessment of energy output from a combination of UK schemes to date.
    - Table 5 (page 43) which provides indicative % change in energy production for each scheme in each scenario, shows clearly where there is an impact of a following scheme. It is important to note that, as described in the scenario observations, some schemes which are incorporated into the scenarios later on have a low energy output due to the preceding schemes and therefore the change in energy due to other schemes is larger in real terms.
    - The CSM scenario run outputs give a clear indication as to the impact at far-field UK sites.
    - The impacts across Europe vary depending on the scenario but Scenario 16, which is the most extreme case of both tidal range and tidal current deployment, shows that there would be an impact on the European coastline.

3. What constraints might these interactions place on the design, development and location of future systems?
    - The information in this report is important and useful information that should be provided to all key decision makers with regards to tidal development, including UK and Scottish Governments, and The Crown Estate. The data and information should be used to inform and educate the process to ensure that the development of the UK's tidal resource is optimised. Clearly, further work is needed (beyond these scenarios already investigated) to support such optimisation.
    - The interactions within and between schemes developed in this report shows that the level of tidal range deployment (for near-field and far-field effects) and tidal current deployment (mainly near-field to regional impacts) would place constraints on the schemes. Both effects could potentially impact the success of projects. Importantly, the installation of later schemes could have an impact (positive or negative) on an existing scheme or its effects.
    - The operating regime at specific sites and overall scheme optimisation could be further developed using the DSCM tool, both at a 'macro' level in terms of optimising the development of the UK resource and in terms of specific site considerations.

The DCSM is a pre-feasibility tool (D01 3.2.4 refers to ‘a feasibility study, which is beyond the scope of the CSM development). The CSM therefore provides the ETI with a UK scale tool for assessing likely interactions between schemes. For detailed site specific investigations, further more detailed analysis is required.

The interactions are likely to place constraints about where and how much energy should be extracted and it is important that the industry is informed. The scenarios in this report provide a very clear indication as to the likely level of impacts in particular locations in reasonable and extreme cases, but this should be investigated further to ensure that the development of the UK resource is optimised.

Project development for a tidal energy scheme involves consenting, and for tidal range schemes this will require longer and more in-depth analysis as the environmental effects are known to be greater than those predicted for tidal current schemes. The consenting process could be extended as a result of the interaction effects (e.g. to research further significant changes to an intertidal habitat of an estuary subject to several schemes being consented).

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From the initial scenario runs completed, it is clear that there is a vast amount of research and development into tidal site selection that could be carried out using the DCSM and, with the incorporation of other data, to optimise the UK resource as a whole (as well as individual schemes).

The scenarios presented provide a broad and indicative impression of the potential interactions across the UK continental shelf, from minor deployments to extreme development. The incorporation of extreme scenarios allowed us to present the most extreme interaction effects. We do not believe that these scenarios necessarily represent realistic development, but provide useful data to allow understanding of the limits of deployment, which is essential.

Moving forward, we would recommend that future scenarios (e.g. those to be put forward by ETI for the remaining 12 scenarios in the current scope of work) consider more realistic levels of energy extraction. After that, although some other extreme cases might be of interest, the best value can probably be obtained from commencing work on investigating optimisation of the UK resource as a whole as discussed in Section 5.2.

2 INTRODUCTION

2.1 Background

The Energy Technologies Institute (ETI) has proposed the development of a *Continental Shelf Model* (CSM) of UK waters to assess the tidal energy potential around the UK, to inform the design of energy harnessing schemes and to evaluate their impact on European coasts. The CSM was delivered to, and signed off by, the ETI as part of Milestone 2 of this Tidal Resource Modelling (TRM) project. *Black & Veatch* (B&V), in collaboration with *HR Wallingford* (HRW) and the *University of Edinburgh* (UoE), is providing support with regard to the development of this model and subsequent use by the tidal power industry. This report has been led by HRW and is part of the *Tidal Resource Modelling* (TRM) scope of work delivered by B&V as prime contractor.

B&V has been consulting on tidal energy since 1975 (B&V was previously Binnie & Partners in the UK until 1995). B&V has a very broad and in-depth experience of both tidal range and tidal current projects, including resource assessment and project development, technology development, due diligence, cost of energy and policy development. Through working on these projects, it has gained a deep technical and commercial understanding of tidal energy projects in addition to simply resource assessment.

HRW has vast experience of numerical modelling of free surface flows using the TELEMAC system and has been instrumental in its continued development. The TELEMAC system is a state-of-the-art free surface flow suite of solvers developed by a kernel of European organisations including HRW and other partners such as *Electricité de France* (EDF) and the Federal Waterways Engineering and Research Institute of Germany (information related to the TELEMAC system is provided in D02). HRW's expertise is acknowledged within the UK tidal modelling community as the only entity with an in-depth experience of TELEMAC and its tailoring to specific problems.

The UoE is one of the largest and most successful universities in the UK with an international reputation as a centre of academic and research excellence. The *Institute for Energy Systems* (IES) is one of five multi-disciplinary research groupings within the School of Engineering at the University. In the most recent UK-wide *Research Assessment Exercise* (RAE 2008), the School was ranked third in the UK for combined research quality and quantity.

The aim of the TRM scope of work is to address the following fundamental questions:

How will the impacts of tidal range and tidal current energy schemes positioned around the UK combine to form an overall effect?
Will the extraction of tidal energy resources in one area affect the tidal energy resources at distant sites around the UK and Europe?
What constraints might these interactions place on the design, development and location of future systems?

This is achieved through a series of work packages and, ultimately, 10 deliverables outlined below.

D01 – Tidal resource characterisation
D02 – Continental Shelf Model (CSM) requirements specification document
D03 – Scenarios modelling
D04 – Cost of Energy Model and supporting documentation
D05 – Interface specification for detailed tidal current model with CSM
D06 – CSM (coarse and detailed versions) with supporting documentation
D07 – Interactions (analysis and conclusions report)
D08 – Interface specification for detailed tidal range model and the CSM

D09 – Tidal Range model and supporting documentation
D10 – Project dissemination

This document is Deliverable 07 - Interactions (analysis and conclusions) report, which summarises the results from the energy extraction scenarios that were designed throughout the delivery of D01, D02, and D03 of the TRM project.

3 PROJECT DESIGN/METHODOLOGY

In this analysis, a series of tidal current and tidal range energy schemes have been defined and implemented in the DCSM that generally reflect realistic developments for different time horizons, dependent upon the available technology and political will. It is noted that the tidal current and tidal range developments were incremental (in keeping with D01 – Tidal resource characterisation, and D03 – Scenarios modelling) and therefore the optimistic cases have fed into the medium cases in the next decade (time horizon).

This section describes the scenarios developed in the DCSM and introduced in D03. Figure 8 and Figure 9 are visual representations of the tidal range and tidal current schemes included within each time horizon, at a national scale. In these figures, green is used for barrages, orange for lagoons and pink for tidal current schemes.

Section 3.1 and 3.2 specifically summarise the schemes adopted for each scenario and define the build out order. Details of the tidal range scheme parameters can be found in Appendix A. The automated procedure used to define the tidal current schemes is described in Appendix B, together with the results of the scenario interactions completed for each time horizon. D02 – Continental Shelf Model (CSM) requirements specification documentation holds details with regard to the numerical implementation of the schemes in the DCSM.

The build out order defines the order in which the schemes are incorporated into the scenarios and therefore the order in which the scenarios were run.

3.1 Definition of tidal range energy schemes

Deliverables D01- Tidal resource characterisation and D02 – Continental Shelf Model (CSM) requirements specification extensively investigated potential locations and configurations for tidal range schemes (barrages and lagoons) with peak power output greater than 100 MW, in UK coastal waters. Ten (10) barrage and eleven (11) lagoon alignments were identified as suitable locations for tidal range schemes. These are identified in Figure 8 – see Section 8 FIGURES (green for barrages and orange for lagoons). They were selected based on a literature review of previous studies (for barrages) and on the tidal range, water depth and coastline shape (for lagoons).

Three possible modes of operation have been considered for a tidal barrage or lagoon:
Ebb-only generation with conventional turbines;
Dual (ebb and flood) generation with conventional turbines; and
Dual generation with Rolls-Royce turbines.

Pumping and dredging scenarios have not yet been included in this project; however, the capability for incorporation of pumping and dredging has been incorporated into the DCSM – note that we would not advise this in the CCSM (other than for testing this caveat) as the resolution is not fine enough to represent the enhanced hydrodynamic influences of pumping and dredging. The incorporation of actual pumping and dredging schemes requires specific parameterisation by the user.

It is also noted (from D01 report, Section 5.23) that:
The ebb-only schemes generally only achieve a tidal range of around 50% of the natural range inside the impoundment (based on 0D model testing of the selected scheme), as expected and agreed with ETI when these schemes were incorporated into the model.
Ebb-only selections have not been made for lagoons since it is anticipated that dual mode generation should give (significantly) greater energy output if 80% of natural tidal range is achieved.
At some locations there is insufficient deep water or estuary width to accommodate sufficient conventional turbines to achieve 80% of natural tidal range (maintaining 80% tidal range was specified as a requirement by the ETI; see D01 Section 4.2 for discussion). In such cases, dual mode schemes have not been selected, although there could be some value in dredging the approaches to accommodate conventional turbines (e.g. Severn Cardiff-Weston).
Schemes have not been selected for the Duddon estuary because there is no deep water channel there to install turbines. Schemes have not been selected for the Dee-Wirral lagoon either on the basis that both the Mersey and the Dee barrages would be enclosed by installation of the Dee-Wirral lagoon and priority has been given to the Mersey and the Dee barrages.

A brief summary of the tidal range scenario selection framework is presented below (Table 1) which indicates the tidal range (TR) consideration and Scenario number e.g. 02. The Scenarios are presented in order of the build out (i.e. the Scenario numbers are not consecutive). The reader is referred to Appendix A for more details about the proposed schemes and to D01 and D03 for the rationale behind the build order.

Before the schemes were input into the DCSM, a ‘flume test’ in TELEMAC was completed to ensure that the scheme operated as intended in the 2D model compared to the 0D model in which they were developed. This test ensures that the parameterisation behaves as intended in a 2D model prior to programming into a larger model with complex hydrodynamics (where it would be more difficult to determine if the parameterisation or the hydrodynamics were causing a particular effect). Appendix A provides the results of these tests, which evidence that the schemes work as intended in the TELEMAC ‘flume test’. The implication of this test is that when the schemes are incorporated into the full DCSM, the different effects (compared to those in the 0D model) are a result of the actual hydrodynamic conditions that are modelled in the 2D model (and not in the 0D model).

As per the D03 report, where a pessimistic tidal range scenario is defined this equates to an extreme case of no tidal range development. This is an extreme political position but it is also used as a tool to test the sensitivity of tidal current energy extraction on its own in the model.

As agreed in D02, Scenario 1, or the base case configuration of the DCSM, represents the existing environment. As such, it only includes La Rance tidal power plant, in France.

In the absence of detailed information about La Rance, it was assumed for deliverable D06 – CSM (coarse and detailed versions) that an ebb-only operation mode (as is the dominant case for La Rance) with conventional turbines could represent the scheme. The parameters subsequently developed by B&V for the La Rance tidal power plant, and provided in A.1 of Appendix A from D06 Part B, were implemented in Scenario 1 (and all subsequent scenarios).

In keeping with D03, Scenarios 6, 22 and 23 were conducted before proceeding further with scenario testing. The principal aim of these simulations was to assess the relative performance of the Cardiff-Weston barrage and Bridgewater Bay lagoon in different combinations. This enabled the decisions with regard to the Bristol Channel/Severn Estuary proposals to be carried forward into the other scenarios (8-16, 18-20, 26-28) and ensures credibility of the later CSM scenario simulations. This test enabled assessment examining the relative performance of the Cardiff-Weston barrage and Bridgewater Bay lagoon in different combinations. If there had been a dramatic reduction in the combined electricity generation by the two schemes in either configuration (scenario 6 or 23) (defined as overall generation of less than 73% of the design case, e.g. the theoretical capacity of the Cardiff-Weston barrage operating in isolation) there was the option to use the Severn Outer barrage in place of the two smaller options.

There was only a minimal change in the generation of the combined schemes (compared to the sum of their generation when implemented in isolation) and therefore the project team made a collective decision to maintain the Cardiff-Weston and Bridgewater Bay schemes in all the scenarios.

With Scenarios 26 to 28, the main goal is to consider the impact of tidal range technology selection throughout the UK sites. As such, in keeping with D03, these 3 scenarios are all based on Scenario 16, where no tidal current schemes are implemented in the DCSM, and where ebb operation mode and conventional turbines are used wherever possible/practical in Scenario 26, dual operation mode and conventional turbines are used in Scenario 27, and dual operation mode, Rolls-Royce turbines are used everywhere in Scenario 28. Also note TR identifier number (i.e. TR **04**) in Table 1 relate directly to the scenario number.

Table 1 Summary of Tidal Range (TR) Scenario schemes and build order

TR 02		
Bridgewater Bay lagoon (dual conventional)		
TR 03		
Bridgewater Bay lagoon (dual conventional) Kirkcudbright Bay lagoon (dual Rolls-Royce)		
TR 05		
Bridgewater Bay lagoon (dual conventional) Kirkcudbright Bay lagoon (dual Rolls-Royce) Cardiff-Weston barrage (ebb conventional)		
TR 06		
Bridgewater Bay lagoon (dual conventional) Kirkcudbright Bay lagoon (dual Rolls-Royce) Cardiff-Weston barrage (ebb conventional) Mersey barrage (dual Rolls-Royce)		
TR 22		
Kirkcudbright Bay lagoon (dual Rolls-Royce) Severn Outer barrage (dual conventional) Mersey barrage (dual Rolls-Royce)		
TR 23		
Bridgewater Bay lagoon (dual conventional) Kirkcudbright Bay lagoon (dual Rolls-Royce) Cardiff-Weston barrage (dual Rolls-Royce) Mersey barrage (dual Rolls-Royce)		
TR 08		
Bridgewater Bay lagoon (dual conventional) Kirkcudbright Bay lagoon (dual Rolls-Royce) Cardiff-Weston barrage (ebb conventional)		Mersey barrage (dual Rolls-Royce) Morecambe Bay barrage (dual Rolls-Royce) Wash barrage (dual conventional)
TR 10		
Bridgewater Bay lagoon (dual conventional) Kirkcudbright Bay lagoon (dual Rolls-Royce) Cardiff-Weston barrage (ebb conventional) Mersey barrage (dual Rolls-Royce)		Morecambe Bay barrage (dual Rolls-Royce) Wash barrage (dual conventional) Dee barrage (dual conventional)

TR 11

Bridgewater Bay lagoon (dual conventional)
Kirkcudbright Bay lagoon (dual Rolls-Royce)
Cardiff-Weston barrage (ebb conventional)
Mersey barrage (dual Rolls-Royce)
Morecambe Bay barrage (dual Rolls-Royce)
Wash barrage (dual conventional)
Dee barrage (dual conventional)
Solway Firth barrage (dual conventional)
West Aberthaw lagoon (dual conventional)
Rhoose lagoon (dual conventional)
Rye Bay lagoon (dual conventional)

TR 12

Bridgewater Bay lagoon (dual conventional)
Kirkcudbright Bay lagoon (dual Rolls-Royce)
Cardiff-Weston barrage (ebb conventional)
Mersey barrage (dual Rolls-Royce)
Morecambe Bay barrage (dual Rolls-Royce)
Wash barrage (dual conventional)
Dee barrage (dual conventional)
Solway Firth barrage (dual conventional)
West Aberthaw lagoon (dual conventional)
Rhoose lagoon (dual conventional)
Rye Bay lagoon (dual conventional)
Wigtown Bay lagoon (dual conventional)
Dymchurch lagoon (dual conventional)
Oxwich Bay lagoon (dual conventional)

TR 16

Bridgewater Bay lagoon (dual conventional)
Kirkcudbright Bay lagoon (dual Rolls-Royce)
Cardiff-Weston barrage (ebb conventional)
Mersey barrage (dual Rolls-Royce)
Morecambe Bay barrage (dual Rolls-Royce)
Wash barrage (dual conventional)
Dee barrage (dual conventional)
Solway Firth barrage (dual conventional)
West Aberthaw lagoon (dual conventional)
Rhoose lagoon (dual conventional)
Rye Bay lagoon (dual conventional)
Wigtown Bay lagoon (dual conventional)
Dymchurch lagoon (dual conventional)
Oxwich Bay lagoon (dual conventional)
Humber barrage (dual Rolls-Royce)
Thames barrage (dual Rolls-Royce)
Cumbria lagoon (dual conventional)
Morte Bay lagoon (dual conventional)

TR 19

Bridgewater Bay lagoon (dual conventional)
Kirkcudbright Bay lagoon (dual Rolls-Royce)
Cardiff-Weston barrage (ebb conventional)
Mersey barrage (dual Rolls-Royce)
Morecambe Bay barrage (dual Rolls-Royce)
Dee barrage (dual conventional)
Solway Firth barrage (dual conventional)
West Aberthaw lagoon (dual conventional)
Rhoose lagoon (dual conventional)
Wigtown Bay lagoon (dual conventional)
Oxwich Bay lagoon (dual conventional)
Cumbria lagoon (dual conventional)
Morte Bay lagoon (dual conventional)

TR 20

Wash barrage (dual conventional)
Rye Bay lagoon (dual conventional)
Dymchurch lagoon (dual conventional)
Humber barrage (dual Rolls-Royce)
Thames barrage (dual Rolls-Royce)

TR 26

Bridgewater Bay lagoon (dual conventional)
Kirkcudbright Bay lagoon (dual Rolls-Royce)
Cardiff-Weston barrage (ebb conventional)
Mersey barrage (ebb conventional)
Morecambe Bay barrage (ebb conventional)
Wash barrage (ebb conventional)
Dee barrage (ebb conventional)
Solway Firth barrage (ebb conventional)
West Aberthaw lagoon (dual conventional)
Rhoose lagoon (dual conventional)
Rye Bay lagoon (dual conventional)
Wigtown Bay lagoon (dual conventional)
Dymchurch lagoon (dual conventional)
Oxwich Bay lagoon (dual conventional)
Humber barrage (ebb conventional)
Thames barrage (ebb conventional)
Cumbria lagoon (dual conventional)
Morte Bay lagoon (dual conventional)

TR 27

Bridgewater Bay lagoon (dual conventional)
Kirkcudbright Bay lagoon (dual conventional)
Cardiff-Weston barrage (ebb conventional)
Mersey barrage (dual conventional)
Morecambe Bay barrage (dual Rolls-Royce)
Wash barrage (dual conventional)
Dee barrage (dual conventional)
Solway Firth barrage (dual conventional)
West Aberthaw lagoon (dual conventional)
Rhoose lagoon (dual conventional)
Rye Bay lagoon (dual conventional)
Wigtown Bay lagoon (dual conventional)
Dymchurch lagoon (dual conventional)
Oxwich Bay lagoon (dual conventional)
Humber barrage (dual Rolls-Royce)
Thames barrage (dual Rolls-Royce)
Cumbria lagoon (dual conventional)
Morte Bay lagoon (dual conventional)

TR 28

Bridgewater Bay lagoon (dual Rolls-Royce)
Kirkcudbright Bay lagoon (dual Rolls-Royce)
Cardiff-Weston barrage (dual Rolls-Royce)
Mersey barrage (dual Rolls-Royce)
Morecambe Bay barrage (dual Rolls-Royce)
Wash barrage (dual Rolls-Royce)
Dee barrage (dual Rolls-Royce)
Solway Firth barrage (dual Rolls-Royce)
West Aberthaw lagoon (dual Rolls-Royce)
Rhoose lagoon (dual Rolls-Royce)
Rye Bay lagoon (dual Rolls-Royce)
Wigtown Bay lagoon (dual Rolls-Royce)
Dymchurch lagoon (dual Rolls-Royce)
Oxwich Bay lagoon (dual Rolls-Royce)
Humber barrage (dual Rolls-Royce)
Thames barrage (dual Rolls-Royce)
Cumbria lagoon (dual Rolls-Royce)
Morte Bay lagoon (dual Rolls-Royce)

3.2 Definition of tidal current energy schemes – 2020 to 2050

An automated methodology was developed to define tidal current schemes corresponding to different search (constraint) criteria for each tidal current (TC) scenario (see Table 2 which is a summary of the tidal current scenarios defined in D03). This automated methodology mostly follows that described in D03 (Section 6.3.2), but it has been slightly adapted for implementation and optimisation purposes, and improved to allow a more precise representation of the tidal current resource and its constraints. The methodology is described in Appendix B. The main goal of the methodology is to determine an appropriate deployment strategy to underpin scenario development.

The aspects which have changed from the methodology are:

In D01/D03, the wave conditions at the proposed development sites were considered as a constraint. However, examination of the wave atlas (mean significant wave height), the Marine Energy Atlas[1], indicated that the zones already leased by The Crown Estate in the Pentland Firth do not comply with the wave criteria defined in D03. In addition, the resolution of the atlas is not sufficiently accurate for sites near-shore. Therefore, this constraint was not used in the analysis.

Constraint on maximum site extraction has been discarded (a full explanation is provided in the Appendix B methodology). This was removed because the site extraction constraint resulted in low extraction levels (in particular, lower than leased sites in the Pentland Firth and Orkney Waters, from which all scenarios are initially built). As the overarching aim of the entire TRM project is to investigate interaction effects within and between proposed tidal range and tidal current schemes, including ‘extreme’ cases, discarding this constraint was clearly a more appropriate and conservative approach to understanding these interaction effects given sites that have already been leased and other proposals for tidal current development. Since the DCSM is planned to be later used to investigate other scenarios, both within and separate from the existing TRM project scope, the impact of constraining tidal current schemes using the previously proposed Flux Method (which assesses the amount of theoretical energy that is available and the proportion of that which can be ‘acceptably’ extracted – see D01 Section 9.1 and D03 Section 6),

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[1] ABPMer, Atlas of UK Marine Renewable Energy Resources, BERR 2007

or an iteration of it, can readily be investigated once the environmental and economic impacts of not using such a constraint have been understood from the results presented in this report, and as noted later the DCSM should be used as a tool to optimise proposed schemes in any case. If this constraint had been applied as initially proposed, it would not have been possible to draw conclusions on the interactions within and between currently proposed arrays, nor on the interactions between any significant level of tidal current developments and the tidal range developments.

Apart from these two aspects, the methodology previously specified (See D03 Section 6.3) for automated selection is used to generate the scenarios for consecutive decades and political will (for example, 2030 medium case). The installed capacity and site areas for each of these scenarios can be found in Appendix B. The special and extreme cases are discussed further below.

The target value of 85 GW in the Pentland Firth in Scenario 24, to align with Salter's proposals, was only achieved with a very tight packing density (c. 5 times the base case packing density), corresponding to an installed capacity of 86GW for the whole of the Pentland Firth. As the CSM was not used to generate the area, there is no summary of the scenario inputs in Appendix B.

There was no target installed capacity *per se* for Scenario 25 but, with the intention of simulating an extreme case, the extreme packing density defined as 1.25D by 5D m^2 in D01 was employed. The intention was to test the potential extraction from the areas defined by Mackay[2]. This yielded an installed capacity of the order of 241 GW, or an indicative energy output of 633.9 TWh/y based on a capacity factor of 0.3 (which is obviously unlikely to be achieved in such an extreme scenario due to the act of harvesting the resource also reducing the resource significantly and the fact that the areas defined included large areas where there is a very low intensity resource). As per Scenario 24, the area for deployment were defined, as described in D03, by using a $1kW/m^2$ power density criteria and certain search areas, as specified by Mackay for tidal current[2] . As the DCSM was not used to define the areas, there is no definition required in Appendix B.

With Scenarios 26 to 28, the main goal was to consider the impact of different technology selection throughout the UK. As such, in keeping with D03, these 3 scenarios are all based on Scenario 16, where no tidal current schemes are implemented in the DCSM, and where ebb operation mode and conventional turbines are used wherever possible/practical in Scenario 26, dual operation mode and conventional turbines are used in Scenario 27, and dual operation mode, Rolls-Royce turbines are used everywhere in Scenario 28.

With Scenarios 29 and 30, the intention was to open up development sites that are currently perceived to have marginal value. It is anticipated that third generation technologies would focus on targeting lower rated velocities than previously examined. It is noted that Scenarios 29 and 30 installed capacity levels are not necessarily anticipated to be realistic due to their extreme nature (in particular the kinetic power density values were not constrained in these cases, as is evident from Table 2, and this is likely to yield to an over-optimistic development of the areas identified and consequent over-prediction of the installed capacity that can practically be achieved). This is as intended, and was specified to test the extremes of the resource.

As per D03 report, where a pessimistic tidal current scenario is defined this equates to an extreme case of no tidal current development. This is an extreme 'political' position but it is also used as a tool to test the sensitivity of tidal range energy extraction on its own in the model. Note, as per the tidal range build order summary, the Scenarios are presented in order of the build out (i.e. the Scenario numbers are not consecutive). Figure 8 provides a map of all the tidal current locations, Figure 41 provides more specific polygons for the tidal current sites – see Section 8 FIGURES.

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[2] Mackay, D Sustainable Energy – Without the Hot Air, 2008

Table 2 Summary of tidal current (TC) energy scenario constraints[3]

Tidal Current Scenario ID	Year	Optimism	Maximum distance from shore	Depth permitted for deployment[4]	Mean kinetic power density (kW/m^2)		Installed capacity (MW)		Restriction on the deployment of 2nd generation technology (MW installed)
					Target value	Absolute value	Minimum	Maximum	
	2010	n/a	n/a	n/a	n/a	n/a	0	0	n/a
TC02	2020	Medium		20 m - 50 m	n/a	n/a	400	400	n/a
TC04	2020	Optimistic		20 m - 50 m	n/a	n/a	700	700	n/a
TC05	2030	Medium	6000 m	20 m – 100 m	3.0	2.25	2,000	3,000	max 500 MW > 60 m
TC07	2030	Optimistic	8000 m	20 m – 100 m	2.25	2.0	3,000	4,000	max 1500 MW > 60 m
TC08	2040	Medium	10000 m	20 m – 120 m	2.0	1.80	4,000	8,000	max 3000 MW > 60 m max 500 MW > 100m
TC11	2050	Medium	15000 m	20 m – 150 m	1.65	1.50	8,000	15,250	Unrestricted
TC14	2050	Optimistic	20000 m	20 m – 150 m	1.50	1.50	1,000	20,000	Unrestricted
TC16	2050	Extreme	25000 m	20 m – 150 m	1.50	1.50	15,250	40,000	Unrestricted
TC21	2050	Special		20 m - 150 m	n/a	n/a	7,787	7,787	n/a
TC24	2050	Special		20 m – 150 m	n/a	n/a	85,000	85,000	Unrestricted
TC25	2050	Special		20 m – 150 m	n/a	n/a	Unlimited	Unlimited	Unrestricted
TC29	2050	Sensitivity		20 m – 150 m	1.4	1.2	30,000	Unlimited	Unrestricted
TC30	2050	Sensitivity		20 m – 150 m	1.0	1.0	Unlimited	Unlimited	Unrestricted
	Multiple	Pessimistic	n/a	n/a	n/a	n/a	0	0	n/a

Note TC identifier number (i.e. TC **04**) in Table 2 relates directly to the scenario number.

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[3] Criterion specified in D03 on maximum annual mean significant wave height has been discarded.
Criterion specified in D03 on maximum site extraction has been discarded (see Appendix B).

[4] Taken as the depth below LWS in the 14.5 day average period the analysis is based upon

The results of the automated methodology are as summarised in Table 3 below for each Tidal Current Scenario (as per ID in Table 2). Note ‘PC’ refers to the technology identifier as per Appendix B and D03 Section 6.6.

Table 3 Summary of tidal current (TC) build order

TC 02 - Pentland Firth	
Ness of Duncansby (PC20.4)	Inner Sound East (PC20.1)
Brough Ness (PC20.8)	Cantick Head (PC20.3)
TC 04 - Pentland Firth	
Ness of Duncansby (PC20.4)	Cantick Head (PC20.3)
Brough Ness (PC20.8)	Westray Firth (PC20.4)
Inner Sound East and West (PC20.1)	
TC 05 (PC30)	
Pentland Firth	Islay, Mull of Oa
Corryvreckan Whirlpool	Race of Alderney
TC 07 (PC30)	
Pentland Firth	Islay, Mull of Oa
Corryvreckan Whirlpool	Race of Alderney
TC 08 (PC30)	
Pentland Firth	Islay, Mull of Oa
Corryvreckan Whirlpool	Race of Alderney
TC 11 (PC30)	
Westray Firth	Mull of Kintyre
Pentland Firth	Rathlin Island, Fair Head, Torr Head
Corryvreckan Whirlpool	Race of Alderney
Islay, Mull of Oa	
TC 14 (PC30)	
North of N. Ronaldsay Firth	Mull of Kintyre
Westray Firth	Rathlin Island, Fair Head, Torr Head
Pentland Firth	Mull of Galloway
Corryvreckan Whirlpool	Ramsey Island
Islay, Mull of Oa	Race of Alderney
TC 16 (PC30)	
North of N. Ronaldsay Firth	Rathlin Island, Fair Head, Torr Head
Westray Firth	Mull of Galloway
Pentland Firth	Carmel Head
Corryvreckan Whirlpool	Uwchmynydd
Islay, Mull of Oa	Ramsey Island
West Islay	Race of Alderney
Mull of Kintyre	Big Russel

TC 21 (PC20)
Pentland Firth Deep
Race of Alderney
Carmel Head
South Jersey
East Casquets
Pentland Firth Shallow
West Islay
North East Jersey
Islay / Mull of Oa
Westray Firth
Bristol Channel – Minehead
North of N. Ronaldsay Firth
West Casquets
Ramsey Island
Mull of Kintyre
Isle of Wight
Mull of Galloway
South Minquiers (Jersey)
N. Ronaldsay Firth
Rathlin Island

TC 24 (PC30)
Pentland Firth

TC 25 (PC30 and PC50)
the English channel (south of the Isle of Wight)
the Bristol channel
to the north of Anglesey
to the north of the Isle of Man
between Northern Ireland, the Mull of Kintyre, and Islay
the Pentland Firth (between Orkney and mainland Scotland), and within the Orkneys

TC 29 (PC30 and PC50)
North of N. Ronaldsay Firth
Westray Firth
Pentland Firth
Corryvreckan Whirlpool
Islay, Mull of Oa
North Channel: Mull of Kintyre,
    Rathlin Island, Fair Head, Torr Head
Mull of Galloway, Isle of Man
Carmel Head
Uwchmynydd
Ramsey Island, Skokholm
Race of Alderney, Casquets
Guernsey, Big Russel
Strait of Dover

TC 30 (PC30 and PC50)
North of N. Ronaldsay Firth
Westray Firth
Pentland Firth
Corryvreckan Whirlpool
Islay, Mull of Oa
North Channel: Mull of Kintyre,
    Rathlin Island, Fair Head, Torr Head
Mull of Galloway, Isle of Man
Carmel Head
Uwchmynydd
Ramsey Island, Skokholm
Barry, Bristol Channel
Isle of Wight, English Channel
Race of Alderney, Casquets
Guernsey, Big Russel
Strait of Dover

3.3 Summary of scenario energy output

A summary of the annual energy production (AEP) from each scheme and scenario is included in Table 4. It is noted that the *annual energy production* (AEP) quoted is indicative only and this level of modelling is defined as pre-feasibility in the IEC Tidal Resource Modelling Standard.

Table 4 Summary of scenario energy output

Year		2010	2020	2020	2020	2030	2030	2030	2040	2040	2040	2050	2050	2050	2050	2050	2050	2050	2050	2020	2030	2030			2050	2050	2050			2030	2030
Optimism (range)			Med	Opt	Med	Med	Opt	Med	Med		Opt	Med	Opt		Med	Med	Ext	Spe	Spe	Med	Spe	Spe			Sens	Sens	Sens			Opt	Spe
Optimism (current)			Med	Med	Opt	Med	Med	Opt	Med	Med	Med	Med	Med	Med	Opt		Ext			Spe	Med	Med	Salter	MacKay				Sens	Sens	Sens	Sens
Scenario no.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**6b**	**23b**
		Installed capacity (GW)																													
Total range			**3.6**	**3.7**	**3.6**	**12.4**	**12.9**	**12.4**	**21.5**	**0.0**	**22.6**	**46.6**	**51.2**	**0.0**	**46.6**	**46.6**	**54.6**	**43.9**	**10.7**	**3.6**	**16.4**	**5.8**	**0.0**	**0.0**	**54.6**	**54.6**	**54.6**	**0.0**	**0.0**	**12.4**	**12.4**
Total current			**0.4**	**0.4**	**0.7**	**3.0**	**3.0**	**4.0**	**7.9**	**7.9**	**7.9**	**15.2**	**15.2**	**15.2**	**19.9**	**0.0**	**39.9**	**0.0**	**0.0**	**7.8**	**3.0**	**3.0**	**86**	**241**	**0.0**	**0.0**	**0.0**	**48.8**	**91.3**	**2.4**	**2.2**
Total UK (range + current)																															
		Annual energy output (TWh/yr)																													
Total ebb						13.0	13.0	13.0	12.7		12.6	12.0	11.9		12.0	11.9	12.1	11.9							36.0	11.9				13.0	
Total dual			6.2	6.3	6.3	4.4	4.4	4.4	10.2		11.9	28.8	35.3		28.6	28.9	37.1	25.1	12.4	6.3	20.4	4.6			19.9	38.1				4.4	4.6
Total R-R				0.4		0.3	1.5	0.3	11.2		11.2	11.3	11.4		11.3	11.4	14.2	11.4	3.0		1.4	16.1			0.3	12.9	65.8			1.5	16.2
Total range			6.2	6.6	6.3	17.8	18.9	17.7	34.1		35.7	52.1	58.6		51.9	52.2	63.4	48.4	15.4	6.3	21.8	20.8			56.3	62.9	65.8			18.8	20.8
Total current			1.2	1.2	1.8	13.0	13.0	17.7	29.0	29.1	29.1	44.9	44.8	45.1	52.8		80.5			24.1	12.9	13.0	28.8	131.8				113.0	217.0	10.8	10.4
Total UK (range + current)			7.4	7.8	8.1	30.8	31.9	35.4	63.1	29.1	64.8	97.0	103.3	45.1	104.7	52.2	143.9	48.4	15.4	30.4	34.7	33.7	28.8	131.8	56.3	62.9	65.8	113.0	217.0	29.6	31.2
Tidal Range Capacity Factor			20%	20%	20%	16%	17%	16%	18%		18%	13%	13%		13%	-	13%	-	-	20%	15%	41%			-	-	-			17%	19%
Tidal Current Capacity Factor			34%	34%	29%	50%	49%	50%	42%	42%	42%	34%	34%	34%	30%	-	23%	-	-	35%	49%	49%	4%	6%	-	-	-	26%	27%	51%	54%
La Rance	Ebb	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Solway Firth	Ebb																								10.0						
Solway Firth	Dual											11.1	10.8		11.0	11.3	10.6	10.7								10.7					
Solway Firth	R-R																										13.8				
Morecambe Bay	Ebb																								5.8						
Morecambe Bay	R-R								9.7		9.7	9.8	9.9		9.8	9.9	9.8	9.9								10.0	9.9				
Mersey	Ebb																								0.9						
Mersey	Dual																									0.3					
Mersey	R-R						1.2		1.2		1.1	1.2	1.2		1.2	1.2	1.2	1.2			1.1	1.1					1.2			1.2	1.1
Dee	Ebb																								1.5						
Dee	Dual										1.7	1.7	1.7		1.7	1.8	1.7	1.8								1.8					
Dee	R-R																										1.7				
Severn - outer	Dual																				20.4										
Cardiff-Weston	Ebb					13.0	13.0	13.0	12.7		12.6	12.0	11.9		12.0	11.9	12.1	11.9							11.8	11.9				13.0	
Cardiff-Weston	R-R																					14.6					14.0				14.7
Thames	Ebb																								0.2						
Thames	R-R																0.3		0.3							0.3	0.3				
Wash	Ebb																								4.1						
Wash	Dual								5.9		5.9	5.9	5.9		5.9	5.9	5.6		5.7							5.7					
Wash	R-R																										6.7				
Humber	Ebb																								1.7						
Humber	R-R																2.6		2.6							2.6	2.7				
Wigtown Bay	Dual												3.6				3.5	3.6							4.1	3.6					
Wigtown Bay	R-R																										3.0				
Kirkcudbright Bay	Dual																									0.4					
Kirkcudbright Bay	R-R				0.4		0.3	0.4	0.3	0.4		0.3	0.3	0.3		0.3	0.3	0.3	0.3			0.3	0.3			0.3		0.3			0.4	0.3
Cumbria	Dual																1.9	2.0							2.2	2.0					
Cumbria	R-R																										1.5				
Oxwich Bay	Dual												0.5				0.5	0.5							0.5	0.5					
Oxwich Bay	R-R																										0.4				
West Aberthaw	Dual											1.3	1.3		1.3	1.3	1.3	1.3							1.3	1.3					
West Aberthaw	R-R																										1.0				
Rhoose	Dual											1.2	1.2		1.2	1.2	1.2	1.2							1.2	1.2					
Rhoose	R-R																										1.0				
Bridgwater Bay	Dual			6.2	6.3	6.3	4.4	4.4	4.4	4.3		4.2	3.9	3.7		3.9	3.8	3.8	3.7		6.3		4.6			3.7	3.8				4.4	4.6
Bridgwater Bay	R-R																										2.6				
Morte Bay	Dual																0.4	0.4							0.4	0.4					
Morte Bay	R-R																										0.3				
Rye Bay	Dual											3.6	3.5		3.6	3.6	3.5		3.6						3.5	3.5					
Rye Bay	R-R																										2.8				
Dymchurch	Dual												3.0				3.0		3.1						3.0	3.0					
Dymchurch	R-R																										2.4				
Current																															
2020	Med		1.2	1.2	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.0		1.0				1.1	1.1									
2020	Opt				0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	0.5		0.4				0.7	0.7									
2030	Med					11.2	11.1	11.0	10.3	10.3	10.3	9.6	9.5	9.7	9.2		8.9				11.1	11.1									
2030	Opt							4.8	4.1	4.1	4.1	3.6	3.6	3.6	3.4		3.3														
2040	Med								12.9	12.9	13.0	10.5	10.5	10.5	9.9		9.1														
2050	Med											19.6	19.6	19.6	18.1		15.6														
2050	Opt														10.7		8.1														
2050	Ext																34.0														
Pentland Firth / Orkneys			1.2	1.2	1.8	6.4	6.4	7.2	14.5	14.6	14.5	19.1	19.0	19.1	20.4		26.2				6.4	6.4	28.8	11.6							
Channel Islands						4.9	4.9	7.9	7.7	7.9	7.7	12.6	12.6	13.0	15.7		26.0				4.8	4.9									
West Scotland						1.7	1.7	2.6	6.8	6.7	6.9	11.9	11.8	11.6	13.5		19.4				1.7	1.7		62.7							
Northern Ireland												1.4	1.4	1.4	2.4		3.7														
Wales															0.9		5.2							48.8							

Note: Scenarios 17 and 18 were the previously planned 3D runs which are not being completed and therefore are being offered back to the ETI for their selection of runs (max 12 in total), see Section 4.2 for more information

Note: TC or TR identifier numbers in Table 2 and 3, respectively, relate directly to the scenario number.

The DCSM was accepted by the ETI as part of Milestone 2 and performs very well overall. However, where there are particularly high tidal ranges, the model tends to overestimate the tidal range, which was highlighted in D06 Section 4.1 which provides the N-RMSE values and was discussed with the reviewers. As a result, and as discussed in D06, the annual energy production resulting from the model in its raw form will be too high on average for the tidal range schemes, and an adjustment has therefore been made during the post processing of data outputs on an individual scheme basis to provide the AEP.

We do not believe that this adjustment has an impact on the overall outcomes discussed in this report in terms of the interactions (the understanding of which is the overall aim of the project). This is because, although the tidal range schemes 'over extract' energy (compared to reality) within the DCSM at these locations, there is also more energy available at these locations (compared to reality) so the overall impacts of the schemes on the resource, and the interactions between the schemes, will be very similar to reality.

3.4 Sensitivity tests

3.4.1 Sensitivity to technology

In accordance with D03, sensitivity tests were performed on the technology used in the modelling. These tests examine the choice of technology/location used to develop the resources in the Bristol Channel (Scenarios 22 and 23), the widespread choice of a particular tidal range technology, wherever possible (Scenarios 26, 27, 28). They also include sensitivity tests to the packing density as described below.

The packing density used in all the Scenarios except for the special cases is by default 2.5 times the diameter of the turbine across by 10 times that same diameter along, or 25 D2, as defined in Section 9.2.3.4 of D01.

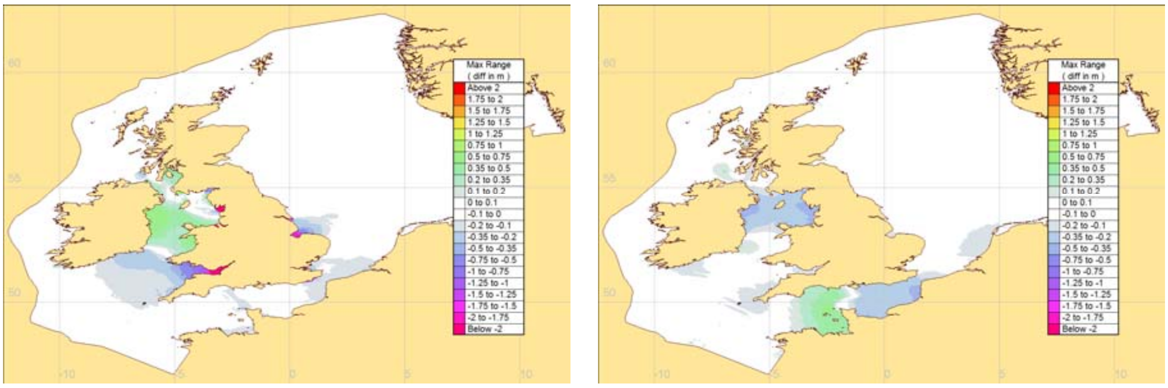
A sensitivity analysis to device packing density has been carried out by introducing two other cases: 100 D2 (or 5 D by 20 D) and 150 D2 (or 5 D by 30 D) to form Scenario 6b and Scenario 23b. Results from this analysis were referenced against the 2030 medium conditions (Scenario 05 and Scenario 22). For the 2030 medium scenarios the targeted maximum tidal current installed capacity was 3,000 MW, which was identified in depths less than 60m for a 25 D2 packing density using the automated search.

The results of the sensitivity indicate that decreasing the packing density to allow more space between turbines has the expected result of decreasing the overall installed capacity but increasing the capacity factor of the turbines installed. In comparison to the 2030 medium scenario (capacity factor of 50%) the installed capacity decreases from 3000MW to 2400MW and 2200MW respectively. The capacity factor increases to 51% and 54% respectively. This indicates the importance of a Cost of Energy optimisation to inform site development decisions because fewer turbines operating more efficiently over the life of the project may be more economically attractive than more turbines working less efficiently.

3.4.2 Sensitivity to boundary location

In keeping with D02 and comments received following the Stage Gate Review meetings, the location of the DCSM offshore boundary was examined during the scenario modelling to ascertain that it was suitable to model interactions between tidal energy schemes. The DCSM offshore boundary is driven by water levels, as described in D02 - Continental Shelf Model (CSM) requirements specification, with the velocities free to vary and provide an 'exit' from the domain. Of particular interest are, therefore, the effects of the implementation of the tidal energy schemes on the water level (or tidal range) at or near the boundary. If it can be shown that the impacts of the tidal energy schemes are predicted not to reach the boundary, then it can be said with confidence that the location of the boundary is appropriate to model scheme interactions.

The results of Scenarios 16 (2050, extreme development) and 30 (extreme tidal current scheme development) were examined to that effect. Scenario 30 was considered alongside Scenario 16 because, although there are no tidal range developments in that case, tidal current developments are more significant than in Scenario 16. It is clear from the Figure 1 (reproduced from the end of the report) that changes in tidal range as a result of tidal energy scheme implementation in UK waters do not reach the model boundary in any of these extreme cases. It is, therefore, deemed that the CSM offshore boundary is suitably located for the purposes of the model.



Scenario 16 (2050, extreme development) Scenario 30 (extreme tidal current scheme)

Figure 1 Scenario 16 and Scenario 30

3.4.3 Sensitivity to tidal conditions

The scenario modelling presented in this document was consistently conducted under what are considered 20-year average tidal conditions, or the period between January 10th and 25th, 2005. Although this is deemed adequate for the examination of scheme interactions, sensitivity tests were performed to the choice of the tidal conditions.

For that purpose, two periods corresponding to 20-year high and 20-year low tides were selected as follows:
20-year high tide: February 5th - 20th 1997
20-year low tide: January 13th - 28th 2006

Scenarios 1 and 6 were subsequently repeated, forcing the model boundary with these new conditions. It was found that the relative changes to the system, resulting from the implementation of (a few) tidal energy schemes, are reasonably insensitive to the selected period, be it a 20-year high, average, or low. Generally, the low tide conditions tend to expand the extent of the impact of a particular scheme a little more, as would be expected.

4 SUMMARY OF INTERACTION EFFECTS OBSERVED

4.1 Presentation of the results

In this document, the DCSM scenario model results are displayed in several different ways, as described below, and the results can be found in the Appendices; however, an example using Scenario 10 (2040 TR Optimistic and TC Medium case), which appears to show the best overall power smoothing from all scenarios as discussed later, is provided within this section of the report to show the DCSM results for changes in tidal range (m) and power density (kW/m^2).

Local colour contour maps illustrating the impact of the deployed tidal range and tidal current schemes on the predicted depth-averaged current speed and depth-averaged kinetic power density, with reference to the base case scenario (Scenario 1). An example of Scenario 6 (See Figure 2 below) is provided below but all the results can be viewed in Section 8. These maps were produced by extracting, at each model grid point, the peak current speed during the neap cycle included in the 14.5 day prediction period (approximating mid-range values) and the mean kinetic power density over the prediction period. They are expressed in relative form (%) for the velocities, where the differences have been normalised using the base case values at each model grid point, and in absolute form (kW/m^2) for the kinetic power densities.

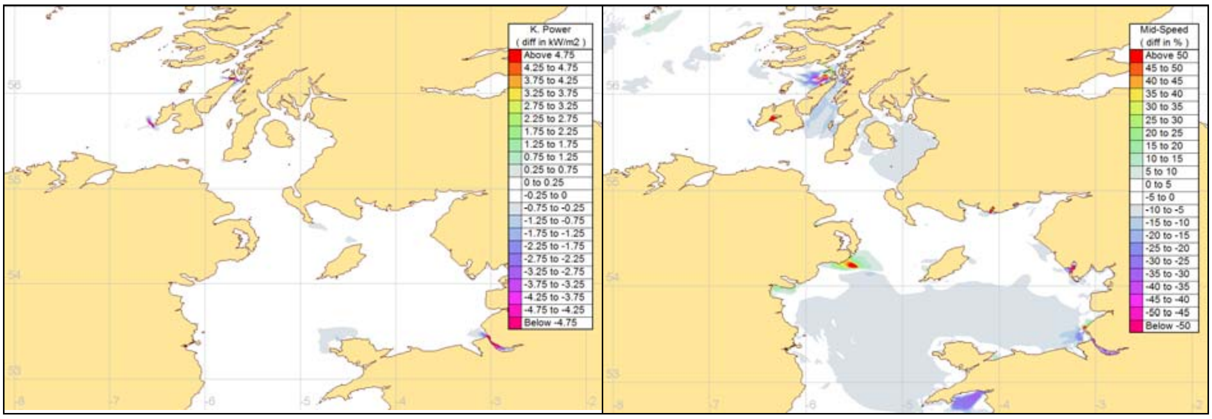


Figure 2 Outcome of the CSM scenario modelling, Scenario 6, Irish Sea and North Channel (Velocity)

Local colour contour maps illustrating the impact of the deployed tidal range and tidal current schemes on the predicted maximum tidal range, with reference to Scenario 1 base case. An example of Scenario 6 (See Figure 3 below) is provided below but all the results can be viewed in Section 8. These maps were produced by extracting, at each model grid point, the maximum tidal range in the 14.5 day period. They are expressed in absolute form (m) as well as in relative form (%), where the differences have been normalised using the Scenario 1 values at each model grid point.

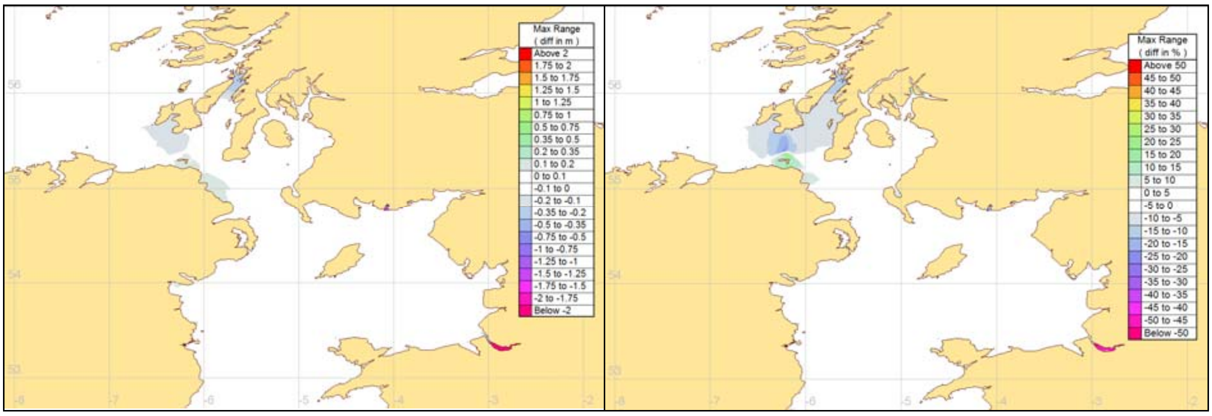


Figure 3 Outcome of the CSM scenario modelling, Scenario 6, Irish Sea and North Channel (Range)

Thresholds for indicatively acceptable changes have been incorporated into the processing of the model results. These are taken from Carbon Trust 2011, where the 'acceptable' tidal range changes were estimated from B&V's understanding of the likely acceptable changes from more detailed work on UK tidal range locations and communications with stakeholders. The 'acceptable' current and power density thresholds were estimated from B&V and the University of Edinburgh's ongoing research and reporting into tidal current energy extraction. The thresholds are explained below:

In the ‘absolute’ tidal range figures the acceptable threshold is 0.2 m. Changes between -0.1 m and 0.1 m of the base case values are therefore displayed in white; changes between -0.2 m and -0.1 m, and between 0.1 m and 0.2 m, are displayed in pale blue/green. Outside of the threshold, 0.25 m bands were used, to a maximum of 2 m, ranging from green to red for positive changes (i.e. when the tidal range is increased with the implementation of the tidal schemes), and from blue to pink for negative changes (i.e. when the tidal range is decreased with the implementation of the tidal schemes).

In the ‘absolute’ tidal power density figures the acceptable threshold used is 0.25kW/m^2 although, as per discussions throughout this report, the flux limitation for energy extraction is site specific and requires detailed optimisation; therefore, this is only indicative.

In the ‘relative’ tidal power density figures the acceptable threshold is 10%. Changes between 0 and 5% of the base case values are displayed in white; changes between 5% and 10% as a pale blue colour (-5% to -10% are as pale green). Outside of the threshold, 5% bands were then used towards a maximum change of 50% (minimum of -50%), adopting the same colour scheme as for the ‘absolute’ tidal range figures.

Colour contour maps at the scale of the DCSM, illustrating the change in tidal range in metres, and the change in kinetic power density in % (both as defined above). An example of Scenario 6 is provided below but all the results can be viewed in Section 8.

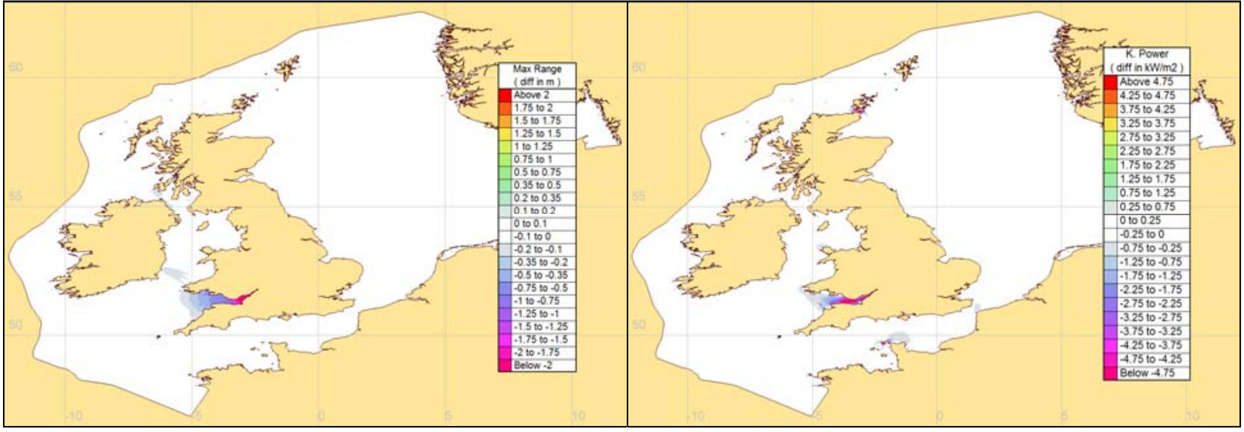


Figure 4 Outcome of the CSM scenario modelling, Scenario 6

Time histories of predicted power output are provided in Appendix F. The time series indicate the tidal range energy generation, tidal current energy generation and total UK energy generation over the spring neap cycle.

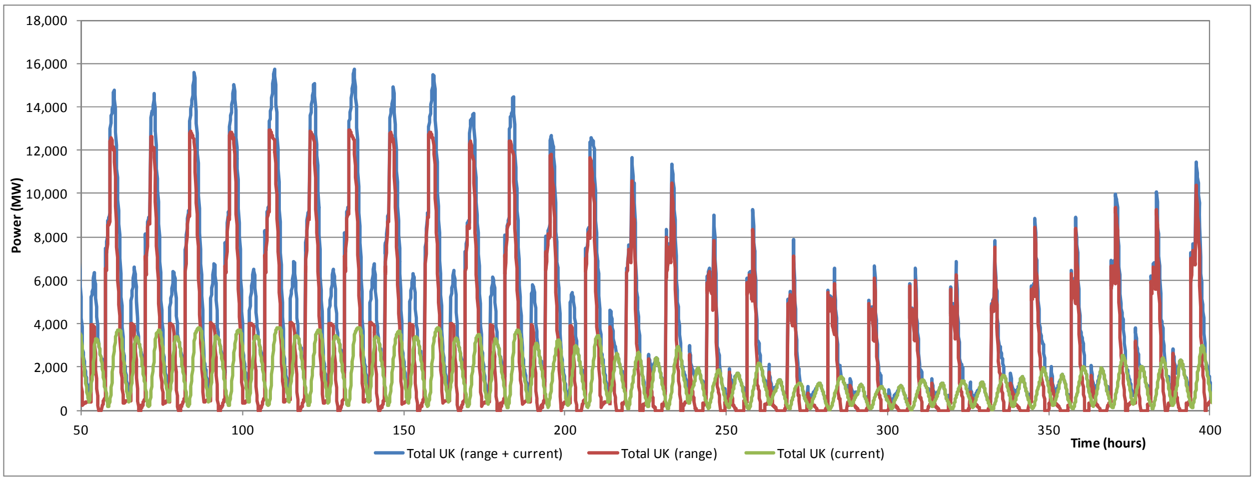


Figure 5 Outcome of the CSM scenario modelling, Scenario 6 – time histories (15 days)

The coordinate system used for graphical output is lat-long, WGS84.

4.2 Discussion of impacts

This section highlights the impacts visible in each of the scenarios and provides explanation, where appropriate, as to why the effects are visible. Key Findings and Conclusions can be found in Sections 6 and 7.

A series of tables are provided below, one for each scenario. Within each table the Scenario number is provided along with a high level description of the scenario. The near-field and far-field effects are also discussed and conclusions drawn. Recommendations have been included, where identified, and general observations are made throughout.

Near-field is defined for tidal range as within the estuary or local surrounding sea (if a lagoon is deployed), and for tidal current as within the footprint of the array (where footprint is the plan area of the array).

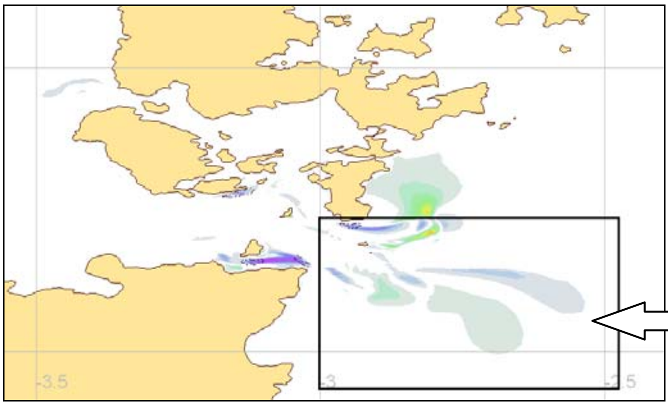
Far-field is defined for tidal range as all the effects outside the estuary or surrounding sea, and for tidal current as all the effects outside the footprint of the array.

To confirm, Scenario 1 is the base case run which is a 2010 base case. This has no deployment in UK waters but it does incorporate the energy extraction of La Rance. La Rance is then incorporated into all the scenarios. Scenario 1 results are used as the base case for all comparisons for each Scenario.

Scenario 2	**Description: 2020 TR medium and TC medium**
Comments on high level interactions	As expected there is no interaction between the TC and TR developments in this scenario.
Near-field	Tidal Range: Bridgwater Bay reduces tidal range in the Severn estuary (less than 5% downstream, 5-10% upstream, 10-15% within lagoon). Tidal Current: Impact varies depending upon the efficiency of the installation (each is representative of 100MW installed). The Inner Sound is the most productive location, producing more than twice the energy observed at Cantick Head, and approximately 50% more than either at Duncansby Head or Brough Ness.

	This is reflected in the increased near-field impact on mid-speed velocity and kinetic power distribution across the 4 sites which is reasonably correlated with the energy generation as expected.
Far-field	Tidal Range: There are no genuine further field effects beyond Swansea/Ilfracombe. Tidal Current: The far-field impact is limited geographically to within the region of the Pentland Firth and Orkney Waters. The significantly reduced velocity and power in the wake of each development site is relatively narrow; there is not significant expansion of the wake from each farm. The reduced wake region appears to follow the prevailing flow direction at each development location, as might be expected. The results indicate an obvious direct cumulative impact on velocity and hence kinetic power distribution due to the close proximity of the Inner Sound and Duncansby Head sites. Patches of increased flow velocity and kinetic power are observed in the regional far-field[1]. Physical reasoning supporting this impact includes the potential for 'blockage' redistributing flow. 1 It is important to recognise that although these values are measurable as a % change, the original energy resource in these particular regions was relatively small. Hence a relatively small change in absolute terms can have a measurable impact in % terms.
Conclusions	Development at this scale only has a local near-field effect for tidal range (1 scheme) and a regional far-field impact for tidal current. However, even a relatively small tidal current development (e.g. 100 MW) can have a significant near-field impact when no consideration of the potential for the resource to support the size of the intended farm is made - as has been the case. If a limitation is applied in line with the resource potential, then the effects would be reduced, although as these Pentland Firth projects are already leased it is most appropriate to view the 'worst case' interaction effects, as completed here.
Recommendations	An interesting comparison would be running cases where array development is limited to achieve a prescribed maximum level of impact, this would involve optimising the sites to obtain the prescribed maximum extractable energy and therefore the maximum installed capacity for each site.

General observations and recommendations on tidal current phenomenon being observed
The time-averaging of a dynamic system produces an interesting pattern reflecting the hysteresis of the tidal regime. In this case, the patchy 'fingers' extending out to the east of the Pentland Firth are an artefact of wake regions from previous flood and ebb cycles being discharged from the Firth. This hysteresis effect will be observed in most simulations, and will only be further commented on in exceptional cases.
The wakes of close proximity TC developments do impinge upon neighbouring developments, highlighting potential for cumulative impact.



The patchy ‘finger’ shapes are shown from an extract from Scenario 3 change in velocity

Figure 6 Patchy ‘finger’ shaped effects in Pentland Firth velocity

Scenario 3	**Description: 2020 TR optimistic case and TC medium case**
Comments on high level interactions	As with Scenario 2, the schemes modelled in this simulation indicate no potential for cumulative interaction between TR and TC developments that are so geographically spread.
Near-field	Tidal Range: Adding Kirkcudbright Bay has no impact except within and just downstream of the lagoon. Tidal Current: No change in near-field impacts is observed from those reported in scenario 2. This is because the differences between scenario 2 and 3 are limited to additional TR development in a geographically remote region (100km+ distant).
Far-field	Tidal Range: Adding Kirkcudbright Bay has minor impact just downstream of the lagoon. Tidal Current: No change in far-field impacts is observed from those reported in scenario 2. This is because the differences between scenario 2 and 3 are limited to additional TR development in a geographically remote region (100km+ distant).
Conclusions	As per Scenario 2.
Recommendations	As per Scenario 2.

Scenario 4	**Description: 2020 TR medium case and TC optimistic case**
Comments on high level interactions	As with Scenario 2 and 3, the schemes modelled in this simulation indicate no potential for cumulative interaction between TR and TC developments that are so geographically spread.
Near-field	Tidal Range: No change in near-field impacts is observed from Scenario 2 as only TC changes in this scenario compared to Scenario 2. Tidal Current: Larger magnitude near-field impacts are observed at the two sites where a 2nd phase of development is imposed, as well as the obviously expected increased extent of the near-field region.
Far-field	Tidal Range: No change in near-field impacts is observed from Scenario 2 as only TC

	changes in this scenario compared to Scenario 2. Tidal Current: As for scenario 2, with the addition of: Re-distribution of flow due to 'blockage' is observed at the Inner Sound, and most classically in Westray Firth, where the near-field flow reduction is partially attributable to the result of flow 'avoidance' around the array (this is best observed by viewing the kinetic power figures). This is an expected fluid dynamic response, as the pressure gradient field is altered around the development. Minor (spatial) alteration of tidal range begins to be observed in the vicinity of the two neighbouring Inner Sound and Duncansby Head developments. The cumulative impact of the two combined is enough to start to cause measurable disturbance of the tidal range.
Conclusions	Developers of the Crown Estate's Pentland Firth and Orkney Waters Round 1 development sites should pay particular attention to matching the intended development footprint to the available resource to minimise flow and energy related impacts. The examples herein indicate potential for over 50% kinetic power reduction if the design is not optimised. This suggests that there may be some optimum scale of development for any particular site that will maximise project profitability and minimise impact.
Recommendations	Further modelling to optimise each site and further optimisation to maximise the potential of the Pentland Firth and Orkney Waters as a whole.

General observations and recommendations for tidal current array development
The scale of tidal current array development should be very closely linked to the resource availability to maximise project profitability whilst minimising impact. The approach to prescription of the developments used herein is akin to the 'farm' method (see CT 2011[5]). The experience of CT2011 suggests that the limiting of farm size by a 'flux' constraint should be further investigated.

Scenario 5	**Description: 2030 TR medium and TC medium case**
Comments on high level interactions	It is difficult to interpret from this scenario whether the far-field flow alterations in the western English Channel are due to TR developments in the Bristol Channel or TC developments around Alderney.
Near-field	Tidal Range: Adding Cardiff-Weston scheme into this scenario increases effects in the Severn estuary as expected. This has a negative impact on the energy output of Bridgwater Bay lagoon (c.30% reduction) and the Cardiff-Weston scheme itself (in comparison to the expected 0D modelling results). In addition, the Bridgwater Bay lagoon also reduces the energy output of the Cardiff-Weston scheme. Tidal Current: The near-field impact in the large scale array between the two islands in the Pentland Firth is lower in comparison to the flow and kinetic power density reduction in the earlier relatively small developments considered in 2020 scenarios. This demonstrates the impact of flow constraint due to depth. In

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[5] Carbon Trust (2011). *UK Tidal Current Resource & Economics*
http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=CTC799

	the deeper mid-channel site development, the devices take up proportionally less of the available cross-sectional area, thereby reducing their impact.
Far-field	Tidal Range: There is a minor far-field change in tidal range (±0.1m) as far as Milford Haven/Cornwall and possibly the south-eastern Irish coast. Tidal Current: The significantly increased scale of development in the Pentland Firth is reflected in the extension of the region impacted. Flow and kinetic power density impacts are spread throughout the extent of the Pentland Firth and extend out of either end of the 'mouths' of the channel. A measurable impact is now observed region-wide. The tidal hysteresis patterns in the Pentland Firth region are maintained and enhanced demonstrating the inter-connectivity, persistence and dynamism of the system. Development at Correyvreckan appears to have a more significant local regional impact than similar scale developments in the other modelled regions – the tidal system would appear to be more sensitive to change in this region. In particular changes to tidal range are more widespread than observed for the other TC developments (this is most likely related to relatively small absolute changes in an amphidromic region (location where the tidal range is theoretically zero)). Development in the North Channel region (Corryvreckan and Islay) appears to also have isolated far-field impacts at other headlands and islands further offshore. This is likely to be because the local tidal system is much more sensitive to change due to the proximity of amphidromes in the region (e.g. the re-distribution of tidal range (%) from around the south of Islay (reduction) across towards Northern Ireland (increased).
Conclusions	Scenario 5 sees the introduction of the Cardiff-Weston barrage into the Severn and cumulative impacts are observed on far-field tidal range effects, but these cumulative impacts are still considered minor. The first true utility scale tidal current schemes are also introduced. These results highlight that the far-field impact of such schemes will present more of a challenge than for mid-size arrays which have a much more localised impact footprint.
Recommendations	Consideration of a scenario with only Cardiff-Weston would be valuable to understand the impact that Bridgewater Bay is having on it, and also to identify the differences with the 0D modelling. The reduced near-field and far-field tidal current impact observed due to increased depth at some locations would benefit from further investigation in the future. As these simulations are 2D, the persistence of the wake observed horizontally in the figures provided needs to also be considered in the vertical dimension. The ETI has other projects that are examining these aspects (e.g. PerAWaT) as CFD is really necessary to properly model such interactions.

Scenario 6	**Description 2030 TR optimistic case and TC medium case**
Comments on high level interactions	This scenario is representative of overall generation by the combined technologies of approximately 10% of the existing UK electricity demand. At this scale (and with judicious siting of projects), there is little or no interaction between TC and TR developments in the UK. Only the most minor impact is observed between the TR and TC systems – the TC overall annual energy generation potential is reduced by < 0.5%.
Near-field	Tidal Range:

	Adding the Mersey into this scenario only affects tidal range within the barrage and immediately downstream of it. The reduction in range downstream (due to constraint of the approach channel which is also related to relatively shallow depths) reduces the energy output of the scheme compared to 0D modelling. Tidal Current: No discernible difference in TC response is observed between scenario 5 & 6.
Far-field	Tidal Range: Compared to Scenario 5 the addition of the Mersey causes the reduction in tidal range to expand around the St George's Channel. Tidal Current: The addition of the Mersey causes some reduction in kinetic power density in the Irish Sea.
Conclusions	The tidal current results from Scenario 5 and this scenario, 6, where the tidal current deployment is the same, show a minor reduction of <0.5% when the Mersey is incorporated. This indicates that there is some interaction between the two technologies in this scenario, but it is very minor.
Recommendations	-

Scenario 7	**Description: 2030 TR medium case and TC optimistic case**
Comments on high level interactions	There is little or no interaction between TC and TR developments in the UK in Scenario 7.
Near-field	Tidal Range: The additional tidal current sites have no effect on tidal range schemes (compared to Scenario 5). Tidal Current: The build-out in this scenario continues to add to existing projects. Hence, the relative scale in most regions has limited impact. The major contribution comes from a significant increase in installed capacity in the Race of Alderney where a more significant impact, akin to that already observed in Pentland Firth, is observed.
Far-field	Tidal Range: The additional tidal current sites have no effect on tidal range schemes (compared to Scenario 5). Tidal Current: The build-out in this scenario continues to add to existing projects. Hence the relative scale in most regions has limited impact. The major contribution comes from a significant increase in installed capacity in the Race of Alderney where a more significant impact is observed, with an increased footprint of impact. More flow re-distribution, even relatively distant from the site (most easily observed when viewing the kinetic power density figure) is observed, with a pattern of reduced flow in the near and far wake, and increased flow further afield attributed to flow 'blockage'.
Conclusions	Increasing the tidal current development has no impact on the tidal range developments.
Recommendations	-

Scenario 8	**Description: 2040 TR medium case and TC medium case**
Comments on high level interactions	There is potential that interaction between TC and TR developments are contributing to the results; however, scenario 9 indicates that the impact observed, although significantly geographically dislocated, is due to TR development.
Near-field	Tidal Range: Adding in Morecambe Bay and the Wash both lead to reductions in tidal range within the schemes as would be expected. Both schemes nevertheless enclose the whole bays and therefore these are the only near-field effects. Tidal Current: Development at many sites is now becoming potentially excessively concentrated along the same flux lines. The Inner Sound has exhibited this since early scenarios, and additional locations are now reaching this stage of 'over-crowding' (e.g. Brough Ness). Reductions in overall kinetic power density would significantly impact project economics, indicating that a better approach to efficiently constraining development may be desirable.
Far-field	Tidal Range: Adding in Morecambe Bay leads to far field effects: only small reduction in range immediately downstream of barrage. only small areas of change in tidal range in eastern Irish Sea. increase in range along east coast of Ireland/Northern Ireland (0.1-0.2m) and larger increase in range in Firth of Clyde (0.2-0.35m), both of which are potentially problematic in terms of flood risk. increased kinetic power density to the north of Northern Ireland. increased area of slightly reduced tidal range in St George's Channel between Ireland and Wales and along Cornish coast. The Wash creates far-field effects for quite a large area downstream of the barrage and effects are seen as far as the English Channel. Tidal range impacts in the North Channel region, and in the waters around Arran and approaching the Firth of Clyde are becoming very significant (likely excessive from an environmental and even safety perspective). The energy output for the Mersey does not change as a result of the Morecambe Bay scheme, but the energy output for Cardiff-Weston and Bridgwater Bay is reduced by 3%. Tidal Current: There is increased kinetic power density to the north of Northern Ireland and this is attributed to the introduction of the tidal range scheme at Morecambe Bay. There are also changes to kinetic power density and velocities in the English Channel which are attributed to the Wash.
Conclusions	There is potential that interaction between TC and TR developments are contributing to the results; however, scenario 9 (below) indicates that the impact observed, although significantly geographically dislocated, is due to TR development.
Recommendations	-

General observations and recommendations about multiple site development
By this stage of development, multiple sites have been identified, but there is a clustering regionally (e.g. around Pentland Firth/Orkneys and Channel Islands), and most projects are in fact extensions of existing developments (e.g. the build-out at Brough Ness and Islay (Mull of Oa)). Hence spatial distribution around the UK does exist, but there is significant regional clustering.

Scenario 9	**Description: 2040 no TR development with TC medium case**
Comments on high level interactions	TR technology development as simulated in scenario 8 is having no discernible impact on the harvestable TC resource.
Near-field	Tidal Range: There are no tidal range schemes implemented. Tidal Current: No reportable near-field impact difference is observed between scenarios 8 and 9, indicating that TR technology development as simulated in scenario 8 is having no discernible impact on the harvestable TC resource.
Far-field	Tidal Range: There are no tidal range schemes implemented. Tidal Current: The far-field impact around the North Channel is significantly different from that observed in scenario 8, providing strong evidence that the alterations in the wider region observed in scenario 8 are attributable to TR development around the Irish Sea. In particular, the major increased in tidal range observed around the Isle of Arran and towards the Firth of Clyde are not experienced now that there is no TR incorporated in this scenario. Additionally, alterations to flow and kinetic power density previously attributed to development at Correyvreckan and Islay (Mull of Oa) development in scenario 5 are now observed to not be as significant. While some of these alterations are still observable, they are much more spatially constrained and their magnitude is reduced. This indicates that the tidal system in this area has some sensitivity to TR developments in the Irish Sea and Bristol Channel. Similarly, in the western English Channel, widespread spatial alteration of the resource is now not observed, so can be directly attributed to TR developments. However, development in the Channel Islands and the Race of Alderney in particular does indicate a higher sensitivity in terms of tidal range variation locally due to TC development.
Conclusions	The footprint of tidal current development impact is to some extent limited to the local region. Cumulative impacts only appear to occur when development sites are geographically close together.
Recommendations	-

Scenario 10	**Description: 2040 TR optimistic case and TC medium case**
Comments on high level interactions	The addition of another tidal range scheme does not have a discernible impact on the tidal current schemes which are the same as Scenario 9.
Near-field	Tidal Range: Incorporating the Dee has a small effect on tidal range immediately

	downstream of the barrage. Tidal Current: No discernible difference in TC response is observed between scenario 8 and 10.
Far-field	Tidal Range: The area of increased tidal range on the east coast of Ireland and the Firth of Clyde has enlarged with the addition of the Dee, showing a further cumulative effect. Tidal Current: No discernible difference in TC response is observed between scenario 8 and 10.
Conclusions	The cumulative impact of Tidal Range schemes on the west coast of the Britain is clearly apparent.
Recommendations	-

Scenario 11	**Description: 2050 TR and TC medium case**
Comments on high level interactions	Interactions between tidal range and tidal current interactions are beginning to negate each other.
Near-field	Tidal Range: Adding Solway Firth has a significant effect. The scheme itself does not work as intended (the annual energy output is less than half that from 0D model) but this is not surprising, given the scale of the scheme and the complex hydrodynamics, and was discussed in D01 section 5.2. We believe that the 2D model gives an accurate reflection of the Solway Firth scheme. During generation, the basin drains and fills too quickly, which means the generating head is low, the turbines work very inefficiently and the energy output is lower than intended (see General observations box below for further comments). Adding in the Rhoose and West Aberthaw lagoons results in a reduction in energy for Cardiff-Weston (5%) and Bridgwater Bay (10%) (which could both possibly also be influenced by introduction of Solway Firth). The resulting Rhoose and West Aberthaw energy outputs are also much lower than expected – due to reduction in tidal range caused by Cardiff-Weston and Bridgwater Bay. This also results in non-optimised operating logic which perhaps could be improved to increase energy output slightly in future scenarios. Adding in the Rye Bay lagoon does not appear to have an impact on the existing schemes energy production and the Rye Bay lagoon itself seems unaffected by other tidal range schemes, showing the value of better geographical diversity amongst schemes. Tidal Current: As previously highlighted, the geographical clustering of TC developments along key energy flux lines causes significant depletion of the resource within arrays and across arrays where the additional development is in reality just a further phase of the same site. Hence, energy generation and revenue potential are significantly impacted. As previously, it continues to be identified that TR development has very limited, if any measurable, impact on TC development. The overall reduction in energy generation potential by c. 22% across this

	scenario in comparison with the potential using the original raw resource as the input is significant.
Far-field	Tidal Range: The far-field effects as a result of adding the Solway Firth scheme are significant and there are large changes (increases and decreases) in velocity and kinetic power density in the Irish Sea and in the North Atlantic. There is also a change in tidal range in the Irish Sea which is now very significant – up to 0.75m on the Irish coast and in the Firth of Clyde. The far-field effects as a result of the Rhoose and the West Aberthaw lagoons are a change in speed/kinetic power density on the south-east Irish coast where a large % change is indicated; however, as there are very small velocities in the locality the actual change is not as dramatic as results suggest. The Rye Bay lagoon produces only a small reduction in downstream tidal range, although this extends across the English channel to the French coast and is likely a cumulative effect. There is also some reduction in velocity and power density in the English channel and North Sea extending from the Wash. Tidal Current: The patterns of impact and spatial distribution remains similar to observed previously; however, the magnitude of the response is increased to reflect the increased deployment of devices and hence energy extraction. The far-field response at the most developed site locations is starting to spread beyond the tidal flushing extent, indicating that these developments are reaching a stage of development that is no longer constrained just to the local region.
Conclusions	The previously observed local area impact on tidal range of TC development around the Channel Islands is reduced in extent in this scenario (compare with scenario 9 output) indicating an interaction between the local TC development and TR developments in the Bristol Channel and Irish Sea that in this case suggests that the cumulative effects negate each other.
Recommendations	Build-order is obviously key to optimising the development of the resource as the best resources are so geographically constrained and often clustered. Hence, an assessment of the specific project by project build-order impact would be desirable.

General observations and recommendations on further site optimisation

The results for the Solway Firth indicate that the CSM has less storage volume than used in the 0D model. To a lesser effect, other schemes are affected by this as well, particularly those with large proportions of intertidal areas such as Kirkcudbright, Morecambe Bay, Mersey, Dee, Thames, Wash, Humber. With further site optimisation and improvement of the bathymetry in the intertidal zones, it would be possible to improve the performance of these schemes further as part of project/site specific investigations.

As was observed in previous scenarios, on the 2050 time horizon, the build-out of TC developments as identified by the model decision-support approach is strongly indicating that regional clustering is dominant, with expansion of existing sites still dominating the emergence of new locations. This highlights the geographic specificity of the tidal current energy resource.

Scenario 12	**Description: 2050 TR optimistic case and TC medium case**
Comments on high level interactions	Range options in open Seas have less of an interaction effect. TR impact in the far-field remote from the installation location has a (minor) impact at the location of some or all TC development sites.
Near-field	Tidal Range: Adding in Wigtown Bay has no real effect on energy outputs elsewhere. Adding Oxwich Bay only has a minor additional effect (except within the lagoon itself as expected). The energy output of the Oxwich Bay lagoon is affected by the reduction in range caused by other schemes in the Severn. Incorporation of Dymchurch lagoon only decreases the energy output of the adjacent Rye Bay lagoon by 1%. Even though the lagoons are close together, it is believed that the wide expanse of sea into which both lagoons open results in there being little effect on one another. There is also little effect on the downstream tidal range which aligns with this explanation. Tidal Current: No discernible qualitative difference in TC response is observed between scenario 11 and 12.
Far-field	Tidal Range: Adding in Wigtown Bay has a small effect on velocities, kinetic energy and range in Irish Sea. Oxwich Bay does not produce significant far-field effects and as above. Dymchurch has little effect on downstream tidal range and the effects are localised. Tidal Current: No alteration in far-field response from scenario 11 can be specifically attributed to TC as TC development scenario remains unchanged. However, quantitatively, the overall energy yield from TC is reduced by 0.12TWh/y (from 44.92TWh/y to 44.79 TWh/y, so only by 0.3%) indicating that TR impact in the far-field remote from the installation location has a (minor) impact at the location of some or all TC development sites.
Conclusions	The Dymchurch and Rye Bay lagoons, although adjacent, have little effect (c.1%) on each other’s energy production if both are operational. This is, we believe, a result of the wide expanse of sea into which both lagoons open, and is an interesting finding in terms of locating other lagoon schemes.
Recommendations	-

Scenario 13	**Description: 2050 TC medium case with no TR development**
Comments on high level interactions	All Tidal range schemes are removed to complete sensitivity on tidal current.
Near-field	Tidal Range: No tidal range deployment. Tidal Current: No discernible difference from cases 11 and 12 can be observed qualitatively. Quantitatively, the following table summarises the AEP (TWh/y) by TC in each scenario (where the TC scenario remains constant, only the level of TR development changes as indicated):

Scenario	TR generation (TWh/yr)	TC generation (TWh/yr)	% Change in TC generation
11	66.7	44.92	-0.421%

12	75.0	44.79	-0.790%
13	0	45.11	0%

	This indicates that even large scale TR development is only having a relatively minor impact on the harvestable TC energy resource.
Far-field	Tidal Range: No tidal range deployment. Tidal Current: Spatially, the extent and patterns of impact are very similar to scenario 9 output, except that the magnitude of change is once more increased, and the outer edges expand a little further (although can still be considered to be constrained to the local region). Impacts on tidal range are starting to be observed in locations where levels of development are particularly high. These do remain geographically constrained and of limited spatial extent. However changes of tens of cms, as simulated in isolated patches, are potentially significant. In the Race of Alderney case, as was observed in scenario 9, there appears to be more sensitivity in terms of tidal range alteration covering a wider area and being of a more significant magnitude. The scale of development at Pentland Firth, Race of Alderney and Islay (Mull of Oa) are of (relatively) similar extent. However it is interesting to note that in the less constrained region in the English and North Channels, more flow 'avoidance' is apparent, as might be expected. This phenomenon is less apparent in the Pentland Firth.
Conclusions	There is no discernible impact due to TC developments simulated thus far in either the Irish Sea, Bristol Channel or southern North Sea.
Recommendations	-

General observations and recommendations
This scenario is simulating annual energy generation by TC technology of 45.11 TWh/y, which is equivalent to just over 12% of UK energy demand in 2011. This is more than double the generation potential proposed by CT2011. However, this level of generation is having more significant impacts on the local tidal system than was permitted in the CT2011 analysis. It remains to be seen whether such developments are acceptable, but these outputs provide valuable information from which stakeholders can start to assess these potential impacts.

Scenario 14	**Description 2050 TR medium and TC optimistic case**
Comments on high level interactions	TR impact in the far-field remote from the installation location has a (minor) impact at the location of some or all TC development sites.
Near-field	Tidal Range: Scenario 11 is used here for tidal range, see Scenario 11. Tidal Current: No discernible difference due to the increase in tidal current deployment.
Far-field	Tidal Range: No difference from Scenario 11. Tidal Current: Pentland Firth – little discernible difference from scenario 12 output – pattern

	is repeated with the extent marginally extended, and the contours representing enhanced impact also marginally expanded. These alterations are only really traceable in the kinetic power density image, the change to velocity is so small that it is indiscernible. This is reflective of the limited additional Pentland Firth (PF) development in comparison with the magnitude of the already simulated installed capacity in scenario 12. The Irish Sea/North Channel and Bristol Channel are unchanged. Changes around the Channel Islands are also marginal, really only noticeable under close scrutiny of the kinetic power density plots (where the velocity-cubed term assists in differentiating change).
Conclusions	The previously observed local area impact on tidal range of TC development around the Channel Islands is reduced in extent in this scenario (compare with scenario 9 and 12 output) indicating an interaction between the local TC development and TR developments in the Bristol Channel and Irish Sea that in this case suggests that the cumulative effects negate each other. No discernible difference in this Scenario 14. As per Scenario 11, the Dymchurch and Rye Bay lagoons, although adjacent, have little effect (c.1%) on each other's energy production if both are operational. This is, we believe, a result of the wide expanse of sea into which both lagoons open, and is an interesting finding in terms of locating other lagoon schemes.
Recommendations	-

Scenario 15	**Description: 2050 TR medium case with no TC development**
Comments on high level interactions	Removal of all tidal current sites to check sensitivity of tidal range (compared to run 14) and confirms changes in the North and English Channel are a result of Tidal Range interactions.
Near-field	Tidal Range: As per Scenario 11. Tidal Current: No tidal current deployment.
Far-field	Tidal Range: Far-field impact due to TR extends beyond the North Channel. With no TC development in this simulation, TC impact is ruled out in this scenario. In some earlier scenarios it was difficult to interpret whether these types of impacts were related to TC or TR development (or both). These results, in combination with scenario 13, confirm that TR impact is responsible. Similar to the above, far-field impact is observed throughout the English Channel, and can now be definitively ascribed to TR development impacts. Tidal Current: No tidal current deployments.
Conclusions	Tidal Range interactions are shown to be responsible for effects seen in the North and English Channel.
Recommendations	-

General observations and recommendations

TC far-field impact in scenarios to date is limited to around the local region. Far-field impacts far from both TR and TC development locations should generally be considered a response to TR development unless other evidence is available.

Scenario 16	**Description: 2050 TR and TC extreme case**
Comments on high level interactions	Widespread interactions observed in the most extreme case of deployment for both range and current, with reduction in tidal current energy output and adverse impacts on tidal range energy output.
Near-field	Tidal Range: Adding Cumbria lagoon at this stage in the scenarios has an adverse impact on the energy production of the Cumbria lagoon itself due to the proximity to the Solway Firth scheme. There is also a small reduction in the Solway Firth energy output, although it is unclear whether this is due to other factors. When Morte Bay is incorporated into the model, the energy production of this lagoon is also adversely affected by the existence of the other schemes. The Thames scheme is not operating effectively in the model and the energy output levels are therefore lower than would be expected. As the error in tidal range in the DCSM base case is low in this area, this can only be because the scheme does not function as intended (it takes too long for the turbines to open). The scheme also has a major effect on immediate downstream water levels, which again reduces energy output. The addition of the Humber has a large effect on the tidal range downstream of barrage, which reduces energy output Tidal Current: New site developments demonstrate similar tendencies to those already observed. Limited discernible difference in flow velocity and kinetic power density. The productivity of most sites is reduced slightly by additional local developments, but this impact is marginal. Tidal range impact in PF is starting to be amplified, but remains isolated (‘patchy’).
Far-field	Tidal Range: The addition of the Cumbria lagoon results in only a minor effect on downstream tidal range. Morte Bay creates no additional far-field effects. The far-field effects are minimal when the Thames is incorporated, therefore the energy output of nearby schemes, e.g. Dymchurch and Rye Bay, remain unchanged. The addition of the Humber reduces energy output in the Wash by c. 5% and there is a combined reduction (with the Wash) in tidal range, velocity and kinetic power density which extends further into North Sea. Tidal Current: New site developments indicate continued aspects of flow ‘avoidance’ behaviour where possible (e.g. North Ronaldsay, Ramsay Island) with the Pentland Firth being the obvious major exception. Impact of new sites in the Irish Sea is limited to the immediate locale of the development. Tidal range impact in PF is starting to be amplified, but remains isolated (‘patchy’). The Chanel Islands have seen most additional development in this scenario.

	However, the impact patterns remain broadly similar, with the impacts increased in magnitude, and higher magnitudes observed across a wider area without the overall footprint growing particularly. The appearance of new development sites around some of the islands in the region is also noticeable.
Conclusions	This extreme case has shown widespread impacts across the UK and Europe to, what we believe would be, very probably unacceptable levels.
Recommendations	It would be instructive to see which development sites the model would select if a 'flux' development constraint was applied, and to therefore identify what the maximum installed capacity and harvestable resource would be for that case. It would be interesting to see whether additional geographically dispersed new sites would start to appear in the simulations as is partially observed herein (e.g. Torr Head and Fair Head in N. Ireland and Ramsay Island in Wales). Geographical dispersion is beneficial for potential smoothing of generation fluctuations and to lessen pressure on grid access in the most over-developed (and remote) regions (e.g. Pentland Firth, Islay).

Scenarios 17-18 have not been completed, as discussed and agreed with the ETI Project Manager. Following review of the scenarios in the preparation of the runs it became apparent that the two base case model runs that we had planned using 3D TELEMAC would not produce different results from the 2D solutions. This is because we are not covering any additional impacts such as temperature, salinity or meteorological effects (in particular, wind). As all our data is depth averaged, these 2 runs that were initially proposed would not produce different results to the 2D modelling. We therefore have offered these 2 additional runs back to ETI so there are 12 instead of 10 runs remaining within the current project scope (more runs are of course possible).

Scenario 19	**Description:** **'West coast TR' – As case 16, but only TR on the west coast, no TC**
Comments on high level interactions	No interaction between tidal range and tidal current locations.
Near-field	Tidal Range: Removing range schemes on east coast and all tidal current (compared to Scenario 16) has a: small increase in energy outputs for Irish Sea schemes (1-2%) small decrease in energy outputs for Severn schemes Tidal Current: No tidal current deployment.
Far-field	Tidal Range: Considering only all the west coast tidal range schemes, there is slightly less change in tidal range in the western Irish Sea but there is an increased change in tidal range off the coast of Cornwall (compared to Scenario 16). Tidal current: No tidal current deployment.
Conclusions	The tidal range effects vary slightly from Scenario 16 in that there is a reduction in tidal range effects in the Irish Sea; however, there is an increased change off the coast of Cornwall. This implies that the combination of schemes on the west and east coast interact to form a combined effect at Cornwall.
Recommendations	-

Scenario 20	**Description: 'East coast TR' – As case 16, but only TR on the west coast, no TC**
Comments on high level interactions	Effects of the east coast tidal range schemes indicate a far-field impact on tidal current sites.
Near-field	Tidal Range: Removing tidal range schemes from west coast and all tidal current (compared to Scenario 16) has a small increase in energy output for all remaining schemes. Tidal Current: No tidal current deployment.
Far-field	Tidal Range: The far-field effects produce slightly reduced changes in velocities, kinetic power density and range in the North Sea (i.e. some of this effect was from the removed schemes). Tidal current: No tidal current deployment.
Conclusions	Noteworthy in scenario 20 is that east coast developments in the North Sea do have a far-field impact on regions as far away as the Pentland Firth (e.g. examine the kinetic power density figure for the PF in scenario 20 vs. scenario 19). These results also indicate that the west coast tidal range schemes have an impact on the east coast tidal range schemes.
Recommendations	-

Scenario 21	**Description: 2020 TR medium case and TC specified replicating the final CT2011 scenario (site specifications, but without any flux constraint)**
Comments on high level interactions	Cumulative impacts of tidal current energy extraction observed
Near-field	Tidal Range: The change in tidal current installations has minimal effect on Bridgewater Bay in comparison to Scenario 4 (or Scenario 2). Tidal Current: This simulation is set-up to attempt to maximise TC generation while limiting impact on tidal range to less than 0.1m and limiting flow velocity reduction to 10% in and around TC development locations. In some of the regions developed, the above criteria are more or less met (e.g. Islay, Anglesey, Ramsay Island). These tend to be the more isolated developments. In other regions, the impact is more than desired. In the Pentland Firth in particular, this is viewed as being related to the cumulative impact of neighbouring locations.
Far-field	Tidal Range: As per Scenario 4 (and Scenario 2). Tidal Current: The distinctive flow and kinetic power density response patterns in the Pentland Firth and Orkney Water region is very similar in shape to that observed before. The desired impact limits are exceeded, most obviously in regions where multiple farms create a cumulative impact. The highlighted

	impact regions outside of the Pentland Firth, to the west of the Orkney mainland and east of South Ronaldsay, appear more significant than if considered from an absolute value perspective, as what is observed is partially the impact of a relatively small absolute value change taking place in regions where the parameter is itself small, hence amplifying the apparent % change presented. The more isolated development locations exhibit only small impact footprints of a magnitude of the order of the desired impact limits underpinning scenario development.
Conclusions	These results suggests that the 'Flux' method does have some potential to be a first-order assessment of TC array development impact, and hence of use in limiting impact during initial TC array prescription.
Recommendations	Evolving how the 'flux' method can be applied in the model site selection pre-processing algorithms to limit development impacts in order to target notional limits would be beneficial. Consideration of how two neighbouring farms can be considered in the method would enable further accuracy in limiting impact while maximising generation.

Scenario 22	**Description: 2030 TR special (Severn Outer) and TC medium case**
Comments on high level interactions	Incorporation of the Severn Outer has minor effect on tidal current sites
Near-field	Tidal Range: Incorporating the Severn Outer instead of Bridgwater Bay and Cardiff Weston (compare to scenario 6) results in minor changes to the in-estuary effects. It is noted that the Severn Outer scheme itself doesn't work well within the model and there is a considerable reduction in downstream tidal range which reduces efficiency of the turbines and substantially reduces energy output compared to that expected from the 0–d model – although this was itself expected, see D01 section 5.7. This is likely to be due to the large number of turbines compressed into the constrained estuary width. Tidal Current: As per Scenario 6.
Far-field	Tidal Range: Changing the scheme to the Severn Outer creates a noticeable reduction in tidal range in the eastern Irish Sea, St George's Channel, to Isles of Scilly and even the English Channel (reducing energy output for the Mersey and Kirkcudbright Bay by 4%). Tidal Current: As per Scenario 6; however, the replacement of the Severn Outer causes an additional minor reduction in the tidal current energy production which emphasizes the (limited) interactions.
Conclusions	Interactions between tidal range and tidal current sites confirmed with a c.1% further reduction of tidal current energy output as a result of the Severn Outer replacing Cardiff-Weston and Bridgwater Bay.
Recommendations	-

General observations and recommendations

This alteration to the TR specification in comparison with scenario 6 reduces the UK Wide TC generation by around 2.7% (0.36TWh/y) in this particular scenario. This is relatively significant considering the additional TR generation gained is only 3.5 TWh/y. This suggests that the Severn Outer barrage has a significantly more severe far-field impact in comparison with the combination of the Cardiff-Weston barrage and Bridgewater Bay lagoon.

Scenario 23	**Description: Scenario 6 - 2030 TR optimistic case and TC medium case –** change is for the TR ebb-only schemes to be replaced by best solution (Rolls Royce or dual mode) to achieve 80% tidal range
Comments on high level interactions	Ebb only schemes
Near-field	Tidal Range: This scenario involves changing the Cardiff-Weston from an ebb only scheme to using Rolls-Royce turbines (and it is compared to scenario 6). No other schemes' generation type is altered. As a result of this change, the Bridgwater Bay lagoon gives slightly better energy output but the Mersey and Kirkcudbright give slightly lower energy output. Tidal Current: As per Scenario 6.
Far-field	Tidal Range: The use of the Rolls Royce turbine results in slightly more impact on velocity and kinetic power density in the Irish Sea but less change in the Celtic Sea. In terms of tidal range, there is a greater change in the Celtic Sea and St George's Channel than in Scenario 6. Tidal Current: As per Scenario 6.
Conclusions	This alteration to the TR specification in comparison with scenario 6 reduces the UK wide TC generation by c. 2.25% (0.30TWh/y) in this particular scenario. This is relatively significant considering the additional TR generation gained is only 2.4 TWh/y. This suggests that operating the Cardiff-Weston barrage using Rolls Royce turbines has a more severe far-field impact than running in conventional ebb-only mode. However, some of this far-field impact can be utilised beneficially (e.g. the Bridgewater Bay lagoon generates 0.293TWh/y (almost 5%) more when operating in combination with a Rolls Royce Cardiff-Weston barrage than when running in combination with a conventional ebb-only scheme.
Recommendations	-

Scenario 24	**Description: Special case – no TR development, and Salter's proposed Pentland Firth TC development (modified)** The installed capacity of this scenario is 86 GW as opposed to Salter's proposed 85GW; however, there is a very low capacity factor as was expected by the project team (suggesting this is an untenable project).
Comments on high level interactions	All Tidal range removed to complete sensitivity on tidal current. The impact of this level of tidal current extraction causes tidal range effects that spread around the north of Scotland into the North Sea and round the east coast of Scotland.

Near-field	Tidal Range: No tidal range deployment. Tidal Current: The impact of this scenario is clearly observed by examining the kinetic power density impact. Almost the whole of the Pentland Firth experiences a reduction of more than 50% in terms of kinetic power density.
Far-field	Tidal Range: No tidal range deployment. Tidal Current: For the first time it is apparent that development in the Pentland Firth is creating a significant and measurable flow 'blockage' impact, as flow is increased more or less all around the northern track of the Orkney archipelago. However, it must be recalled that small changes in absolute value in low energy regions are amplified when considered as a % change. Significant alteration to the tidal range in the Pentland Firth is also observed, with the range reduced by more than 0.6m around Duncansby Head, Stroma and Swona. The footprint of tidal range alteration is also significantly increased over anything that has been previously observed, both throughout Pentland Firth and in the neighbouring Scapa Flow region. The impact of such an extreme scenario is that for the first time the far-field impact of TC deployment is not just limited to the development region, with kinetic power density reduction measurable far into the North Sea and down the east coast of Scotland for example.
Conclusions	The installed capacity for the UK (all in the Pentland Firth) of this scenario is 86 GW as opposed to Salter's proposed 85GW. The annual energy production is restrained compared to what Salter expected, as a result of the flux issues – as expected by the project team. The impacts, however, are still excessive and it is unlikely that this can be considered representative of credible near term TC development scenario. The impact of such significant reductions in the kinetic power density would have major impacts on project economics.
Recommendations	-

Scenario 25	**Description: Special case – no TR development, and Mackay's proposed TC development (modified) for the UK**
Comments on high level interactions	All Tidal range removed to complete sensitivity on tidal current. Wide-scale effects from extreme tidal current extraction.
Near-field	Tidal Range: No tidal range deployment in this scenario Tidal Current: The near-field effects are extreme with all sites developed extracting up to 50% in terms of kinetic power density. The areas developed are large scale deployments in north of Scotland, south-west Scotland, north of Wales and a smaller development south of the Isle of Wight. Note there are no deployments in the Channel Islands under this scenario.
Far-field	Tidal Range: No tidal range deployment.

	Tidal Current: The tidal current deployment at this scale causes a reduction in tidal range across the Irish Sea and an increase in tidal range across St George's Channel. The key difference identified in this case is that the scale of development has a similar impact on the Irish Sea as wide-scale barrage deployment. The change in tidal range throughout the Irish Sea varies between 0.5 and -0.5m. There are also effects seen in the English Channel from this extreme case of energy extraction from tidal current. The tidal range around the Channel Islands is slightly increased and although the tidal power density is substantially decreased in the near-field effects, across the width of the English Channel towards the Channel Islands the power density is increased.
Conclusions	The model allows an installed capacity for this scenario of 240GW. However, annual energy generation is only c.130TWh/yr which is lower than the generation potential (of the order 200TWh/year) proposed by Mackay. This indicates that there is a maximum power that can be extracted and that after this point additional turbines become less and less efficient.
Recommendations	Identifying the key criteria that create the 'tipping point' at which stage the Irish Sea starts to be significantly impacted, from a tidal range perspective in particular is quite crucial in terms of appropriately constraining development (although it must be highlighted that previous TC scenarios also included quite significant energy harvesting in adjacent regions (e.g. scenario 13) without having any major impact on the Irish Sea system. Conducting a basic economic assessment of each scenario would also benefit in differentiating scenarios (e.g. the expectation is that this scenario included installation of devices in regions with weak tidal currents. Hence, devices in these area will rarely be operational as the local flow conditions fail to reach the cut-in velocity the majority of the time.

Scenario 26	**Description: Scenario 16 with TR in ebb-only where possible (no TC)** All tidal range schemes from Scenario 16 are run in ebb-only generation where this operational mode is possible.
Comments on high level interactions	All tidal current removed to complete sensitivity on tidal range.
Near-field	Tidal Range: the switch to ebb-only generation for Solway Firth makes a major difference to local effects – there is a local reduction rather than increase in velocities and kinetic power density, the increase in tidal range along Irish coast and Firth of Clyde is still significant but smaller than with the dual scheme, and there is less effect on energy output at Kirkcudbright Bay, Wigtown Bay and Cumbria lagoons. See Table 4. the Solway Firth scheme change to ebb-only generation reduces the immediate downstream water level (although not as much as the dual scheme), which reduces the energy generation by 20% compared to 0D modelling. the Morecambe Bay ebb-only scheme works well with only a small effect on immediate downstream water levels. the Mersey ebb-only scheme works reasonably well but the immediate downstream range is reduced, which reduces the energy output (the effect is relatively large due to the constrained approach in the estuary rather than open sea).

	Tidal Current: No tidal current deployment.
Far-field	Tidal Range: there is a greater reduction in tidal range in the Celtic Sea, which extends round to the English Channel, including on the French coast in the Gulf of St Malo. there is less reduction in tidal range in the North Sea –the Wash and Humber schemes have less effect on the immediate downstream tidal range than with dual generation. Tidal Current: No tidal current deployment.
Conclusions	Operating the Solway Firth in ebb-only generation changes the local effects, and in comparison to operating in dual model the detrimental effects on neighbouring schemes are reduced.
Recommendations	-

Scenario 27	**Description: Scenario 16 with TR in dual mode where possible (no TC)** All tidal range schemes from Scenario 16 are run in dual mode generation where this operational mode is possible.
Comments on high level interactions	All tidal current removed to complete sensitivity on tidal range.
Near-field	Tidal Range the Mersey dual scheme has a major effect on immediate downstream range, which reduces the energy output of the Mersey considerably compared to the results in ebb-only operation, or with Rolls Royce turbines. Tidal Current: No tidal current deployment.
Far-field	Tidal Range: dual generation schemes have greater impact in Irish Sea than ebb-only schemes, which is probably dominated by the Solway Firth scheme. increases in tidal range of up to 1m on the Irish coast and over 1m in the Bay of Luce. less reduction in tidal range in the Celtic Sea. similar conditions in the English Channel and North Sea. Tidal Current: No tidal current deployment.
Conclusions	The Solway Firth has the most significant impact on the far-field changes experienced but the Mersey performs poorly in dual mode.
Recommendations	-

Scenario 28	**Description: Scenario 16 with TR using Rolls Royce turbines where possible (no TC)** All tidal range schemes from Scenario 16 are run using Rolls Royce turbines where operationally possible.
Comments on high level interactions	All tidal current removed to complete sensitivity on tidal range.

Near-field	Tidal Range: The near-field effects within the impoundment area are pronounced. Tidal Current: No tidal current deployment and therefore no effects.
Far-field	Tidal Range: the changes in the Irish Sea are less pronounced than with conventional turbines but show the same pattern and are still significant. there is slightly greater reduction in tidal range in the Celtic Sea but slightly less change in tidal range in the English Channel and North Sea. Tidal Current: No tidal current deployment.
Conclusions	The change between turbines and operating regimes shows slight variations in the scenario outputs.
Recommendations	-

Scenario 29	**Description: 2050 TC sensitivity test case (no TR deployment)** This scenario assumes that technology development means that lower velocity sites can be developed economically. This scenario accesses down to 1.2kW/m^2 but deployment levels are unrestricted.
Comments on high level interactions	All tidal range removed to complete sensitivity on this extreme special tidal current case. Tidal current extraction is so extreme that large scale far-field effects are observed.
Near-field	Tidal Range: No tidal range deployment. Tidal Current: As in scenarios 24 and 25, the extensive packing of devices across wide swathes of the available resource is demonstrated to probably be severely sub-optimal in terms of maximising energy generation at lowest cost of energy, as the resource then available within a array for harvesting is severely curtailed.
Far-field	Tidal Range: No tidal range deployment. Tidal Current: This relative scale of impact in the North Channel/Irish Sea is very close to reaching the ‘tipping point’ observed previously in the Irish Sea in Scenario 29 and Scenario 16 where very significant tidal range changes are observed. The tidal current schemes reduce tidal range in the Irish Sea, have almost no effect in the Severn, increase range in the English Channel from Torquay to Bournemouth (particularly in the area south of Weymouth) and Gulf of St Malo but reduce range in the English Channel near Dover. Flow ‘avoidance’ is increased due to increased fluid resistance being imparted by the altered pressure gradient fields. The regional impact of developments in the English Channel Islands is also reaching a ‘tipping pint’ at which the far-field impact extends far beyond the flow exchange region. Measurable impacts from developments in the Pentland Firth and Orkney Waters (PFOW) region can be observed as far away as off the coast of Yorkshire.

Conclusions	The impacts observed associated with this level of energy extraction are considered to be outside any reasonable bounds of reality in terms of presenting a credible case for consented development. This is not surprising, as the AEP associated with this scenario is almost 110 TWh/y (which is similar to energy production from most studies undertaken before the Flux methodology was proposed in CT 2005 and updated in CT (2011)[6].
Recommendations	This level of development, concentrated in so few clustered locations, is not appropriate for informing TC development decision-making other than to flag the dangers of over development.

General observations and recommendations for future Scenario development
Although it is beneficial to test the limits of energy extraction to understand the interaction effects, additional scenario runs should focus on trying to generate more realistically consentable UK wide development scenarios to support the industry development.

Scenario 30	**Description: 2050 TC sensitivity test case (no TR deployment)** This scenario assumes that technology development means that lower velocity sites can be developed economically. This scenario accesses down to 1kW/m^2 but deployment levels are unrestricted.
Comments on high level interactions	All tidal range removed to complete sensitivity on this extreme special tidal current case. Tidal current extraction is so extreme that large scale far-field effects are observed (this is more so than for Scenario 29).
Near-field	Tidal Range: No tidal range deployment. Tidal Current: The same response as was observed in scenario 29 is repeated except the area of extent is significantly increased.
Far-field	Tidal Range: No tidal range deployment Tidal Current: The same response as was observed in scenario 29 is repeated except that the area of extent is significantly increased. Additional wide-scale impacts are observed in the far-field remote from TC development locations.
Conclusions	The impacts observed associated with this level of energy extraction are considered to be outside any reasonable bounds of reality in terms of presenting a credible case for consented development. This is not surprising, as the AEP associated with this scenario is over 200 TWh/y (well over half of UK electricity demand in 2011). See comments on Scenario 29.
Recommendations	This level of development concentrated in so few clustered locations is not appropriate for informing TC development decision-making other than to flag the dangers of over development.

General observations and recommendations

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[6] Carbon Trust, 2011. *UK Tidal Current Resource & Economics* http://www.carbontrust.co.uk/Publications/pages/publicationdetail.aspx?id=CTC799

This scenario is only useful in demonstrating and defining unacceptable upper limits to energy extraction. Further simulations should focus on more realistic consentable scenario options.

A summary of the impacts of interactions is provided in Table 5. It includes a list of all the scenarios and all the possible schemes (with varying operating modes). The percentage difference shown provides an indication as to the effects of introducing other schemes.

By comparing, for example, Scenario 14 and 15 which have the same tidal range deployment it is possible to see that the introduction of the tidal current schemes in Scenario 14 has no discernible effect on the tidal range outputs.

Table 5 Summary of percentage change in scheme energy output*

Year		2010	2020	2020	2020	2030	2030	2030	2040	2040	2040	2050	2050	2050	2050	2050	2050	2010	2050	2050	2050	2020	2030	2030	2050	2050	2050	2050	2050			2030	2030
Optimism (range)			Med	Opt	Med	Med	Opt	Med	Med		Opt	Med	Opt		Med	Med	Ext		Ext	Spe	Spe	Med	Spe	Spe			Sens	Sens	Sens			Opt	Spe
Optimism (current)			Med	Med	Opt	Med	Med	Opt	Med	Med	Med	Med	Med	Med	Opt		Ext		Ext			Spe	Med	Med	Salter	MacKay				Sens	Sens	Sens	Sens
Case no.		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**56**	**73**
		Energy output compared to maximum across scenarios																															
Total ebb						36%	36%	36%	35%		35%	33%	33%		33%	33%	33%			33%							100%	33%				36%	
Total dual			16%	16%	16%	12%	12%	11%	27%		31%	75%	92%		75%	76%	97%			66%	33%	17%	53%	12%			52%	100%				11%	12%
Total R-R				1%		1%	2%	1%	17%		17%	17%	17%		17%	17%	22%			17%	4%		2%	25%			1%	20%	100%			2%	25%
Total range			10%	10%	10%	27%	29%	27%	52%		54%	79%	89%		79%	79%	96%			74%	23%	10%	33%	32%			86%	96%	100%			29%	32%
Total current			1%	1%	1%	6%	6%	8%	13%	13%	13%	21%	21%	21%	24%		37%					11%	6%	6%	13%	61%				52%	100%	5%	5%
Total UK (range + current)			4%	4%	5%	16%	17%	19%	33%	13%	34%	51%	55%	21%	55%	31%	75%			29%	9%	15%	19%	18%	13%	61%	33%	37%	39%	52%	100%	16%	17%
La Rance	Ebb	95%	95%	95%	95%	94%	94%	94%	94%	96%	94%	93%	91%	96%	93%	91%	92%			92%	93%	96%	93%	95%	95%	95%	90%	90%	92%	98%	100%	94%	95%
Solway Firth	Ebb																										100%						
Solway Firth	Dual											98%	96%		97%	100%	93%			95%								94%					
Solway Firth	R-R																												100%				
Morecambe Bay	Ebb																										100%						
Morecambe Bay	R-R								97%		97%	99%	99%		99%	99%	99%			100%								100%	99%				
Mersey	Ebb																										100%						
Mersey	Dual																											100%					
Mersey	R-R						98%		98%		96%	98%	98%		98%	99%	98%			99%			94%	97%					100%			98%	97%
Dee	Ebb																										100%						
Dee	Dual										97%	98%	98%		97%	98%	97%			99%								100%					
Dee	R-R																												100%				
Severn - outer	Dual																						100%										
Cardiff-Weston	Ebb					100%	100%	100%	97%		97%	92%	92%		92%	92%	93%			91%							91%	91%				100%	
Cardiff-Weston	R-R																							100%					95%				100%
Thames	Ebb																										100%						
Thames	R-R																90%				94%							92%	100%				
Wash	Ebb																										100%						
Wash	Dual								100%		100%	100%	99%		100%	100%	95%				96%							96%					
Wash	R-R																												100%				
Humber	Ebb																										100%						
Humber	R-R																98%				100%							100%	100%				
Wigtown Bay	Dual												87%				86%			88%							100%	87%					
Wigtown Bay	R-R																												100%				
Kirkcudbright Bay	Dual																											100%					
Kirkcudbright Bay	R-R			100%		99%	99%	99%	99%		99%	91%	90%		91%	92%	90%			90%			96%	98%			93%		93%			99%	99%
Cumbria	Dual																90%			92%							100%	93%					
Cumbria	R-R																												100%				
Oxwich Bay	Dual												98%				100%			97%							97%	98%					
Oxwich Bay	R-R																												100%				
West Aberthaw	Dual											100%	98%		100%	99%	99%			97%							98%	99%					
West Aberthaw	R-R																												100%				
Rhoose	Dual											100%	97%		100%	100%	99%			97%							97%	97%					
Rhoose	R-R																												100%				
Bridgwater Bay	Dual		99%	100%	100%	70%	70%	69%	68%		67%	61%	60%		61%	61%	60%			59%		100%		73%			59%	60%				69%	73%
Bridgwater Bay	R-R																												100%				
Morte Bay	Dual																100%			98%							99%	99%					
Morte Bay	R-R																												100%				
Rye Bay	Dual											98%	97%		98%	98%	98%				100%						98%	98%					
Rye Bay	R-R																												100%				
Dymchurch	Dual												96%				96%				100%						97%	97%					
Dymchurch	R-R																												100%				
Current																																	
2020	Med		100%	100%	93%	96%	96%	94%	90%	90%	91%	90%	90%	90%	87%		81%						96%	95%									
2020	Opt				96%	100%	99%	99%	98%	97%	98%	78%	78%	77%	72%		63%						99%	99%									
2030	Med					100%	100%	99%	92%	92%	92%	86%	85%	86%	82%		80%						99%	100%									
2030	Opt							100%	85%	85%	85%	75%	74%	76%	72%		69%																
2040	Med								100%	100%	100%	81%	81%	81%	76%		71%																
2050	Med											100%	100%	100%	92%		79%																
2050	Opt														100%		76%																
2050	Ext																100%																

*This is in comparison to the schemes' highest energy output from all the Scenarios

4.2.1 Phasing

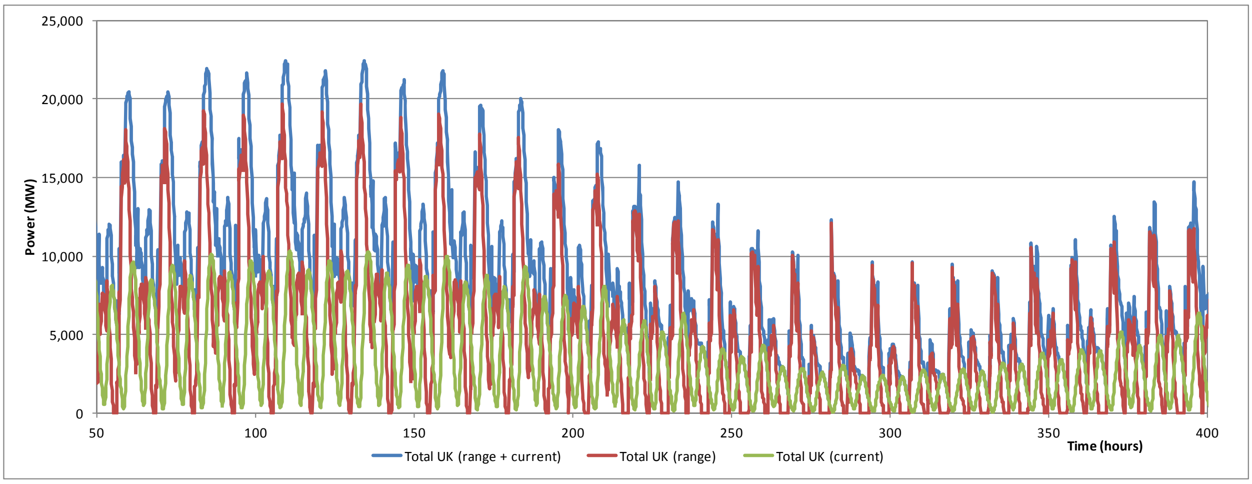
The time history plots can be found in Appendix E and an example of Scenario 10 is provided below.

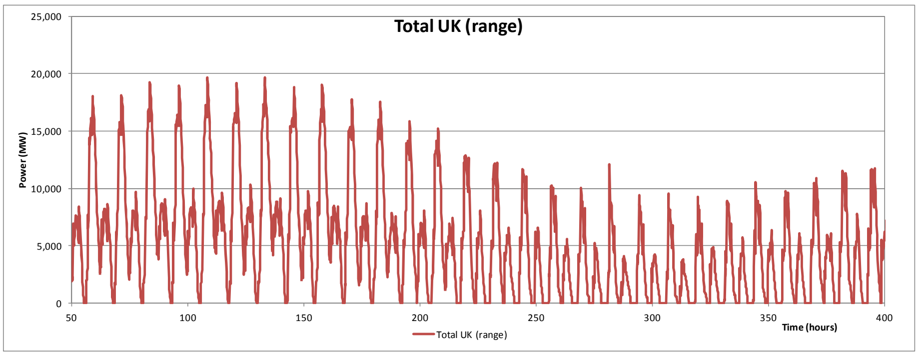
Scenario 10 is a 2040 scenario with optimistic case tidal range deployment and medium case tidal current deployment.

The tidal range sites included, in order of power generation, are Cardiff-Weston in ebb only generation (12.6TWh/yr), Morecambe Bay in dual mode generation with Roll Royce turbines (9.7TWh/yr), the Wash in dual mode with conventional turbines (5.9TWh/yr), the Bridgewater Bay in dual mode with conventional turbines (4.2TWh/yr), the Dee in dual mode with conventional turbines (1.7TWh/yr), the Mersey in dual mode with Roll Royce turbines (1.1TWh/yr) and Kirkcudbright Bay in dual mode with Rolls Royce turbines (0.3TWh/yr).

The tidal current sites included in Scenario 10 contribute 29.1TWh/yr.

The combination of this level of energy extraction produces the smoothest power output of all the scenarios that have been completed to date, which is shown in Figure 7 that provides the time series data for a 15 day spring-neap cycle and a 24 hour cycle on both the spring and the neap tides.





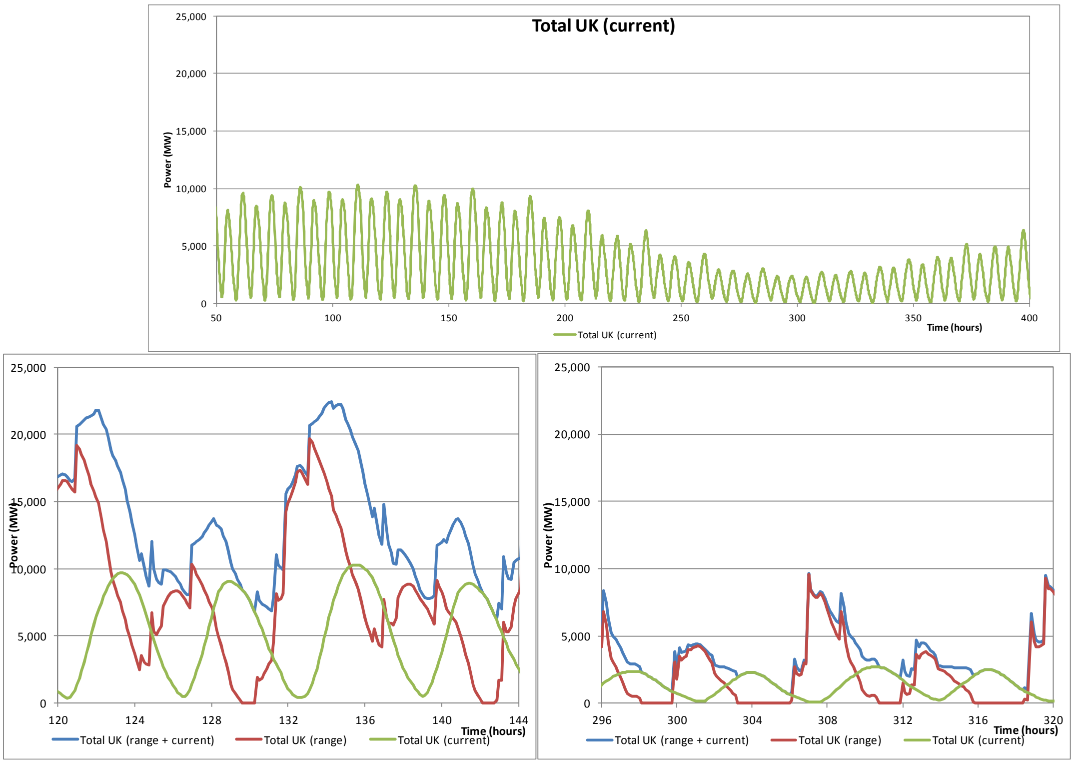


Figure 7 Time series data for Scenario 10

Only the Wash tidal range scheme is on the east coast of the UK and the remaining tidal range schemes are all on the west coast of the UK. The tidal current deployment is spread across the north of Scotland, the Channel Islands, north of Wales and south-west of Scotland.

The tidal range phasing results for all the scenarios can be summarised as:

- Severn and east coast sites are in phase with each other;
- Irish Sea sites are 6 hours out of phase with Severn and east coast sites.

The result of this is that all tidal range sites are almost in phase when working with dual generation schemes, and even with (mainly) ebb generation schemes (scenario 26) there are significant peaks and troughs in the combined UK power output over a 24 hour and a spring neap cycle which indicates that there is little ‘power smoothing’ effect of multiple tidal range deployments. The maximum power at the spring tide for tidal range deployment is c. 2 times that during the neap tide.

The tidal current sites are all generally essentially in phase with each other over a 24 hour and a spring neap cycle which indicates that there is little ‘power smoothing’ effect of multiple tidal current deployments, at least when developing the resource in the manner used in this report. The maximum power at the spring tide for tidal current deployment is c. 4 times that during the neap tide.

Tidal range and tidal current developments are generally out of phase, so the combination of tidal range and tidal current developments could achieve a smoother power output, with careful selection and optimisation of sites, as is evident here, particularly from the 24 hour plots. However, although the 24 hour cycle can be ‘smoothed’ significantly through judicious selection of the combination of tidal range and tidal current sites, the spring-neap cycle of course cannot be ‘smoothed’ in the same way and the maximum power at spring tide is still c. 2-3 times that available at neap tide. The only way that this spring-neap factor could be reduced would be to reduce the installed capacities of the schemes so that the capacity factor would naturally increase.

4.2.2 Dredging

The impact of dredging was discussed previously with the ETI during project scoping and review of Milestone 1 and it was confirmed that it is not being considered in the DCSM for this interactions analysis as it is a site specific optimisation which is beyond the scope of the project. We were expecting potential reduction in annual energy output for schemes in estuaries with shallow depth close to the turbines and the schemes expected to cause problems were the Mersey, Dee and Morecambe Bay (See D01 – Section 5.23).

Of these, only the Mersey with dual generation appears to have a significant energy reduction compared to 0D model. This may be because the Dee and Morecambe Bay discharge into relatively open sea, not within their estuaries. However, an alternative possible explanation is that the bathymetry used for the development of the DCSM (200m resolution) has not accurately captured the shallow depths close to the turbines in the Dee and Morecambe Bay (and possibly overestimated the storage volumes in these impoundments due to poor representation of the intertidal zone).

As discussed previously in Scenario 16 summary table for the Thames, there are issues with the operation of the Wash, Thames and Humber schemes. Without further investigations, we are unable to confirm whether this is due to genuine shallow depths, artificial shallow depths (due to poor bathymetry) or some other reason. If the ETI was interested, one of the additional runs could be used to test a scenario with lower bed levels, artificially lowered close to the turbines (which would represent dredging).

5 CRITICAL FACTORS AND OPTIMISATION OF TIDAL DEPLOYMENTS

5.1 Critical factors for optimising tidal power systems

The potential for optimisation of tidal power system identification and scheme design is highly dependent upon the availability of accurate input data. The majority of input data that would be desired to conduct such an optimisation can be derived from desk-based study in combination with a well planned field monitoring/survey program. Significant value can additionally be added through the provision of accurate modelling of various key input parameters. Modelling adds value in three key forms:

1. Providing output of new data metrics that cannot be directly measured in the field,
2. Providing a representation of the spatial variability of key field monitoring/survey parameters that can only be reliably monitored in the field at isolated measurement locations, and
3. Providing the potential to ‘assess the future’ by incorporating representations of the intended tidal power scheme in operation within the model.

Clearly, the TRM Project is aimed at providing a series of tools, most notably the CSM, to allow the above modelling exercises at a UK scale, and they can provide value in the three key forms discussed above.

Hence, the application of optimisation for tidal power system identification and scheme design should be considered as a two part process. The first part would be based upon desk-based study informed by a suitably specified field monitoring/survey program. The second part would be informed by appropriate modelling of key parameters. After the modelling exercise, the outputs derived can also be fed back into the first part of the optimisation process to provide additional data to inform analysis and decision-making. An optimal decision support tool would be provided by merging the outputs from the desk based study informed by a field monitoring/survey program in combination with model outputs in a Geographical Information System (GIS).

Ten critical optimisation factors, and their associated metrics, that best inform tidal power system identification and scheme design have been identified from our previous experience of tidal range and tidal current schemes and from the results of the scenarios discussed in previous sections:

- Identify the most energetic resource locations available for exploitation
- Identify limiting technology design constraints related to the local resource characteristics
- Identify approximate capital cost
- Identify environmental constraints
- Identify grid connection constraints
- Identify construction/installation and O&M constraints
- Quantify the energy delivered to the grid
- Identify optimal generation technology characteristics
- Identify optimal scheme design and interactions
- Identify the network integration requirements of the project into the existing grid and network infrastructure.

Each of the key factors identified require various data inputs to best inform optimisation. The ten identified critical factors can be further sub-divided by consideration of whether any form of modelling is necessary to provide the required input data. The first six factors listed can be assessed without the use of outputs from modelling, although clearly the base case ‘static’ resource maps from the TRM Project add considerable value compared to the existing public domain information in terms of the most energetic resource locations (particularly for tidal current). This does not however mean that model outputs cannot add value to consideration of these critical factors. Alternatively, the final four identified critical factors require various model outputs as the basic input data required to conduct an optimisation. The requirements of each identified critical factor are considered in more detail in the tables that follow.

NOTE: It is important to recognise that although each critical optimisation factor is listed separately, decisions informed by optimisation of one factor may have a positive or negative impact on the optimisation of another. To provide some clarity, the desk-based and then model informed critical factors are ranked in general order of importance from 1-6 and 1-4 respectively. However this ranking is not a rigid structure – for example the most economically viable project in all categories that cannot gain the required environmental consent and permitting to enable project development is of no value. Hence, an appropriate optimisation decision support tool would have multiple interactions *between* the critical optimisation factors. In reality, the ranking is more of an identification of the order in which each critical factor should be considered – for example, there is no need to worry about the availability of a suitable grid connection or appropriate harbour access if the local tidal resource is not energetic enough to warrant consideration for exploitation. Hence, an appropriate optimisation decision support tool would have multiple loops as well as interactions between the critical optimisation factors

Part 1: Critical factors that can be provisionally assessed without requiring inputs from models			
1	**Identify the most energetic resource locations available for exploitation**		
	Important metrics and considerations:		Units:
	Tidal current	Mean kinetic energy flux (power density)	kW/m^2
		Mean tidal velocity magnitude	m/s
		Maximum spring tide velocity	m/s
	Tidal range	Mean tidal range	m
	General comment: A first order ranking of potential development sites is generally based upon identifying the most economically advantageous resource available.		
	Tidal current: At a basic level, this can be summarised as the resource exhibiting the highest mean kinetic energy flux (the average amount of energy in the water column passing through a prescribed cross-sectional area). As assessment of the mean kinetic energy flux requires (preferably multiple) velocity time-series, and an accurate understanding of the local bathymetry characteristics, hence an even simpler but less accurate measure in the absence of such data would be to consider the mean tidal velocity magnitude. The most basic measure of resource value appropriate for informing initial site screening is identifying a high spring tide velocity.		
	Tidal range: The available resource can be assessed directly from the mean tidal range, which can be calculated from information given in Admiralty tide tables and/or the Atlas of UK Marine Renewable Energy Resources (BERR, 2008).		
2	**Identify limiting technology design constraints related to the local resource characteristics**		
	Important metrics and considerations:		Units:
	Tidal current and tidal range	Water depth at the intended installation site (LAT)	m
		Extreme and mean wave heights	m
		Storm surge extreme velocities and heights	m/s + m
		Tidal range characteristics	m
	Tidal current	Turbulent intensities and length scales at different key stages of the tidal cycle	% + m
		Extreme and mean wind velocities (typically measured at 10 m above sea level)	m/s
	General comment: In order to maximise the revenue generation potential of an identified location, minimising the cost of development is paramount. Having identified the optimal resource for		

<table>
<tr><td rowspan="3"></td><td colspan="3">exploitation, it is then necessary to assess the potential technology design constraints, limitations or show-stoppers related to the local resource and site characteristics. The foremost of these potential show-stoppers is the depth at the intended installation site. If the available technology solutions are incompatible with the depth at the identified site, then the value of the resource is significantly diminished at the current time. In future, technology innovation may open up the identified location as being suitable for development.</td></tr>
<tr><td colspan="3">Tidal current: As an example, existing tidal current technologies at the stage of full-scale testing are limited to depths of the order 25-60 metres by design and installation constraints. If this mismatch is identified having considered the existing state-of-the-art in proven technology, it may therefore be more appropriate to consider the next best energetic site identified at stage 1 of the process. Alternatively, if there is a good match between technologies and depth characteristics, then additional criteria should also be considered – the metocean conditions (which describe the physical conditions offshore), at a particular site. The various metocean criteria define aspects of technology selection, define the technology design extremes (e.g. minimum surface clearance, fatigue loads and ultimate limit loads). These criteria include the tidal range at the identified site, extreme and mean wave conditions, storm surge heights and induced velocities, extreme and mean wind conditions and the local turbulent flow properties.</td></tr>
<tr><td colspan="3">Tidal range: The base level of a 9m diameter bulb turbine needs to be submerged to about 20m below spring low tide level to avoid cavitation problems. For a 9m diameter Rolls-Royce turbine, the equivalent submergence is 10m as these machines do not include an expanding draft tube and cavitation is less of an issue because of their slower rotation speed. The required submergence for either bulb or Rolls-Royce turbines can be achieved by dredging (cost and bed materials permitting). A second constraint on turbine siting is the depth of water into which the turbines will discharge. If the turbines discharge into shallow water there will be a large energy penalty due to additional head losses downstream of the turbines. This is because of the high velocities that will be forced to occur in these shallow waters as water flows away from the turbines.</td></tr>
<tr><td rowspan="6">**3**</td><td colspan="3">**Identify approximate capital cost**</td></tr>
<tr><td colspan="2">Important metrics and considerations:</td><td>Units:</td></tr>
<tr><td rowspan="3">Tidal range</td><td>• Minimum embankment length and depth</td><td>km / m</td></tr>
<tr><td>• Impounded area (as a proxy to estimate turbine numbers)</td><td>km^2</td></tr>
<tr><td>• Grid connection</td><td>£k</td></tr>
<tr><td colspan="3">Comment: This is a major consideration for tidal range schemes as a ‘stand-alone’ figure as tidal range schemes have an extremely large capital cost outlay; however, capital cost is also a consideration for tidal current schemes as a contributor to cost of energy.</td></tr>
<tr><td></td><td colspan="3">Tidal Current:
An estimate of the capital cost for a tidal current array can be determined by using a parametric model (similar to that developed for tidal range in D04 – Cost of Energy model and supporting information). A tidal current installation can be installed in smaller phases than a tidal range scheme and the capital costs can also be spread over the deployment phase during which some parts of the scheme can start generating.</td></tr>
<tr><td></td><td colspan="3">Tidal Range:
A qualitative estimate of the likely capital cost of a scheme can be made simply from the embankment length and impounded area. The Severn Tidal Power study (DECC, 2010) investigated three large barrages and two large lagoons in the Severn estuary in detail. It concluded that these schemes were unlikely to attract the necessary private investment so would require the public sector to own much of the cost and risk. In the current economic climate, obtaining government investment of the magnitude required for these large schemes is challenging. As such, smaller scale schemes potentially become more attractive because of the possibility of private financing. These could be barrages in smaller estuaries than the Severn, or lagoons significantly smaller than the 90km^2 Bridgwater Bay lagoon. Another benefit of lower capital cost schemes is that there is less demand on the supply chain (such as materials, turbines</td></tr>
</table>

	and vessels). A smaller footprint should reduce the complexity of the planning consents and reduce the total construction time. The cost of energy, however, is likely to be higher for smaller schemes due to economies of scale.		
4	**Identify environmental constraints**		
	Important metrics and considerations:		Units:
	Tidal current and tidal range	• Environmentally designated areas such as Special Protection Areas (SPAs) under the Birds Directive; Special Areas of Conservation (SACs) under the Habitats Directive; Ramsar Wetlands of International Importance; Sites of Special Scientific Interest (SSSIs); Scheduled Ancient Monuments (SAMs); and Areas of Outstanding Natural Beauty (AONBs).	-
		• Shipping lanes and shipping intensity	-
		• Fishing intensity	
		• Existing mammal and sea-life activity	-
		• Existing industrial or general public use of the resource	-
		• Sediment transportation	-
		• Ordnance dumps/ shipwrecks	-
		• Contaminated sea-bed/land	-
	Tidal range	• Ports	-
		• Flood protection and land drainage	-
		• Bathing waters	-
		• Intertidal areas	km^2
	General comment: Gaining consent can be complicated for sites that overlap with protected or designated areas, and can have the potential to be an ultimate show-stopper in terms of limiting the potential for a site to ever obtain appropriate consent. Marine mammals, waterbirds, migratory and estuarine fish and other sea-life are a significant consideration in terms of gaining consent for project development. Other sea users can lead to a conflict of interest with a particular marine energy development, and can further complicate the consenting process. The presence of existing complicating issues such as contamination of the sea-bed or shipwrecks can also limit the potential development of a site, or ability to gain consent for development. Mitigation measures may well be required in order for a project to proceed. Examples of the overlap of the sites investigated in the scenarios with potential exclusion zones and high constraint areas are shown in Figure 41, Figure 42 and Figure 43. The GIS layers used to generate these figures have been derived from public domain information, e.g. the MAGIC database amongst others. Additional project size and scale constraints can be envisaged as the industry matures that will likely impose limitations to the total energy that can be extracted in a region in order to minimise near and far field effects such as flow reduction, alteration to sediment transport patterns and impacts on tidal range.		
	Tidal current: Tidal current locations require particular optimisation and resource management as the economically useful resources are constrained to relatively small areas around the UK, and as per the results presented in earlier sections the potential interaction effects are high, particularly in more extreme cases. To avoid any detrimental impact on an existing or future site, a full understanding of the resource is required.		
	Tidal range: A barrage/lagoon will affect the operation at any ports contained within the impounded area. There are three main possible negative impacts: navigation locks will be required (increasing the construction cost of the scheme); there is a detrimental effect on port operations such as freight traffic and fishing due to the additional transit time through the locks; and if the scheme lowers high tide levels, this reduces the clearance for ship access into the ports. A tidal barrage/lagoon will generally provide increased flood protection from tidal flooding for the coastline within the impounded area. The embankment and turbines limit the flow of water into the impounded area and hence reduce extreme tide levels. In contrast, however, barrages/		

<table>
<tr><td></td><td colspan="3">lagoons can have a negative impact on land drainage since schemes generally raise low water levels within the impounded area. Tide-locking (when sea levels are higher than the upstream river levels and so prevent any flow through the (usually flapped) tidal outfalls) of the outfalls into the estuary or sea may be impeded, leading to upstream flooding during high river flows. This particularly applies to ebb-only generation schemes.
Recreational beaches within a barrage/lagoon impoundment could be affected by scheme operation. For example: with an ebb-only generation scheme, much of the beach foreshore may be permanently submerged; the sediment transport regime could be disrupted, changing the beach composition from sand to mud; and the rapid change in water levels from low to high and high to low tides with dual generation conventional turbines could be dangerous for beach users.</td></tr>
<tr><td rowspan="7">5</td><td colspan="3">Identify grid connection constraints</td></tr>
<tr><td colspan="2">Important metrics and considerations:</td><td>Units:</td></tr>
<tr><td rowspan="2">Tidal current and tidal range</td><td>• Grid connection availability and capacity</td><td>-</td></tr>
<tr><td>• Distance to mainland sub-station</td><td>km</td></tr>
<tr><td rowspan="3">Tidal current</td><td>• Site distance from shore</td><td>km</td></tr>
<tr><td>• Availability of beaching location</td><td>-</td></tr>
<tr><td>• Cable routing</td><td>-</td></tr>
<tr><td colspan="3">Comment: Without an appropriate grid connection, a marine renewable energy project cannot function. Therefore grid connection plays a vital role and can often be a major bottle neck for project development. Herein, connection to the National Grid transmission is assumed due to the size of the intended projects (minimum 60MW installed capacity, often significantly larger). For tidal current schemes, the distance to the grid connection sub-station is determined by three main components:
1. Distance to shore from the offshore project site,
2. Availability of a suitable beaching location (without which the offshore cable length may be significantly increased), and
3. The onshore distance to the appropriate transmission network connection point from the beaching location.
For tidal range, only the third of these components is significant since the barrage/lagoon embankment forms a path for the offshore cable routing (which also gives an opportunity to split the power output between two locations).
A further issue is the availability of spare capacity within the transmission network locally to enable connection of new projects without the need for significant (costly and time-consuming) grid reinforcement. An additional grid connection issue is identification of a suitable cable routing route and methodology that ensures reliable connection.</td></tr>
<tr><td rowspan="13">6</td><td colspan="3">Identify construction/installation and O&M constraints</td></tr>
<tr><td colspan="2">Important metrics and considerations:</td><td>Units:</td></tr>
<tr><td rowspan="4">Tidal current and tidal range</td><td>• Depth</td><td>M</td></tr>
<tr><td>• Seabed/bedrock characteristics</td><td></td></tr>
<tr><td>• Port distance</td><td>Km</td></tr>
<tr><td>• Road access</td><td>-</td></tr>
<tr><td rowspan="6">Tidal current (and minor impact on tidal range)</td><td>• Quayside storage</td><td>-</td></tr>
<tr><td>• Tidal slack characteristics</td><td>Minutes</td></tr>
<tr><td>• Tidal range</td><td>M</td></tr>
<tr><td>• Wave resource for weather windows</td><td>-</td></tr>
<tr><td>• Vessel availability</td><td>-</td></tr>
<tr><td>• Device characteristics</td><td>-</td></tr>
<tr><td colspan="3">General comment: Construction/Installation/Decommissioning and ongoing Operation & Maintenance (O&M) costs and constraints can severely impact the viability of a marine energy project.</td></tr>
</table>

	Tidal current: Deeper sites limit technology choice, installation methodologies and by default tend to be further from shore and more difficult to access. Similarly, the seabed and bedrock characteristics define the load bearing capacity of the region and hence impact on technology selection and design which often entail cost penalties. Both installation and O&M are very sensitive to periods of appropriate weather conditions for on-site activity. These so-called ‘weather windows’ are themselves defined not only by the local meteorological and oceanographic conditions, but additionally by the ease of access to appropriate facilities for safe harbouring, storage of resources, etc.. Hence port and vessel availability, appropriate road access and quayside storage are all factors impacting on defining weather windows, as well as having their own direct implications on project cost. Any factor that impacts on O&M operations can significantly increase device downtime impacting on overall technology availability and hence revenue generation. This is such an important issue that many technology developers are embodying the maintenance strategy at the heart of their device design, either through the fundamental device design decision making, and/or through provision of redundancy in their systems. These mitigation measures come at an economic cost impacting the capital cost of any project development.
	Tidal range: A minimum seabed depth is required to install turbines but if the bed is too deep, especially for the remaining embankment, the cost and difficulty of construction will increase considerably. The seabed geology will determine the constructability of the embankment. O&M costs are less of a factor for tidal range than for tidal current schemes as the embankment, turbines and sluices provide a means of access and way of controlling internal sea conditions.

Part 2: Critical factors that fundamentally require inputs from models			
1	**Quantify the energy delivered to the grid**		
	Important metrics and considerations:		Units:
	Tidal current and tidal range	• Energy is best measured annually for comparison between projects	TWh/year
		• Installed capacity	MW
		• Average availability	% uptime
	Comment: Energy delivered to the grid is a direct measure of the revenue generation potential of a tidal energy project. The energy delivered to the grid should generally be normalised by the installed capacity of the project in order to enable comparison between potential projects. The best comparison would be the levelised cost per kWh of generation delivered across the project lifetime. However, to compare on that basis would require detailed project and technology design decisions to enable an accurate assessment. Hence, the energy delivered to the grid per MW installed can be used as a simple proxy, in combination with the capital cost/MW and an estimated O&M cost. Additional relevant criteria that impact across all projects, but are technology, project and site specific relating to energy delivered to the grid include the average availability (uptime) across the scheme, and the phasing of when power is delivered to the grid. Tidal range schemes tend to have much larger installed capacity than tidal current schemes, so availability and phasing is likely to be more critical for tidal range when considering individual schemes.		
2	**Identifying optimal generation technology characteristics**		
	Important metrics and considerations:		Units:
	Tidal current and tidal range	• Rated power	MW
		• Device/turbine type	
	Tidal current	• Rated velocity	m/s
		• Directionality	-
		• Bias (flood/ebb)	degrees

		• Cut-in velocity	m/s
		• Cut-out velocity	m/s
	Tidal range	• Mode of operation (ebb/flood/dual)	
		• Starting head	m
		• Turbine diameter	m
	General comment: In order to have an efficient device/turbine and overall an optimised scheme, meeting certain site specific characteristics are key. Best matching the generation technology operational characteristics to the local resource provides an optimal return on investment.		
	Tidal current: The rated velocity and power of a device are intrinsically linked. However, the directionality and bias of the underlying resource can alter device performance significantly, and must be accounted for. As an example, the directionality of the flow may inform technology selection between a fixed and yaw-capable device. Linked to this would be the additional capital cost and potential O&M overhead associated with a yaw-capable device which might alter the overall project economics in such a way as to alter the overall site ranking towards a region where the flow is more aligned (rectilinear). Other device characteristics such as the cut-in and cut-out velocities will impact on the overall generation capability in combination with the underlying resource variability. Optimal matching of device and resource characteristics lies at the heart of ensuring a cost effective project.		
	Tidal range: The key considerations are the type and size of turbines, the mode of generation and when generation begins on each tide.		
3	**Identifying optimal scheme design and interactions**		
	Important metrics and considerations:		Units:
	Tidal current and tidal range	• Inter-scheme interactions	-
	Tidal current	• Overall array efficiency	-
		• Inter-device interactions	-
		• Inter-array interactions	-
	Tidal range	• Number of turbines	-
		• Turbine placement	-
		• Barrage/lagoon embankment alignment	-
	General comment: The potential impact of other planned development projects on the underlying resource requires assessment. These developments need not be limited to other marine energy project developments; other anthropogenic uses of the coastal environment (e.g. offshore wind farms, land reclamation, coastal defences, etc.) may have an impact on the underlying resource, and hence on project economics that has to be defined.		
	Tidal current: Viable economic marine energy development projects are unlikely to consist of only single devices – the overhead associated with installation, grid connection, O&M, etc. is minimised when spread across multiple devices. However, there are limiting factors to the optimal size, shape and arrangement of an array of multiple devices that require consideration. The purpose of array design is to maximise power generated by the devices working in combination, rather than maximising for individual devices. Hence the overall array efficiency is of much more importance than individual device efficiency. Maximising array efficiency requires an understanding of the impacts of inter-device interactions to optimise device spacing and layout. This understanding is also required to enable an accurate forecast of future device performance in a tidal environment that is itself altered by the presence of the array.		
	Tidal range: By fine tuning of the installed capacity and barrage/lagoon placement, it should be possible to increase the energy output of the scheme. This could be assessed first with a simple 0D model and then revised with the outputs of the full 2D (CSM) model.		

4	**Identify the network integration requirements of the project into the existing grid and network infrastructure**

	Important metrics and considerations:		Units:
	Tidal current and tidal range	• Total national (UK) and regional generation	-
		• Overall contribution of tidal energy to UK energy mix	-
		• Overall contribution to temporal averaged (UK wide) tidal energy generation	-
	Comment: Tidal site phasing can have an economic benefit or disincentive depending upon the timing of delivery of generation – this is a factor that interacts with the characteristics of the existing energy mix and time-varying demand profiles. Depending upon the structure of the Power Purchase Agreement (PPA) associated with the project, the economic value of power delivered to the grid may, or may not vary in time. There are wider issues to consider relating to these issues as the marine energy sector develops. A significant body of academic literature and governmental technical reports exist that debate the viability of various levels of distributed generation, non-dispatchable power and correlated renewable resources either specific to the UK or in other markets. Hence, the phasing of different tidal sites will most likely assume more significance as the tidal energy sector matures, but must also be considered in the wider context of the evolving energy mix. Predicting the potential future power generation profile for tidal energy will enable the industry to position itself appropriately in discussions such as grid reinforcement, energy market reform, and integration with other renewable sources. Industry and government decision making in the interim period while tidal energy matures will also have potentially large impacts on future tidal energy project financial viability. Section 4.2.1 already discusses the phasing of the existing schemes in some detail. It is obvious that although there is the potential for improving the phasing of the overall electricity generation across a daily period for the UK grid as a whole using different combinations of tidal range and current schemes, and that tidal power is generally well predictable, this improvement may not have such a significant impact on the grid requirements regionally, and it is also important to note that the difference between the spring and neap impact on the grid will still be significant in all situations.		

5.1.1 Conclusion

In conclusion, a host of criteria that impact on the critical factors required for optimisation of tidal current and range systems have been identified and discussed. In fulfilling the scope of work to date, it has been necessary to incorporate some of these optimisation factors directly into the modelling tools that have been provided. The definition of the tidal current scenarios already addresses a number of the criteria that impact on the critical factors highlighted, ranging from identification of the most economic resource for exploitation automatically through the model, to informing the best matching of technology and resource characteristics.

The project has therefore gone beyond the original scope of work already. The modelling tools being used to deliver the TRM scenarios are therefore already a long way towards providing an efficient and effective optimisation tool while meeting the original scope of examining the cumulative impacts of various development scenarios. The identification of additional critical factors provides a blueprint for further evolution of the modelling tools towards a one-stop-shop decision and design support tool.

5.2 Exploration of optimisation outcomes

Optimisation of any problem requires an overarching theme or outcome that drives the optimisation process. Optimisation of a tidal power project could be driven by a number of outcomes, singly or in combination. The identified overarching outcomes addressed within this section provide examples of how the model and associated tools provided as part of the TRM scope of work could be used to optimise the UK tidal resource. The outcomes and the potential scope of work associated with their optimisation are summarised below. We believe that the costs for the actual optimisation itself, which is not part of the current scope of work, will vary widely depending on the level of detail actually requested by ETI if such work was to progress, and on the party contracted to complete the work. The scope and costs would also depend on whether various recommendations provided in other deliverables are addressed before or as part of such optimisation work. Given that such future work would also depend on the feedback on the critical factors and optimisation outcomes from ETI, and would be the subject of a variation to the TRM contract, or the subject of a future contract, we do not believe that the cost of such work should be provided in this report.

The key optimisation outcomes that we propose are:

1. Maximising energy generation (largely independent of a cost of energy threshold).
2. Maximising energy generation (minimising cost of energy or to various threshold(s)).
3. Minimising the impacts on environmental / other constraint factors (i.e. ability to consent).
4. Maximising power smoothing from tidal power generation (regionally or nationally).
5. Minimising impacts on the existing grid network (i.e. short-term ability to build capacity).

Certain key critical factors within this optimisation will be difficult to frame and ultimately optimise using the existing raw data and knowledge. An example would be how to best quantify and qualify the positive benefits and negative impacts of a particular project on the environment / other constraints. Nonetheless, it is often possible to attach a monetary value to such benefits and impacts, for example by considering the appropriate cost of mitigation measures in the case identified.

A potential high-level scope of work for each of the optimisation outcomes is provided below.

1. Maximising energy generation without cost of energy limitations
    - Implement 'technical' cost of energy models for tidal range schemes within the DCSM (the cost of energy model exists as per D04 - Cost of Energy Model and supporting documentation) and for tidal current schemes (would need to be developed, but this is feasible). Such a 'technical' cost of energy model could also be modified to encompass all critical factors which all have an impact on the final cost of energy, by assigning monetary values to each, e.g.:
        1. environmental – through cost of compensatory habitat;
        2. ports – loss of earnings / compensation;
        3. cost of onshore grid connections and upgrades;
        4. value of energy delivered to the grid, to encourage smoother output.
    - Initially, allows a cost of energy and ranking of schemes as implemented in DCSM.
    - Later, may allow a cost of energy optimisation routine in the DCSM for a scheme.

2. Maximising energy generation (with various cost of energy approaches/thresholds)
    - Using output from (1), and any proposed targeting of / thresholds for cost of energy, maximise the energy from individual schemes within those constraints.
    - Create a 'resource-cost of energy' curve for UK tidal energy generation, based on above.
    - Investigating positive and negative interactions to develop a resource-cost of energy curve that integrates the impact of all schemes on each other (where possible/within reason).

3. Environmental constraints
    - One option would be to avoid high constraint, e.g. designated, areas completely, whilst maximising tidal generation within CoE thresholds as in (1) & (2).
    - Another option would be to weight and score the constraints on their ability to impact on the generation of a scheme, and use this as a proxy for the tidal generation associated with a scheme that overlaps constrained areas.

- Another option would be to include a cost associated with overcoming constraints in CoE calculation, as discussed above.
- Another option, as recommended in D01, could use an automated GIS routine to select optimum tidal range sites (barrage/lagoon alignments) based on minimising environmental constraints whilst keeping within cost of energy thresholds and maximising tidal power generation.

4. Maximising power smoothing
    - In combination with the constraints imposed by other outcomes, the power smoothing could be maximised, either regionally or nationally.
    - An approach could be to add/remove schemes from the resource-cost of energy curve discussed earlier to investigate the impact on power smoothing.
    - In addition, consideration of different generation types for range could be included.
    - As per the results from the scenarios, there would need to be a combination of tidal range and tidal current schemes to optimise power smoothing.

5. Minimising impacts on the existing grid network
    - Data on the ability of the existing grid network to accept new generation and the required costs and timescales for various upgrades would be required, which is generally not simple to access.
    - With such data, the impact of any scheme on the existing grid network could be modelled.
    - Optimisation of short-term ‘buildability’ could then be undertaken in tandem with other optimisation outcomes as discussed above.

Table 6 summarises the degree to which we believe that the critical factors would affect optimisation outcomes. A high, medium or low score is provided where we believe there will be an effect and not applicable (n/a) indicates where we believe there would be no effect from the critical factor.

The results indicate that the (1) CoE outcome, along with (2) maximum energy generation, would be the outcomes most impacted by the critical factors.

Table 6 Degree to which critical factors effect optimisation outcomes

	Optimisation Outcomes				
Critical Factors	1 - CoE	2 - Max energy generation	3 – Environmental constraints	4 – Power smoothing	5 – Min impacts on existing grid network
Identify the most **energetic resource** locations available for exploitation	H	H	L	L	H
Identify limiting **technology design** constraints related to the local resource characteristics	M	H	M	L	L
Identify approximate **capital cost**	H	L	L	M	H
Identify **environmental constraints**	M/H	H	H	n/a	n/a
Identify **grid connection constraints**	M	M	n/a	M	H
Identify **construction/installation and O&M constraints**	H	M	M	n/a	L
Quantify the **energy delivered to the grid**	H	H	M	L	H
Identify optimal **generation technology characteristics**	H	H	L	H	L
Identify optimal **scheme design and interactions**	H	H	H	M	M

6 KEY FINDINGS

The procedure described in this document differs slightly from that laid out in Section 6.3.2 of D03. Changes were made for optimisation purposes. The improvements have been agreed within the project team and include:

Removal of the significant wave height constraint.
Removal of maximum extraction limit.

The DCSM has proven, as expected, to be an extremely useful tool for the analysis of tidal characteristics on the UK's continental shelf and, most importantly for this project, the energy extraction and interactions resulting from the development of schemes to harness these tidal characteristics, be they tidal range or tidal current schemes.

There are a number of clear conclusions that can be drawn from the results of the scenarios:

- That any credible tidal current development does not impact on the tidal range sites.
- That there is only a minimal impact of tidal range sites on tidal current sites, in the most extreme cases. In less extreme cases, there is essentially no impact.
- Extreme scenarios (22) suggest that the Severn Outer barrage has a significantly more severe far-field impact (on tidal current sites) in comparison with the combination of the Cardiff-Weston barrage and Bridgewater Bay lagoon.
- 'Mega' schemes with dual generation (Severn Outer, Solway Firth) do not work as intended, and effectively cannot move the water away fast enough, impeding generation.
- Noticeable benefits in using Rolls-Royce turbines in dual-mode schemes were observed for the Solway Firth, Mersey, and the Wash as there are reduced impacts on downstream tidal range than equivalent dual schemes.
- Large reduction in downstream tidal range for major barrages/lagoons in estuaries (Bridgwater Bay, Cardiff-Weston, Mersey, Thames, Wash, Humber) reduces their energy output compared to 0D modelling, as expected.
- Much less effect on downstream tidal range for lagoons on open coastlines (Rye, Dymchurch, Cumbria, Wigtown) or smaller lagoons, suggesting these may be worth further investigation.
- The increased tidal range which is visible, in particular in the Irish Sea and surroundings, when there is large scale deployment of tidal range schemes in that area, is unlikely to be acceptable in terms of environmental (and safety) impacts.
- Significant interactions (i.e. a negative effect on tidal range and potential energy) within the Severn – e.g. the Cardiff-Weston barrage reduces energy output for lagoons downstream.
- Almost no interaction between tidal range schemes in Irish Sea, despite the impacts on increased tidal range discussed earlier.
- In UK waters, large scale utilisation of the tidal resource requires significant optimisation to avoid potentially unacceptable cumulative impacts and to ensure the most energy can be extracted from the resource (potentially at least cost, with least impact on the grid etc.).

From the time series analysis, tidal range deployment around the UK is all essentially in phase if dual mode generation is used, reducing the options for power smoothing. With ebb-only generation the options for power smoothing are improved. The tidal current sites, although they are generally all in phase with each other, are out of phase with the tidal range schemes. Therefore it is possible to develop a combination of range and current schemes to contribute to power smoothing, and scenario 10 represents the best scenario investigated to date. However, although the 24 hour cycle can be 'smoothed' significantly through judicious selection of the combination of tidal range and tidal current sites, the spring-neap cycle of course cannot be 'smoothed' in the same way and the maximum power at spring tide is still c. 2-3 times that available at neap tide. The only way that this spring-neap factor could be reduced would be to reduce the installed capacities of the schemes so that the capacity factor would naturally increase.

10 critical factors for optimising tidal power systems have been identified and 5 optimisation outcomes have been identified. Optimisation of a tidal power project could be driven by a number of outcomes, singly or in combination. We believe the best single optimisation would be based on maximising energy generation within CoE thresholds/constraints as it would ultimately be possible to incorporate all critical factors (and other optimisation outcomes) as a relative cost. Alternatively, it is

possible, that optimisation could focus on maximum power generation unconstrained by CoE thresholds/constraints, minimising environmental impacts, maximising power smoothing or minimising impacts on the available grid network.

7 CONCLUSIONS AND RECOMMENDATIONS

The aim of the TRM scope of work is to address the following fundamental questions:

1. How will the impacts of tidal range and tidal current energy schemes positioned around the UK combine to form an overall effect?
    - The 30 scenarios that have been run and are summarised in this report provide a good representation of possible tidal deployments through to 2050. From these scenarios, we have summarised the implications on the overall near-field and far-field effects.
    - In general, the extraction of tidal current energy has been shown to have a severe near-field effect when extraction is unlimited and therefore extraction requires close management of the resource both within and between nearby projects to ensure that the resource is not over exploited (which could potentially cause detrimental economic and environmental effects). However, there is no far-field effect that impacts any tidal range locations (as specified in this report).
    - The extraction of tidal range energy in UK waters has been shown to have wide-scale and significant effects in the extreme cases. The combination of all schemes on the west coast causes tidal range changes which we believe would be unacceptable.

Therefore, optimisation for environmental/human impact, energy output, economics or power smoothing is needed if the overall tidal resource is to be exploited to its full potential.

2. Will the extraction of tidal energy resources in one area affect the tidal energy resources at distant sites around the UK and Europe?
    - The results of the scenario runs completed using the DCSM give the most in-depth and accurate assessment of energy output from a combination of UK schemes to date.
    - Table 5 which provides indicative % change for each scheme in each scenario, shows clearly where there is an impact of a following scheme. It is important to note that, as described in the scenario observations, some schemes which are incorporated into the scenarios later on have a low energy output due to the preceding schemes and therefore the change in energy due to other schemes is larger in real terms.
    - The CSM scenario run outputs give a clear indication as to the impact at far-field UK sites.
    - The impacts across Europe vary depending on the scenario but Scenario 16, which is the most extreme case of both tidal range and tidal current deployment, shows that there would be an impact on the European coastline.

3. What constraints might these interactions place on the design, development and location of future systems?
    - The information in this report is important and useful information that should be provided to all key decision makers with regards to tidal development, including UK and Scottish Governments, and The Crown Estate. The data and information should be used to inform and educate the process to ensure that the development of the UK’s tidal resource is optimised. Clearly, further work is needed (beyond these scenarios already investigated) to support such optimisation.
    - The interactions within and between schemes developed in this report shows that the level of tidal range deployment (for near-field and far-field effects) and tidal current deployment (mainly near-field to regional impacts) would place constraints on the schemes. Both effects could potentially impact the success of projects. Importantly, the

installation of later schemes could have an impact (positive or negative) on an existing scheme or its effects.

- The operating regime at specific sites and overall scheme optimisation could be further developed using the DSCM tool, both at a ‘macro’ level in terms of optimising the development of the UK resource and in terms of specific site considerations.
- The DCSM is a pre-feasibility tool (D01 3.2.4 refers to ‘a feasibility study, which is beyond the scope of the CSM development). The CSM therefore provides the ETI with a UK scale tool for assessing likely interactions between schemes. For detailed site specific investigations further more detailed analysis is required.
- The interactions are likely to place constraints about where and how much energy should be extracted and it is important that the industry is informed. The scenarios in this report provide a very clear indication as to the likely level of impacts in particular locations in reasonable and extreme cases, but this should be investigated further to ensure that the development of the UK resource is optimised.
- Project development for a tidal energy schemes involves consenting, and for tidal range schemes this will require longer and more in-depth analysis as the environmental effects are known to be larger than those predicted for tidal current schemes. The consenting process could be extended as a result of the interaction effects (e.g. to research further significant changes to an intertidal habitat of an estuary subject to several schemes being consented).

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From the initial scenario runs completed, it is clear that there is a vast amount of research and development into tidal site selection that could be carried out using the DCSM and, with the incorporation of other data, to optimise the UK resource as a whole (as well as individual schemes).

The scenarios presented provide a broad and indicative impression of the potential interactions across the UK continental shelf, from minor deployments to extreme development. The incorporation of extreme scenarios allowed us to present the most extreme interaction effects. We do not believe that these scenarios necessarily represent realistic development, but provide useful to data to allow understanding of the limits of deployment, which is essential.

Moving forward, we would recommend that future scenarios (e.g. those to be put forward by ETI for the remaining 12 scenarios in the current scope of work) consider more realistic levels of energy extraction. After that, although some other extreme cases might be of interest, the best value can probably be obtained from commencing work on investigating optimisation of the UK resource as a whole as discussed in Section 5.2.

8 FIGURES

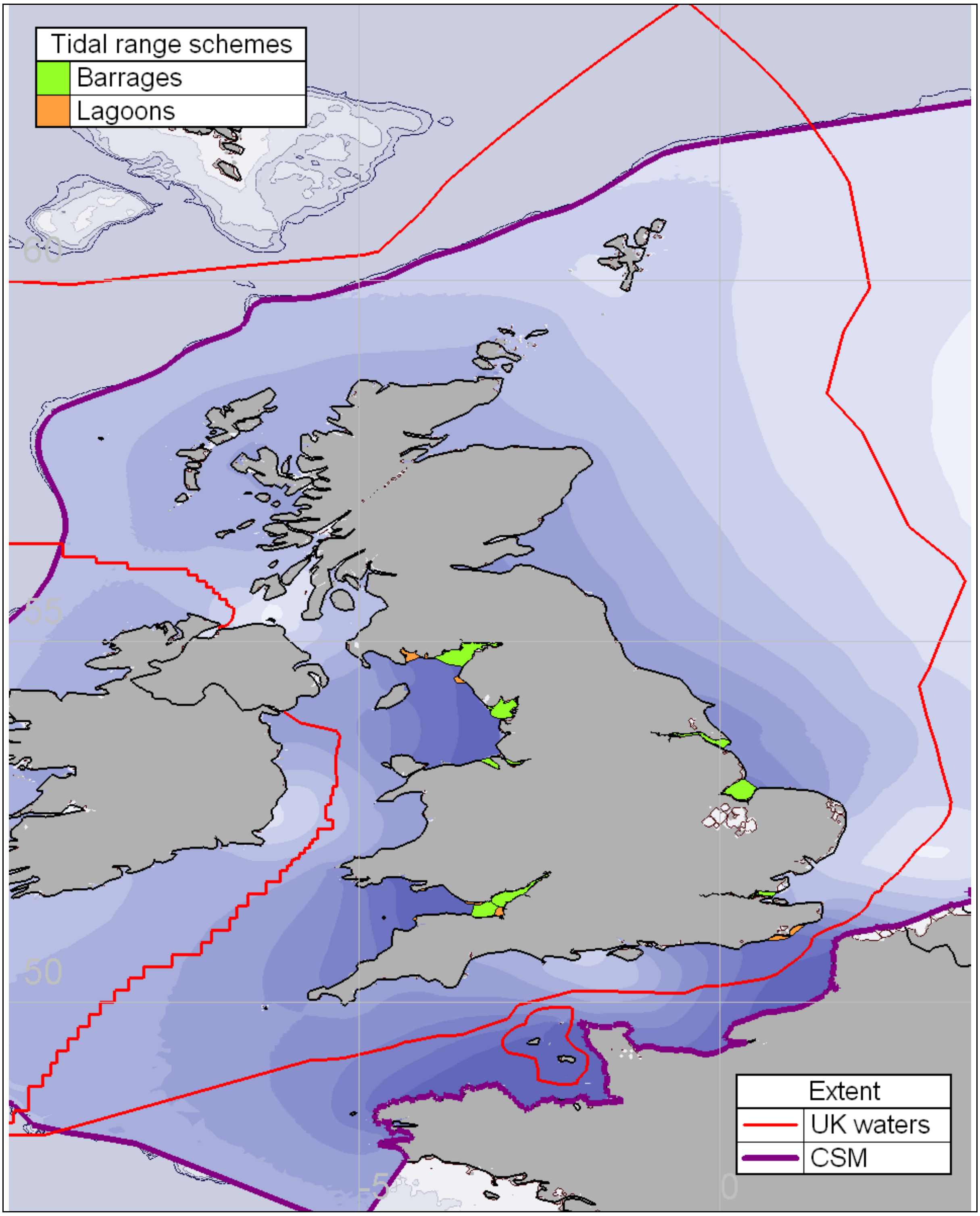

Figure 8 Tidal range locations included in the CSM scenario modelling

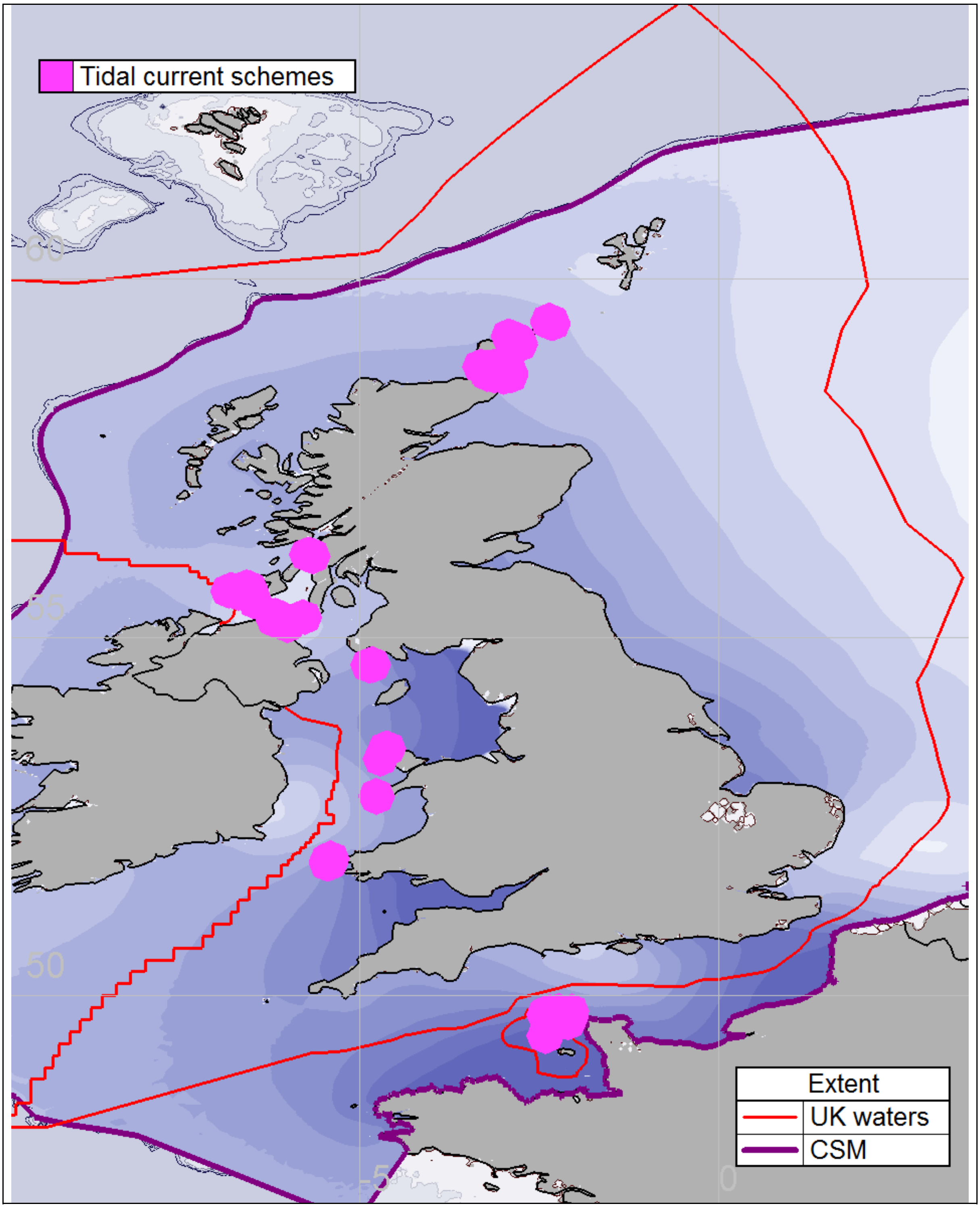

Figure 9 Tidal current locations identified in the CSM scenario modelling

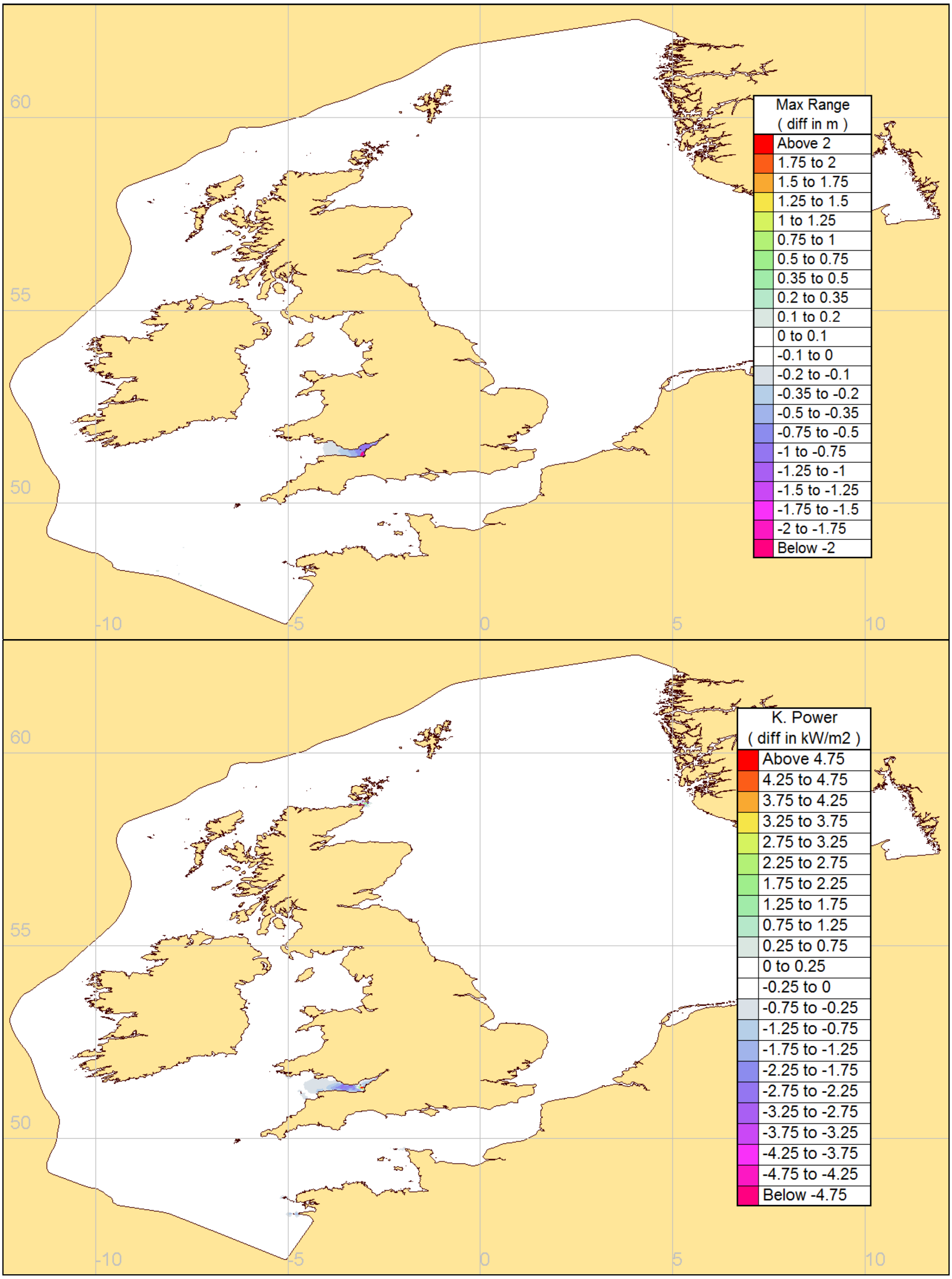

Figure 10 Outcome of the CSM scenario modelling, Scenario 2

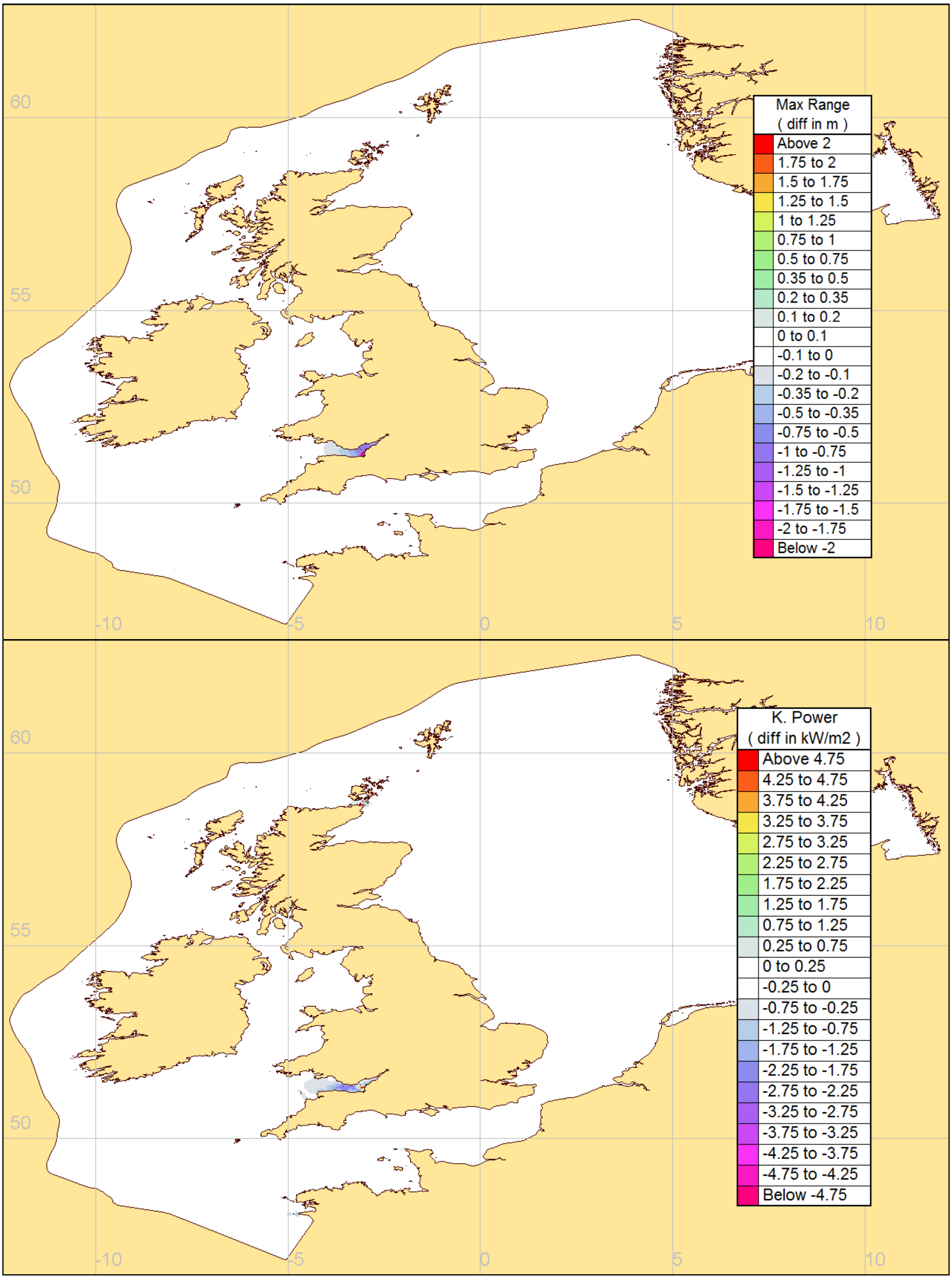

Figure 11 Outcome of the CSM scenario modelling, Scenario 3

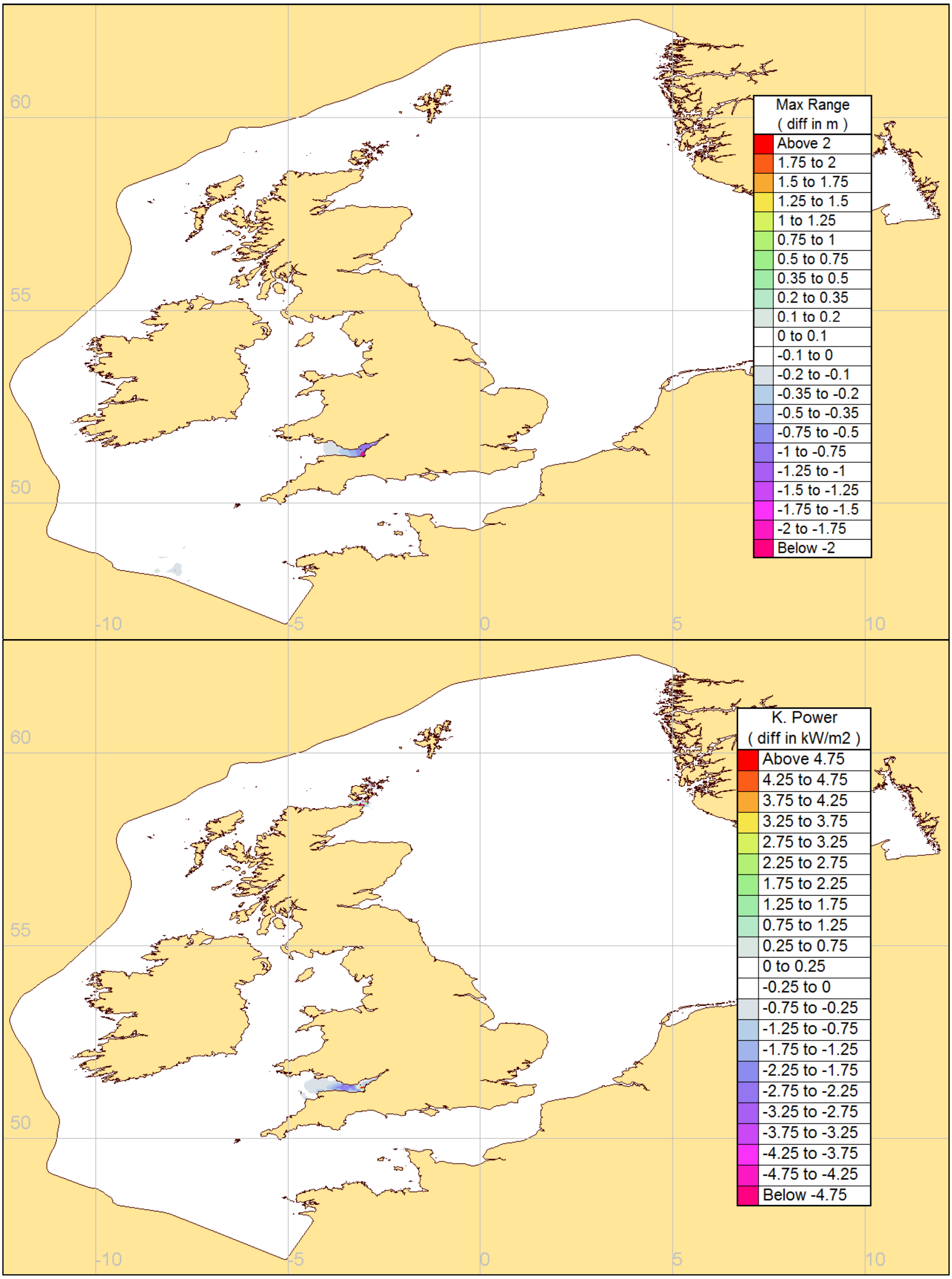

Figure 12 Outcome of the CSM scenario modelling, Scenario 4

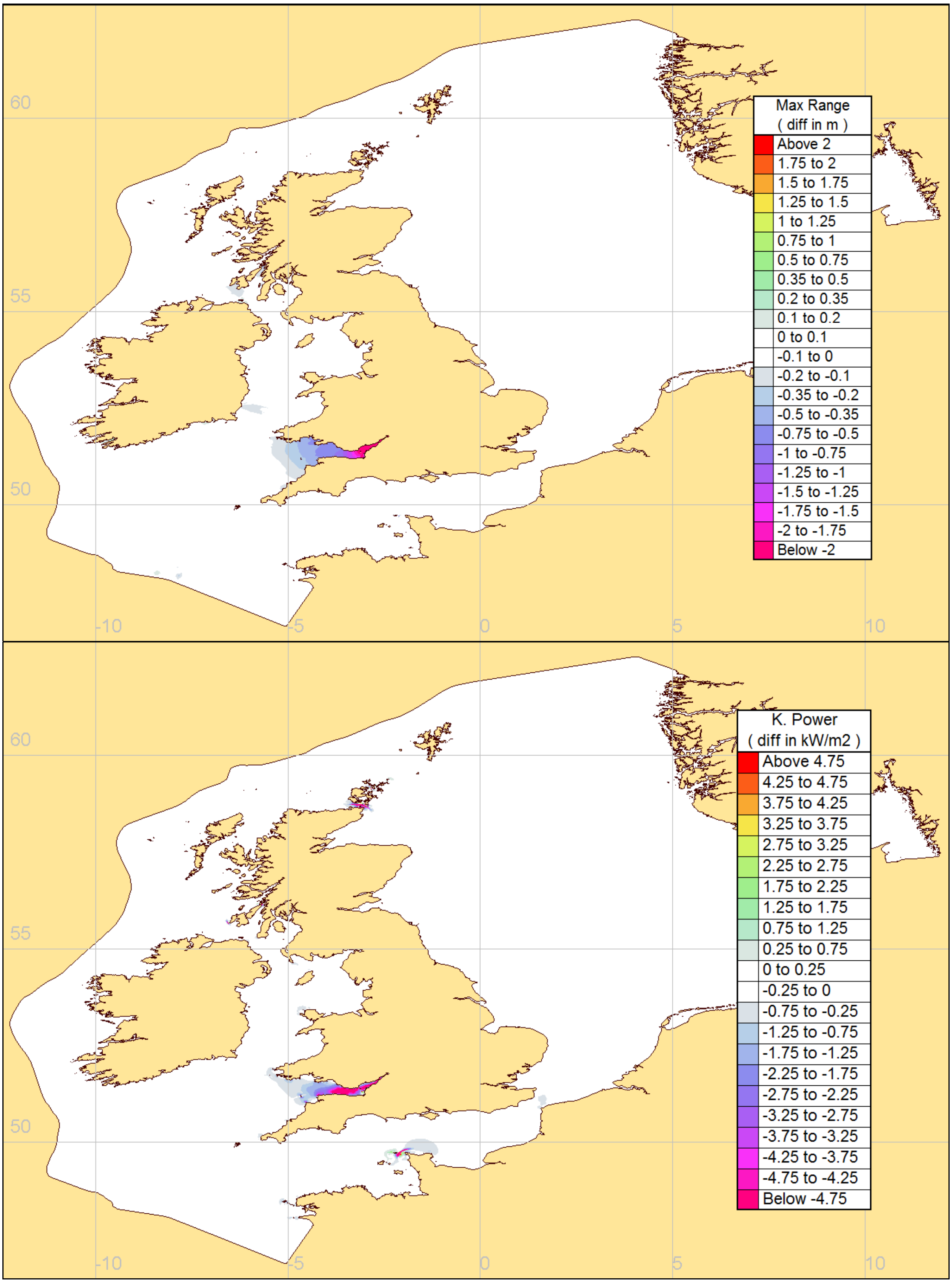

Figure 13 Outcome of the CSM scenario modelling, Scenario 5

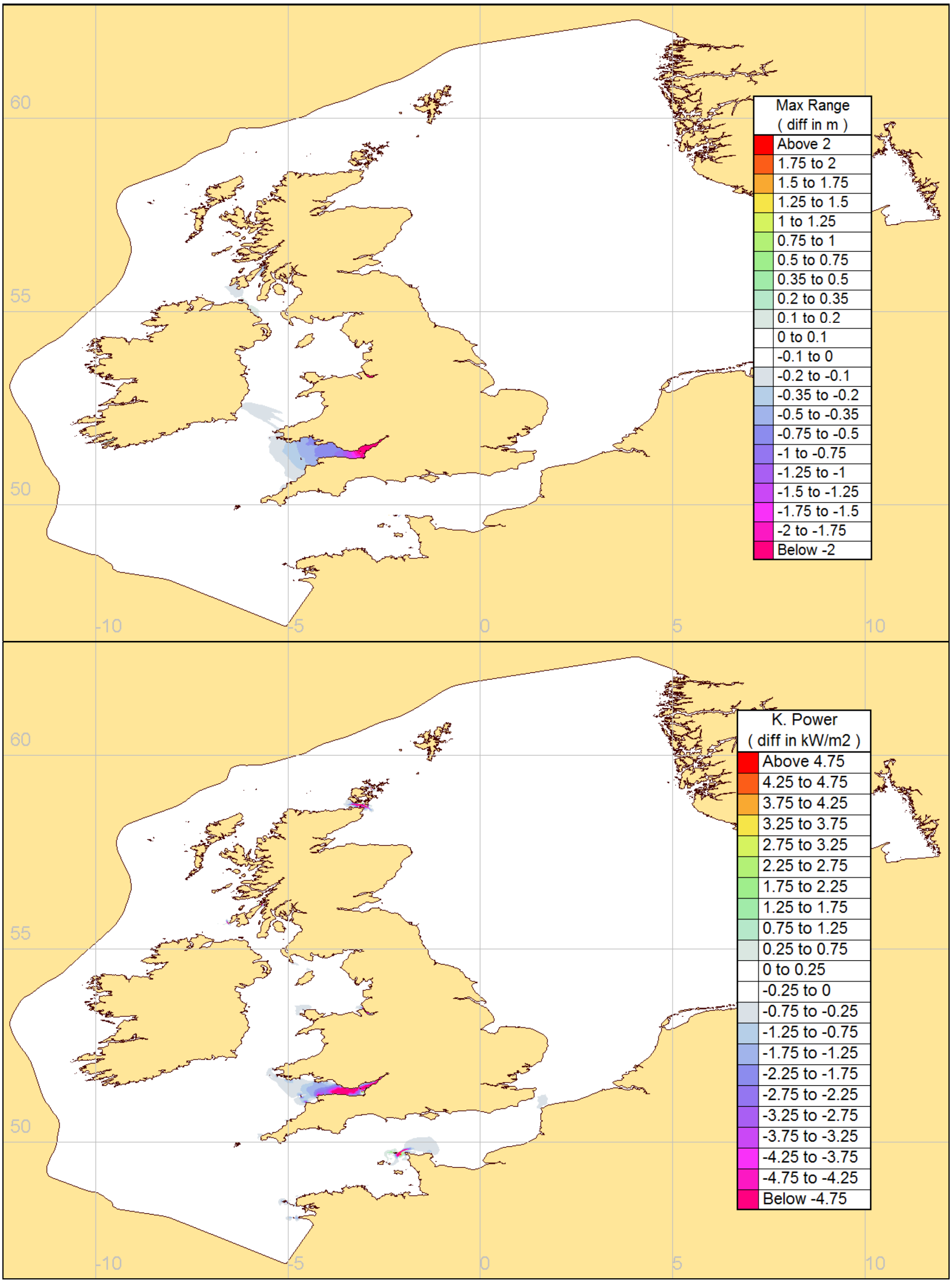

Figure 14 Outcome of the CSM scenario modelling, Scenario 6

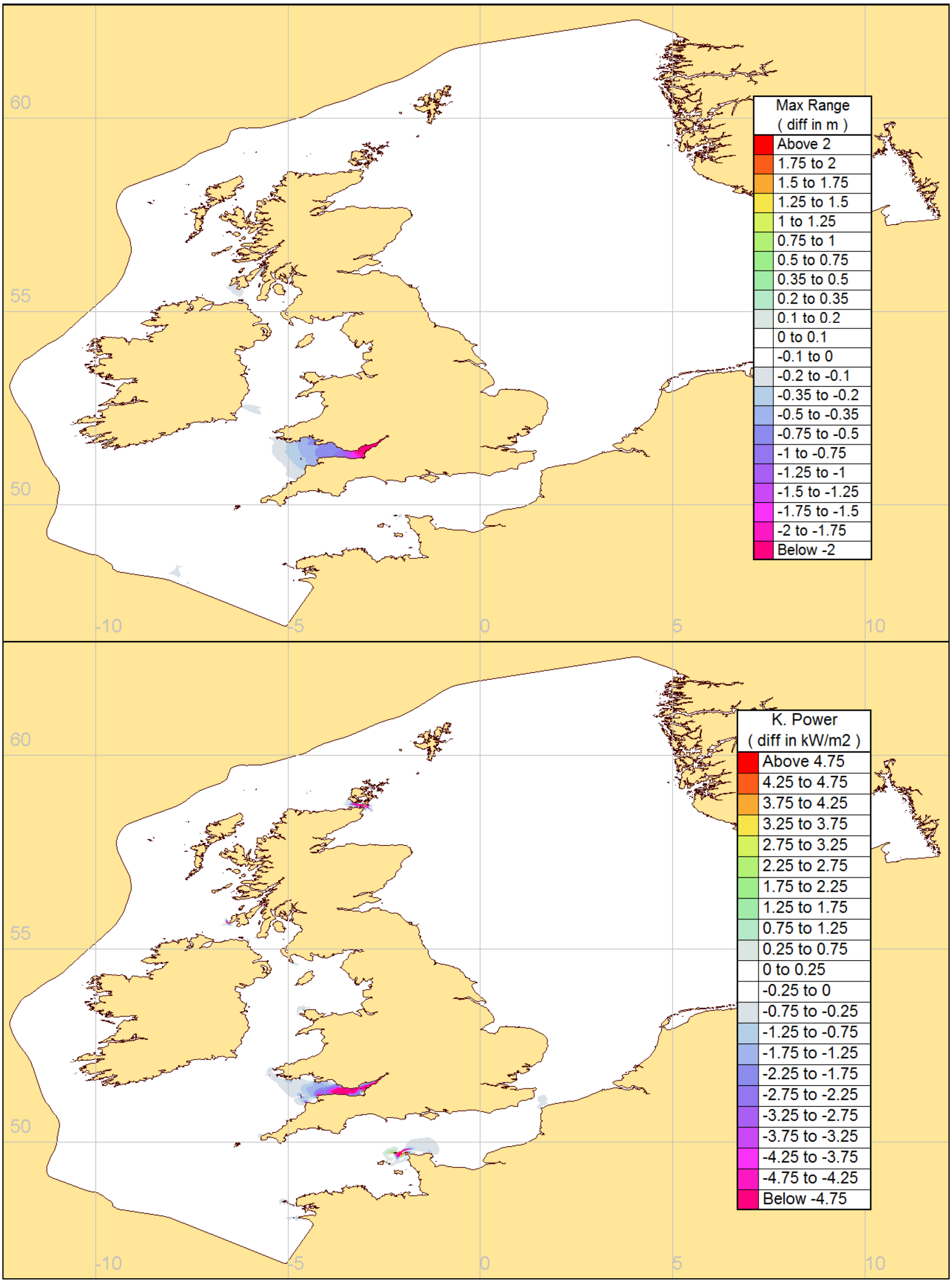

Figure 15 Outcome of the CSM scenario modelling, Scenario 7

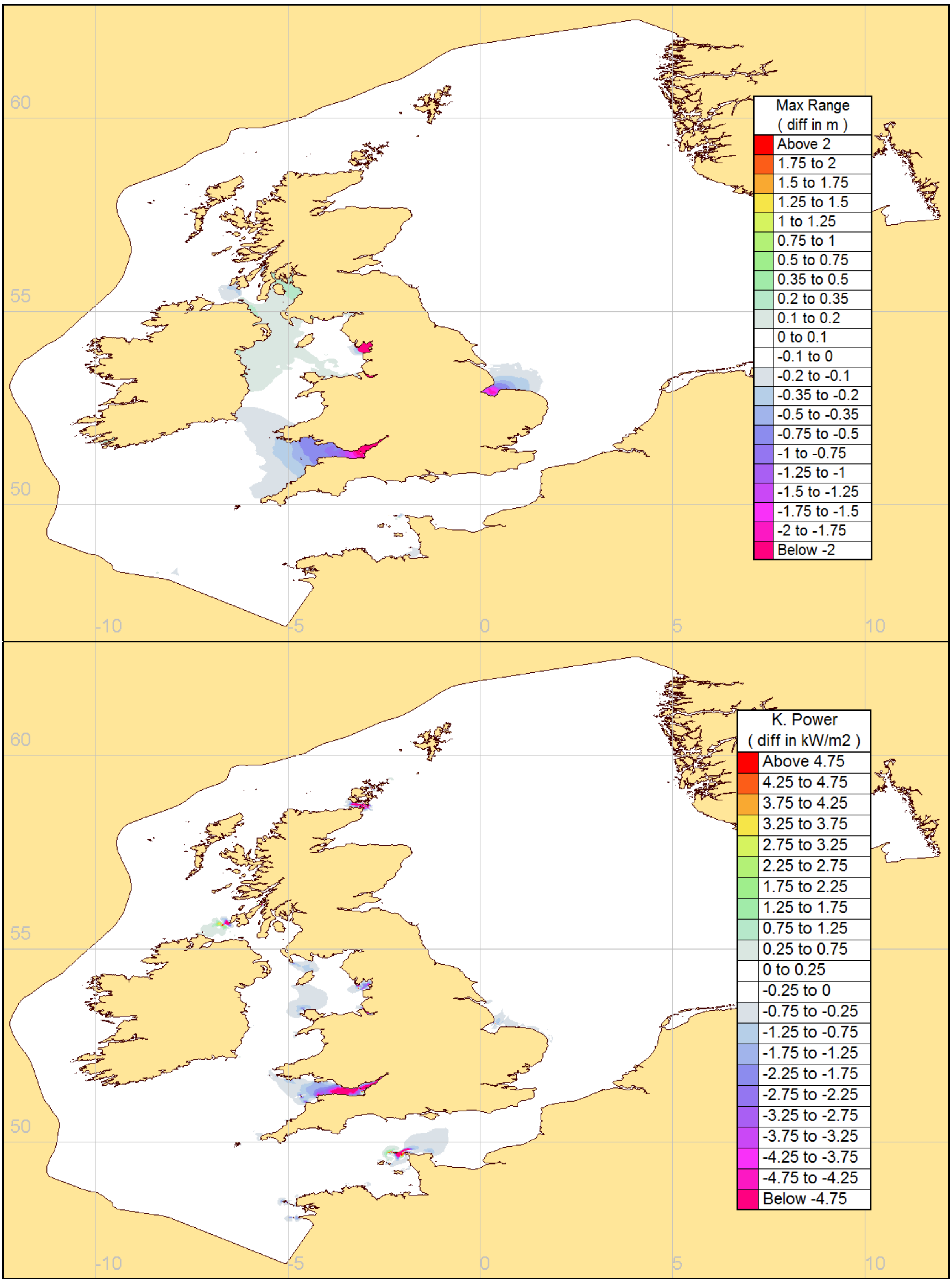

Figure 16 Outcome of the CSM scenario modelling, Scenario 8

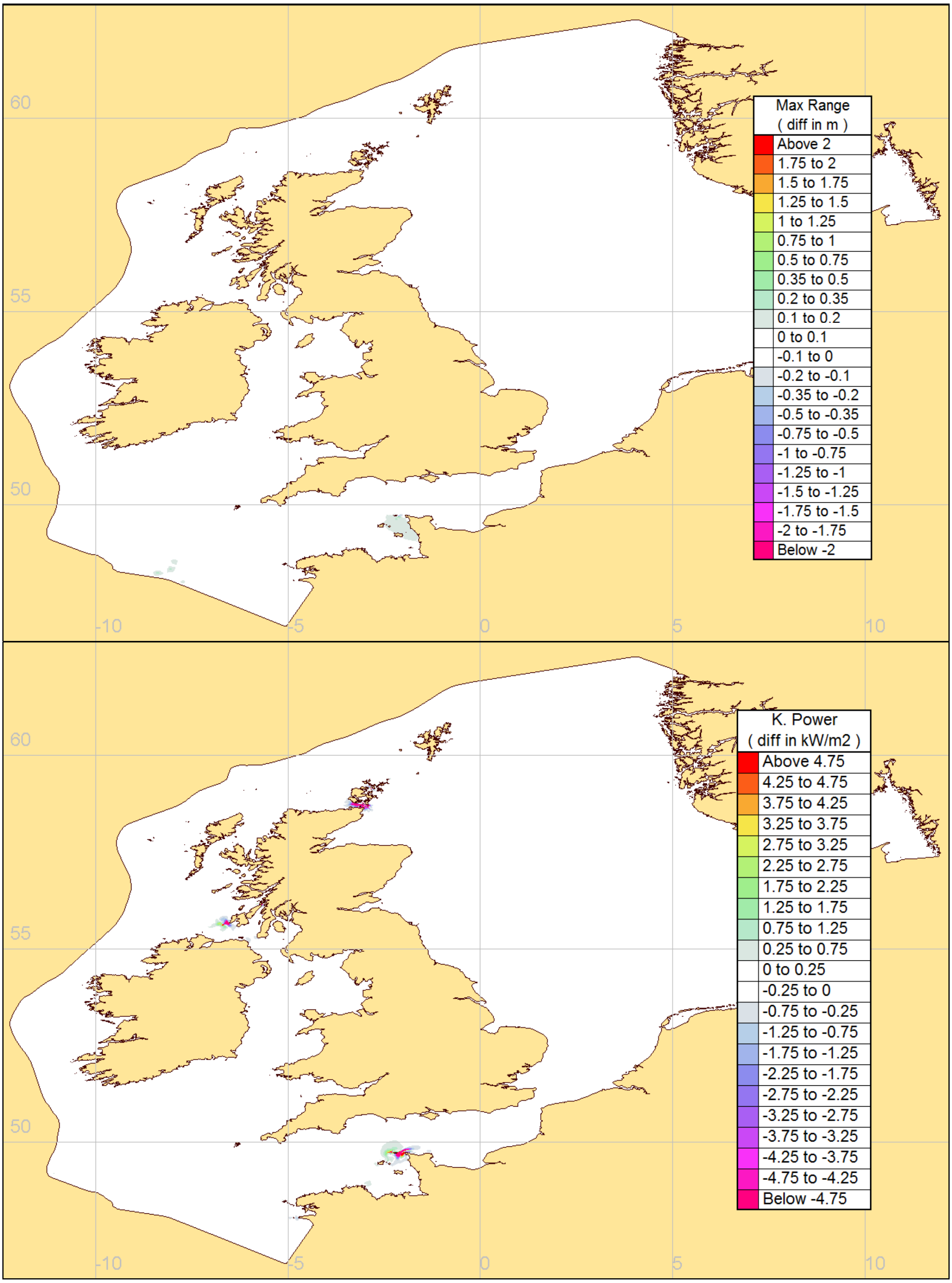

Figure 17 Outcome of the CSM scenario modelling, Scenario 9

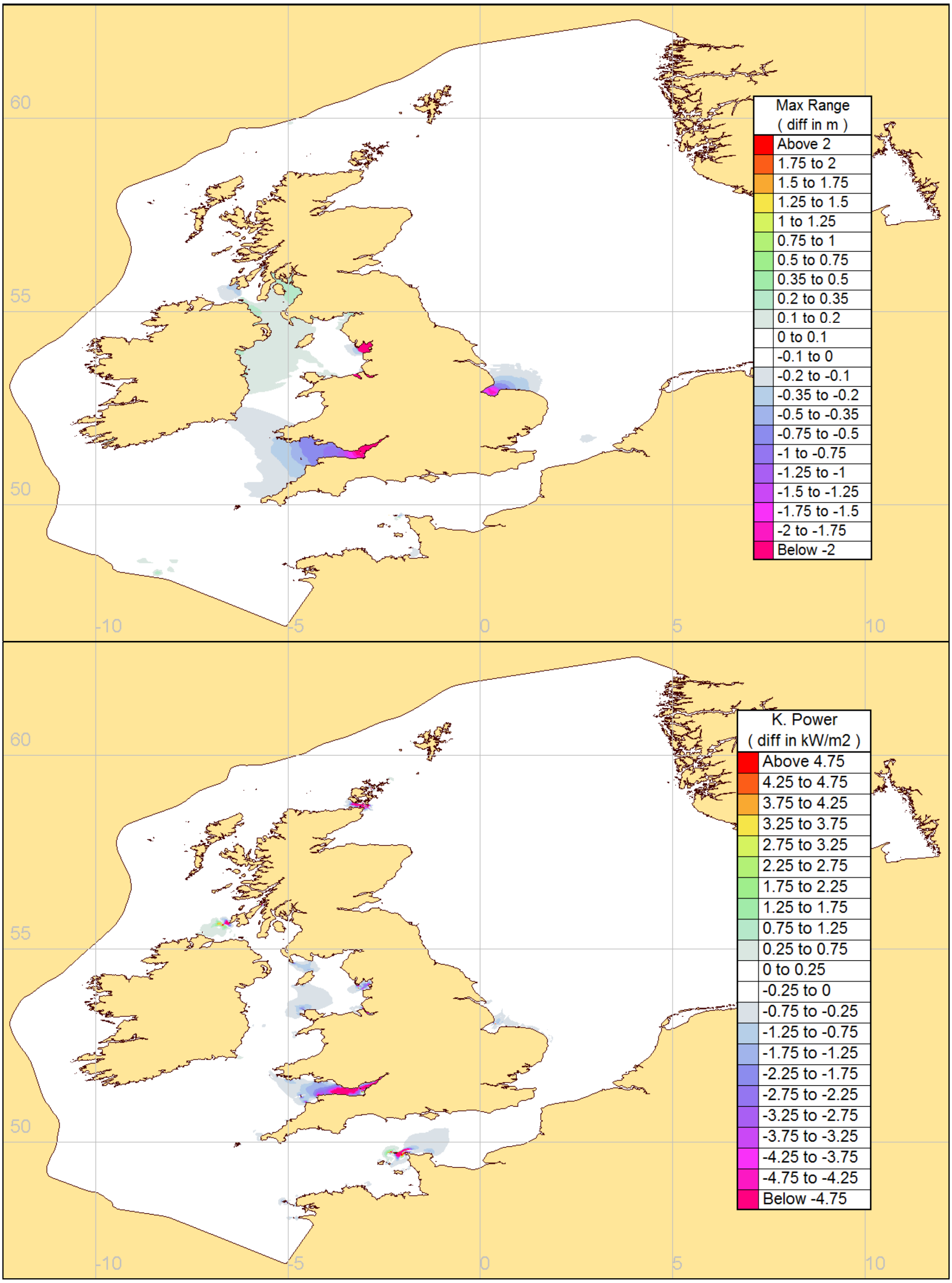

Figure 18 Outcome of the CSM scenario modelling, Scenario 10

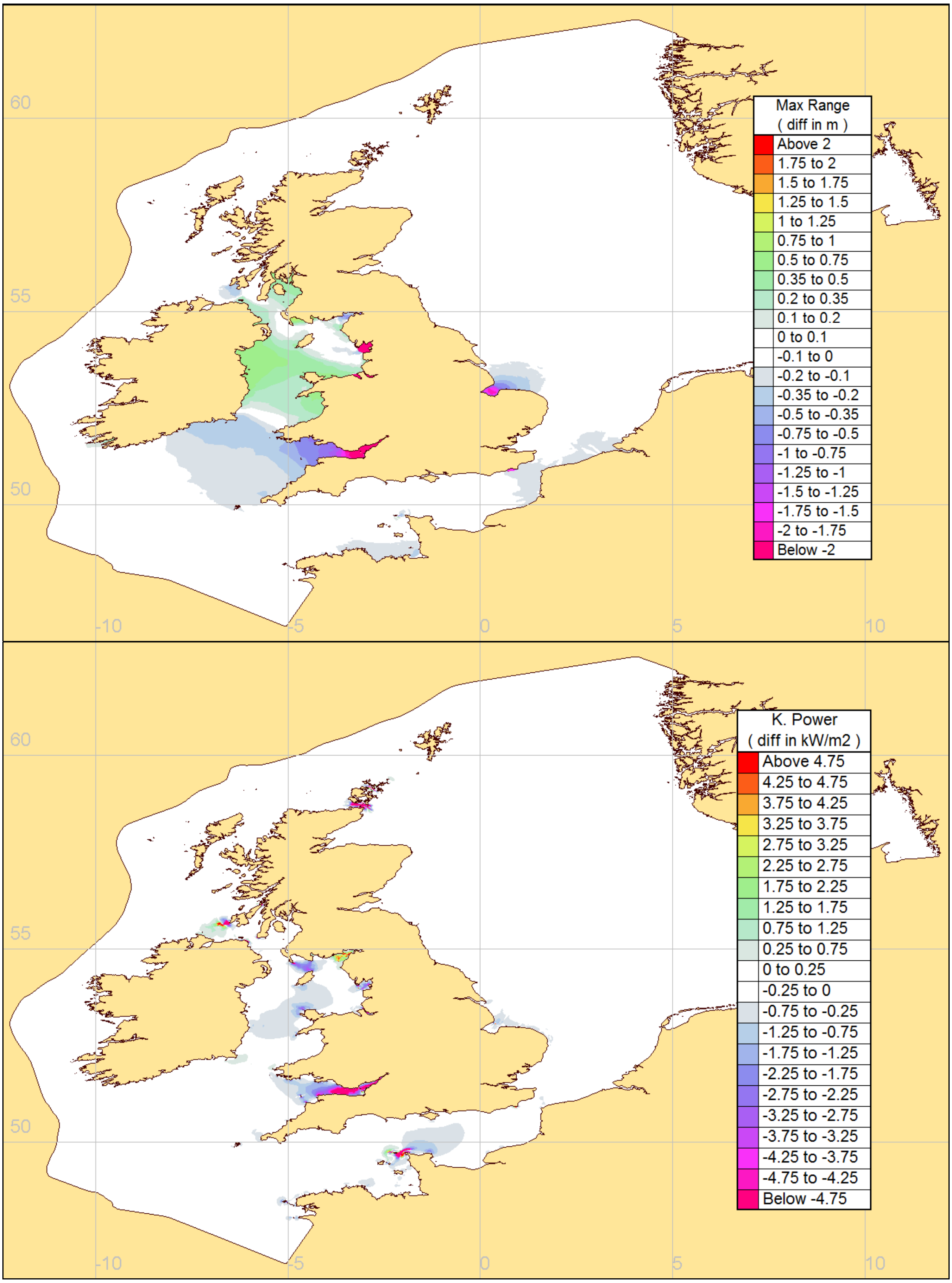

Figure 19 Outcome of the CSM scenario modelling, Scenario 11

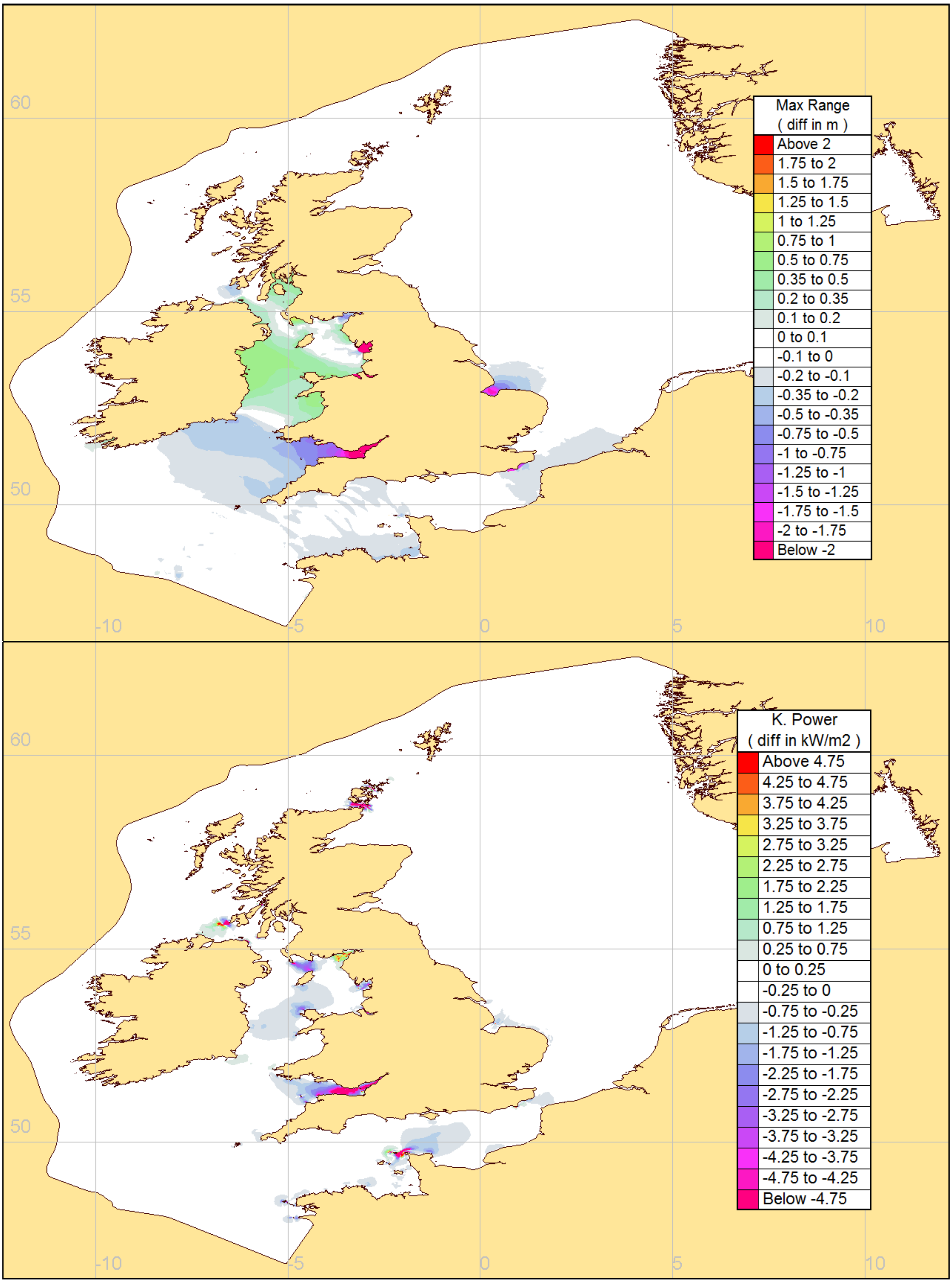

Figure 20 Outcome of the CSM scenario modelling, Scenario 12

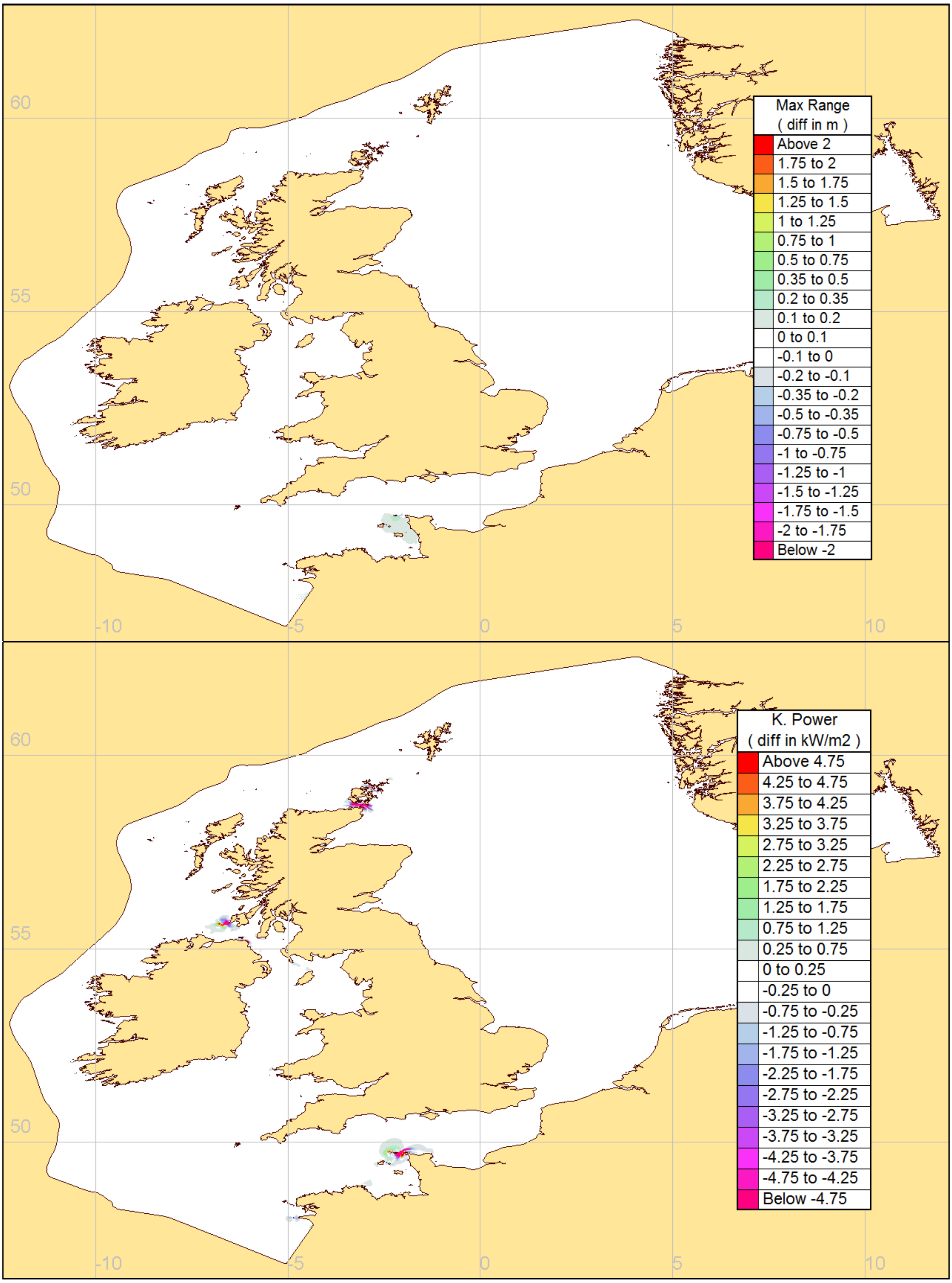

Figure 21 Outcome of the CSM scenario modelling, Scenario 13

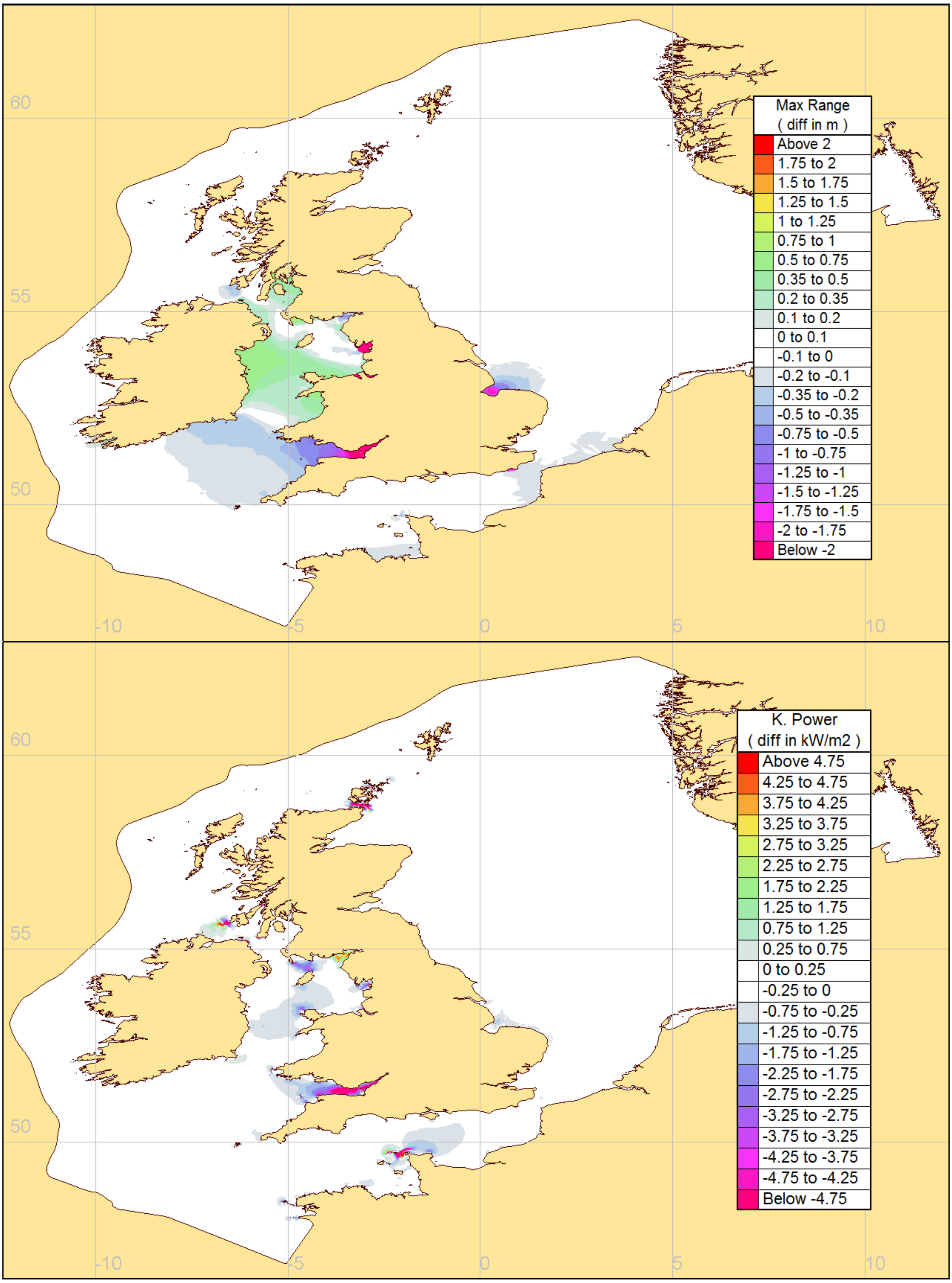

Figure 22 Outcome of the CSM scenario modelling, Scenario 14

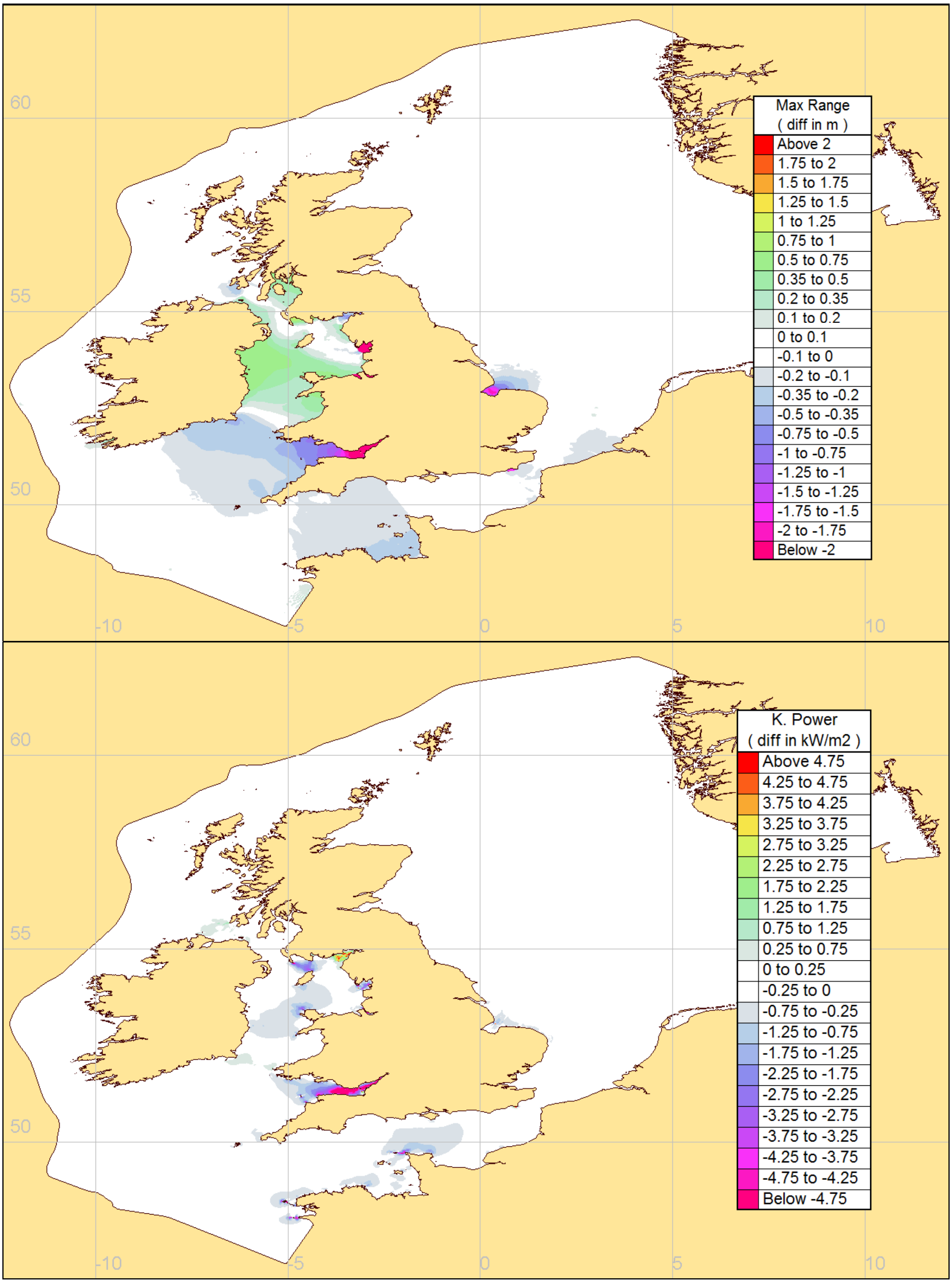

Figure 23 Outcome of the CSM scenario modelling, Scenario 15

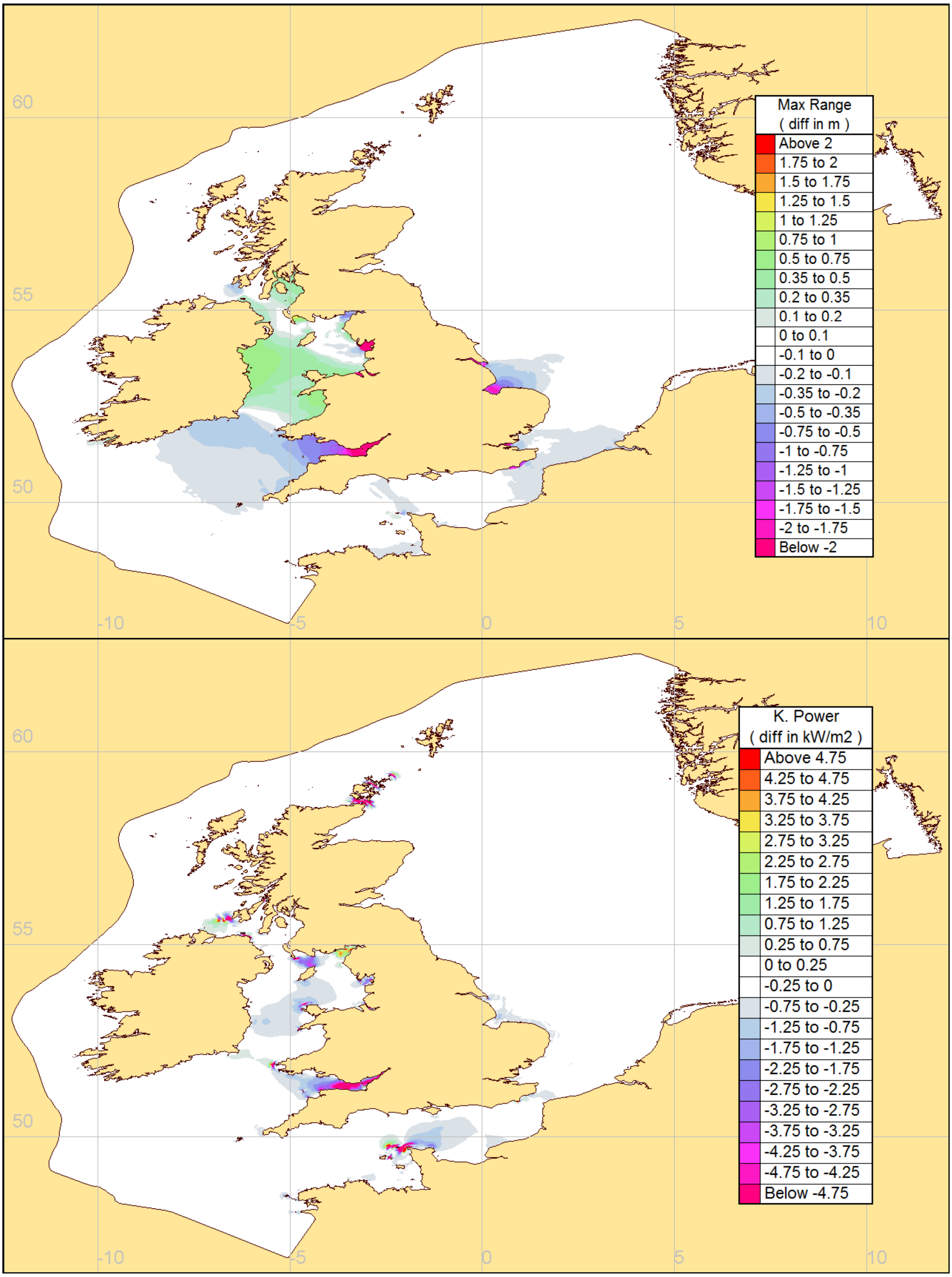

Figure 24 Outcome of the CSM scenario modelling, Scenario 16

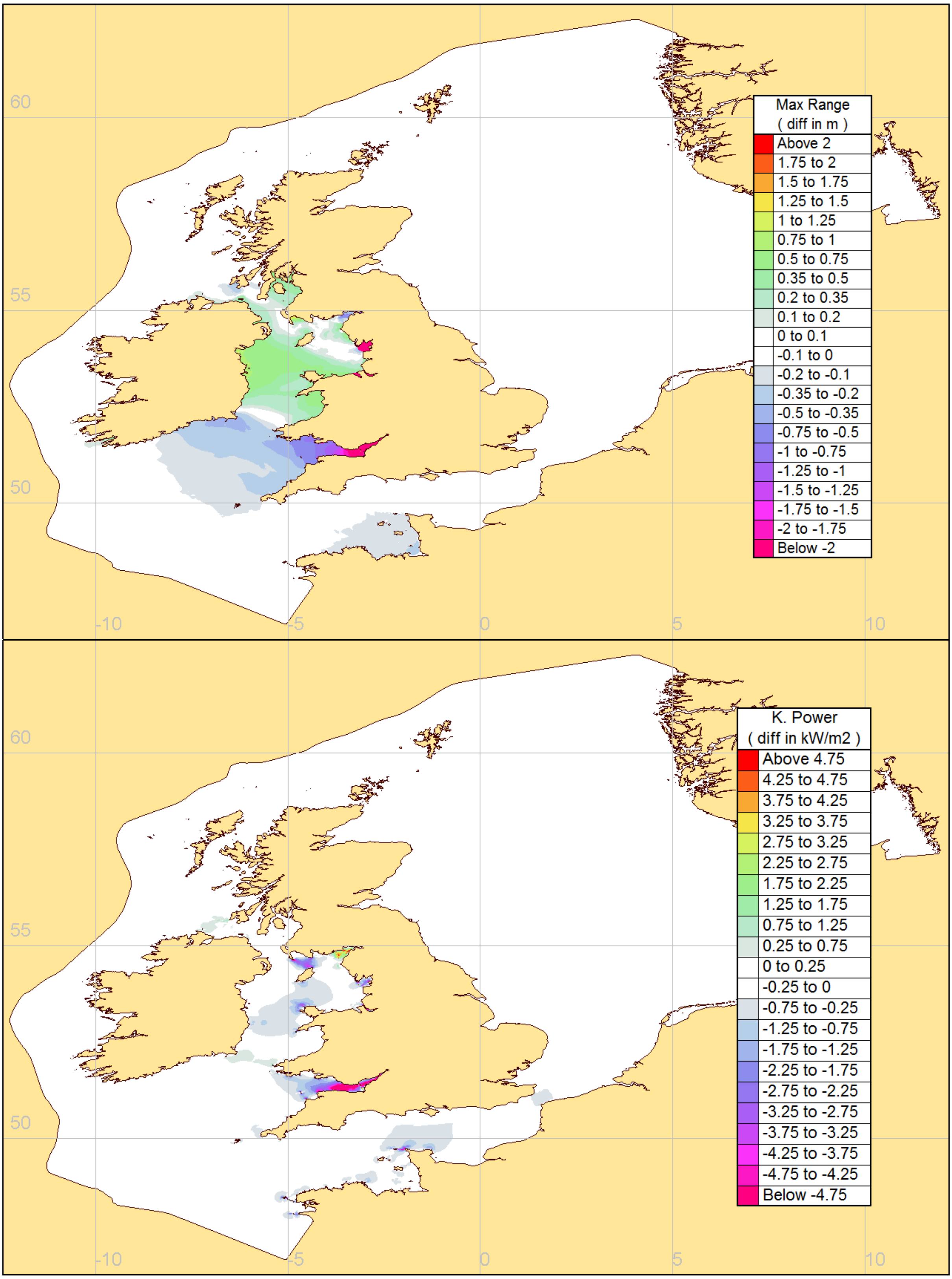

Figure 25 Outcome of the CSM scenario modelling, Scenario 19

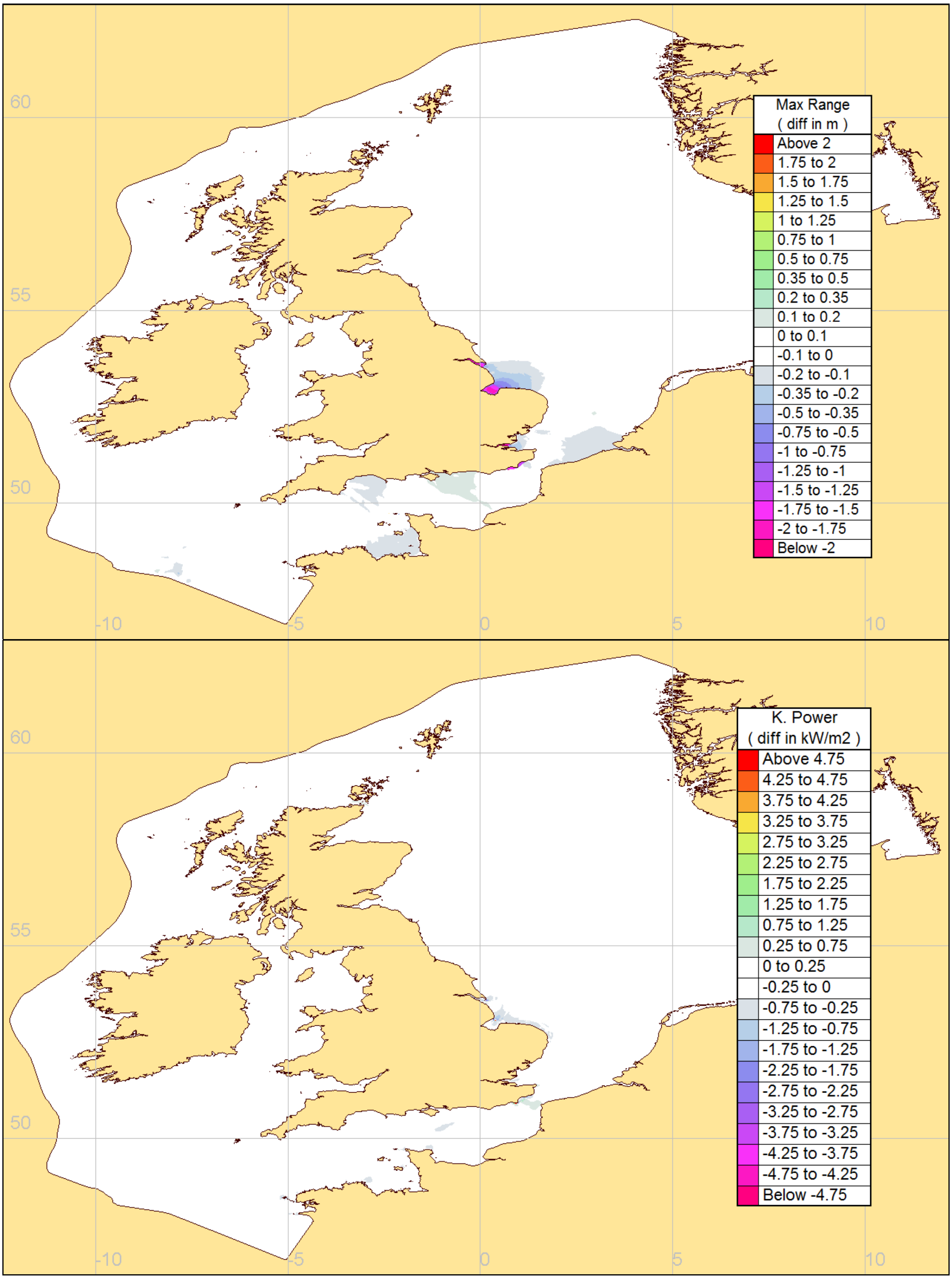

Figure 26 Outcome of the CSM scenario modelling, Scenario 20

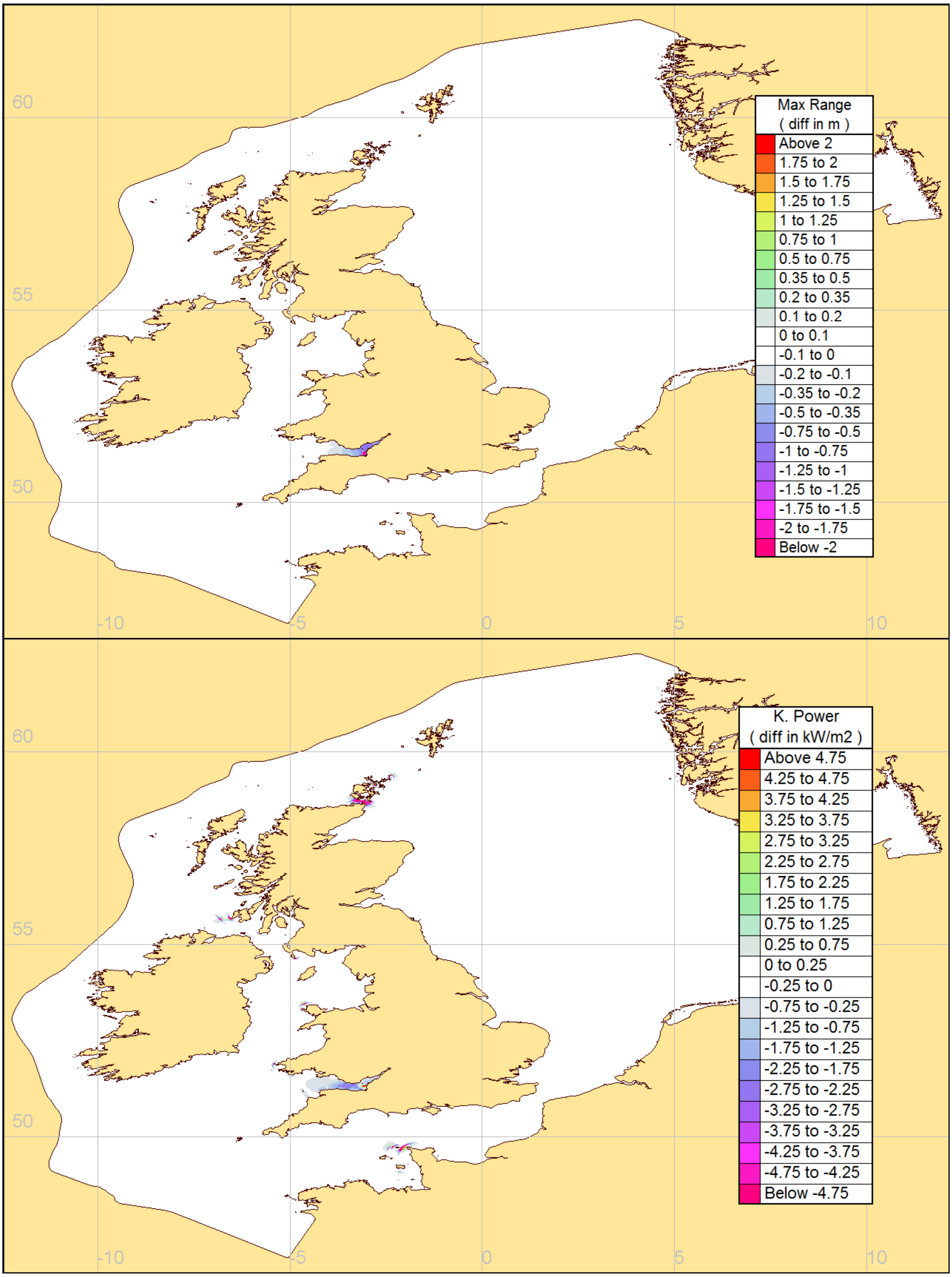

Figure 27 Outcome of the CSM scenario modelling, Scenario 21

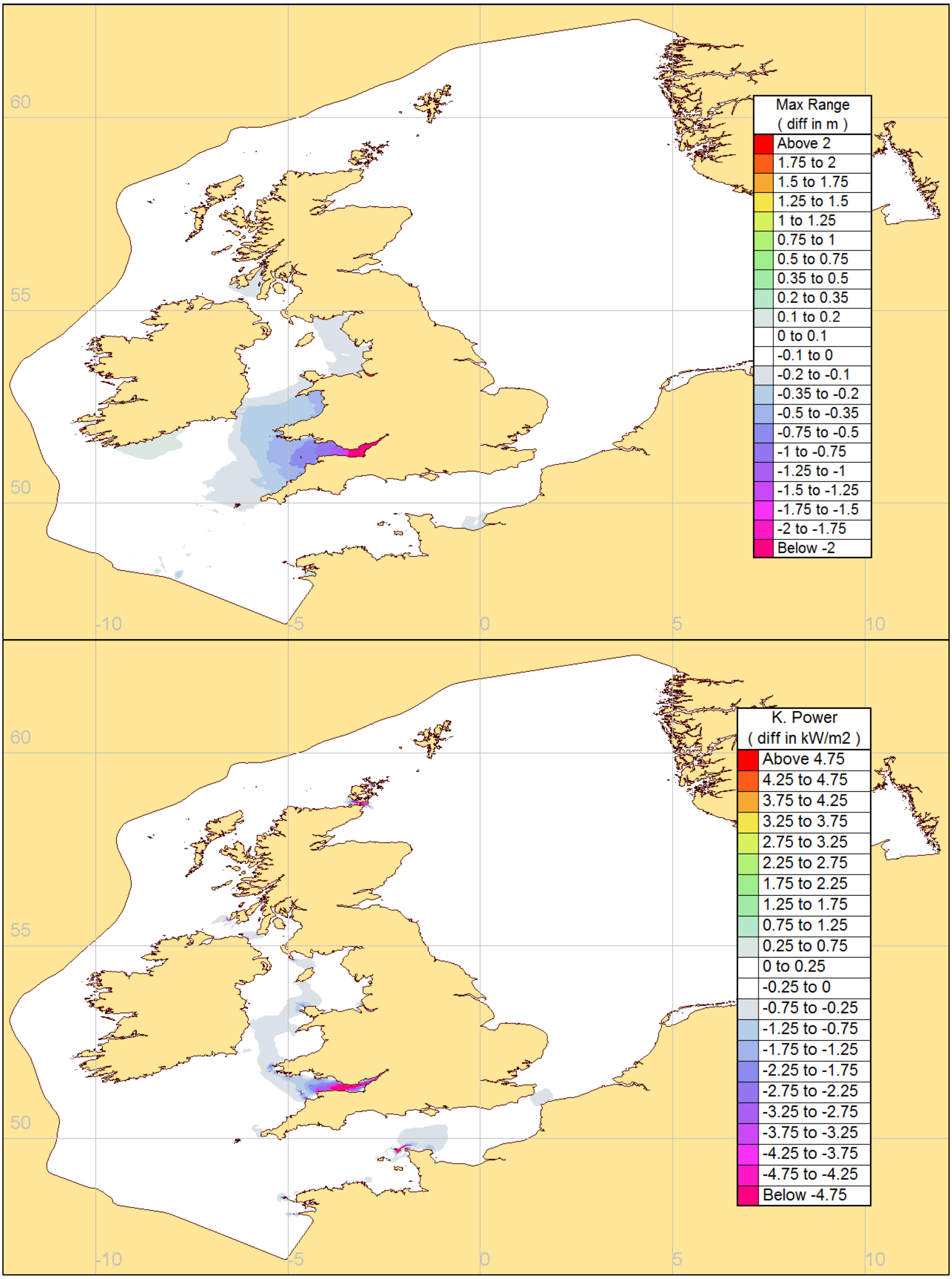

Figure 28 Outcome of the CSM scenario modelling, Scenario 22

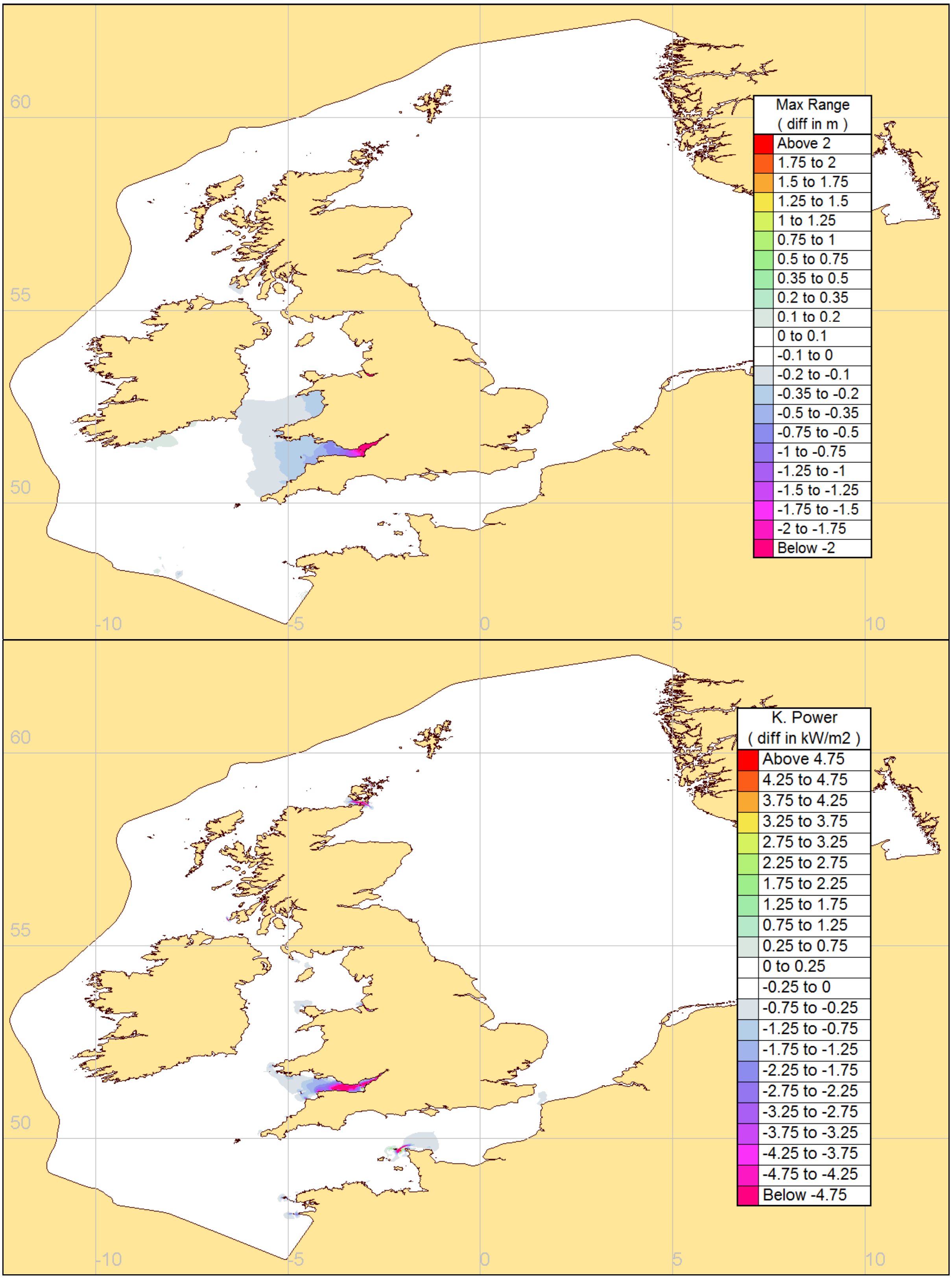

Figure 29 Outcome of the CSM scenario modelling, Scenario 23

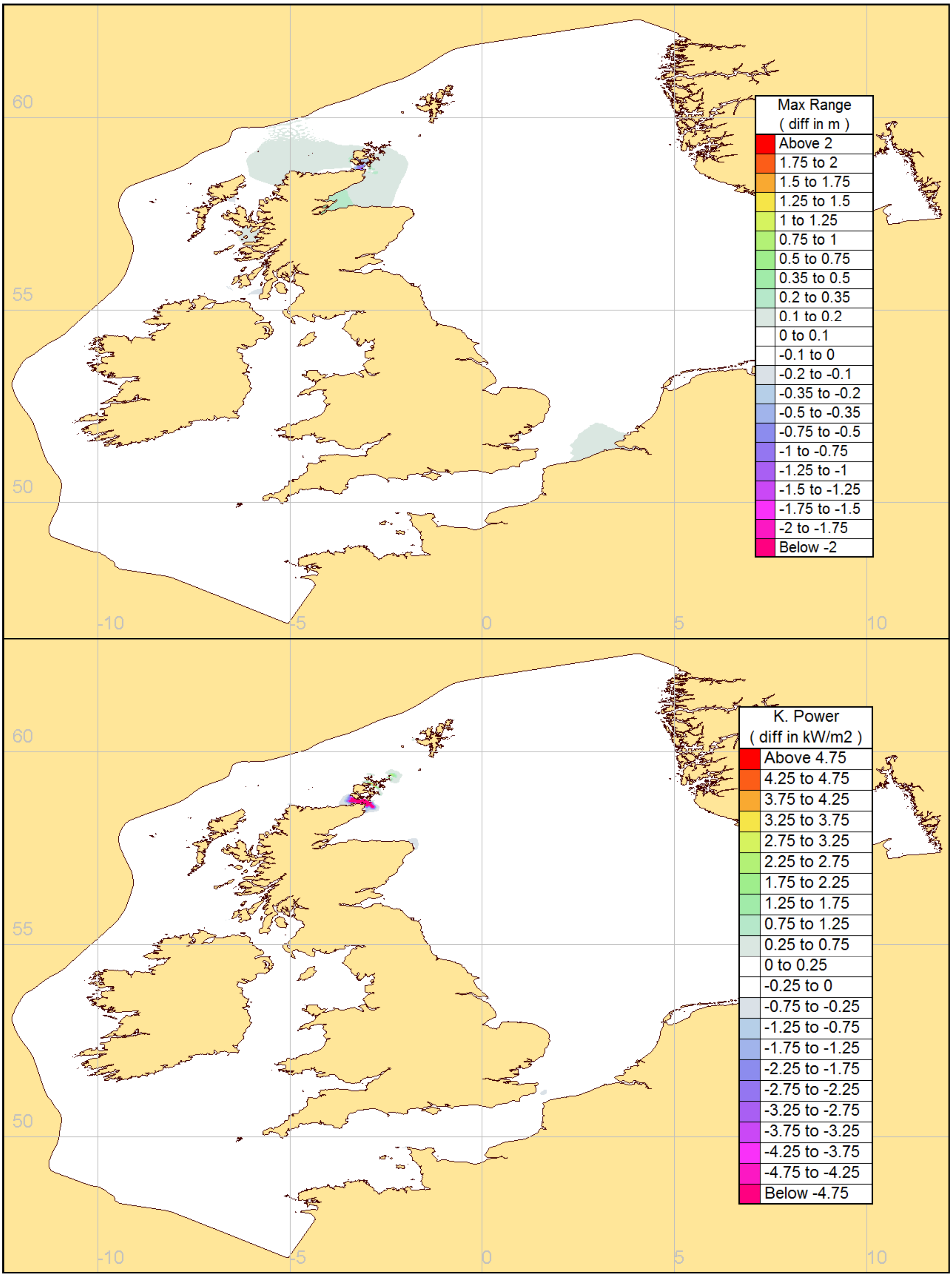

Figure 30 Outcome of the CSM scenario modelling, Scenario 24

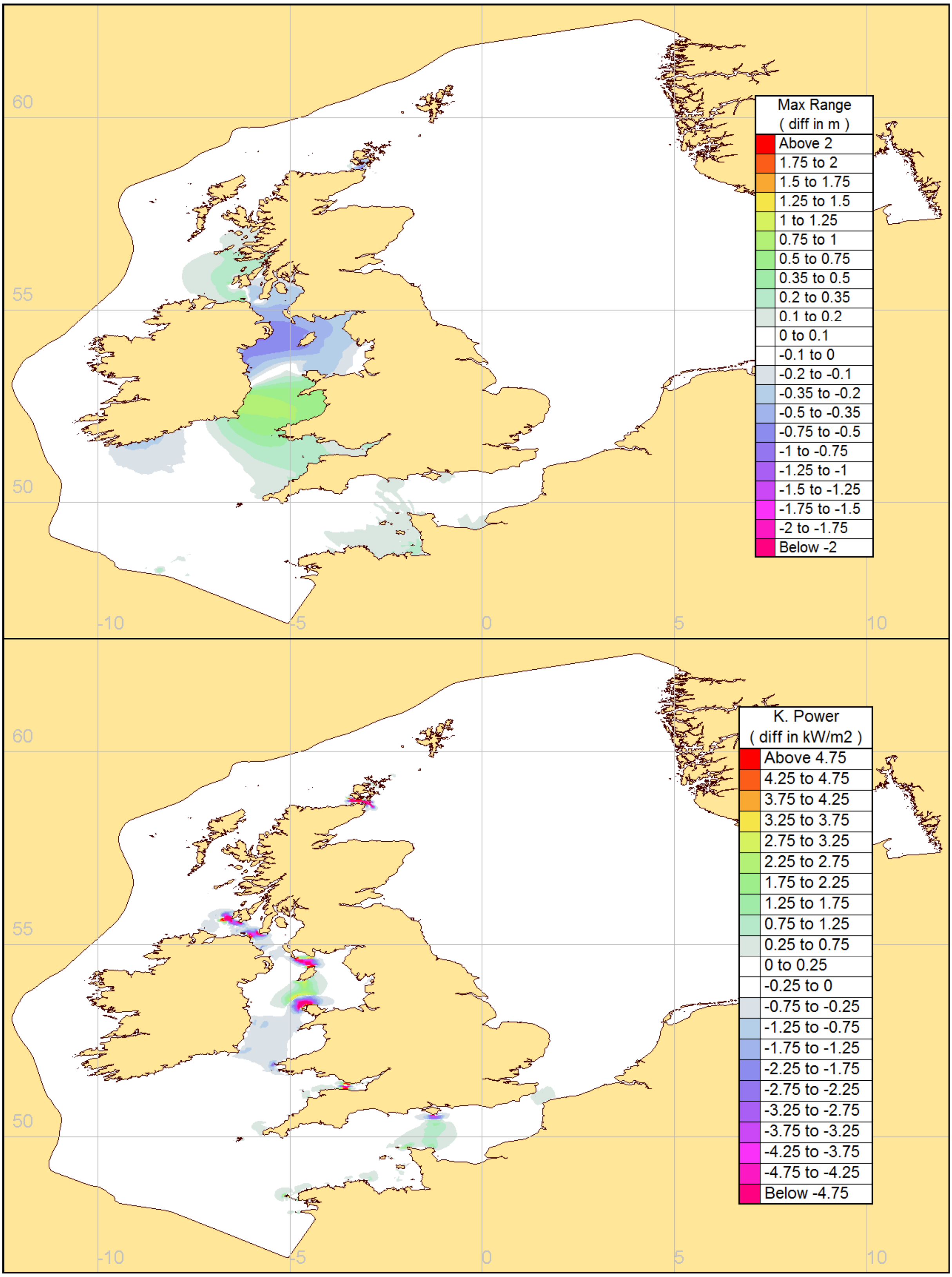

Figure 31 Outcome of the CSM scenario modelling, Scenario 25

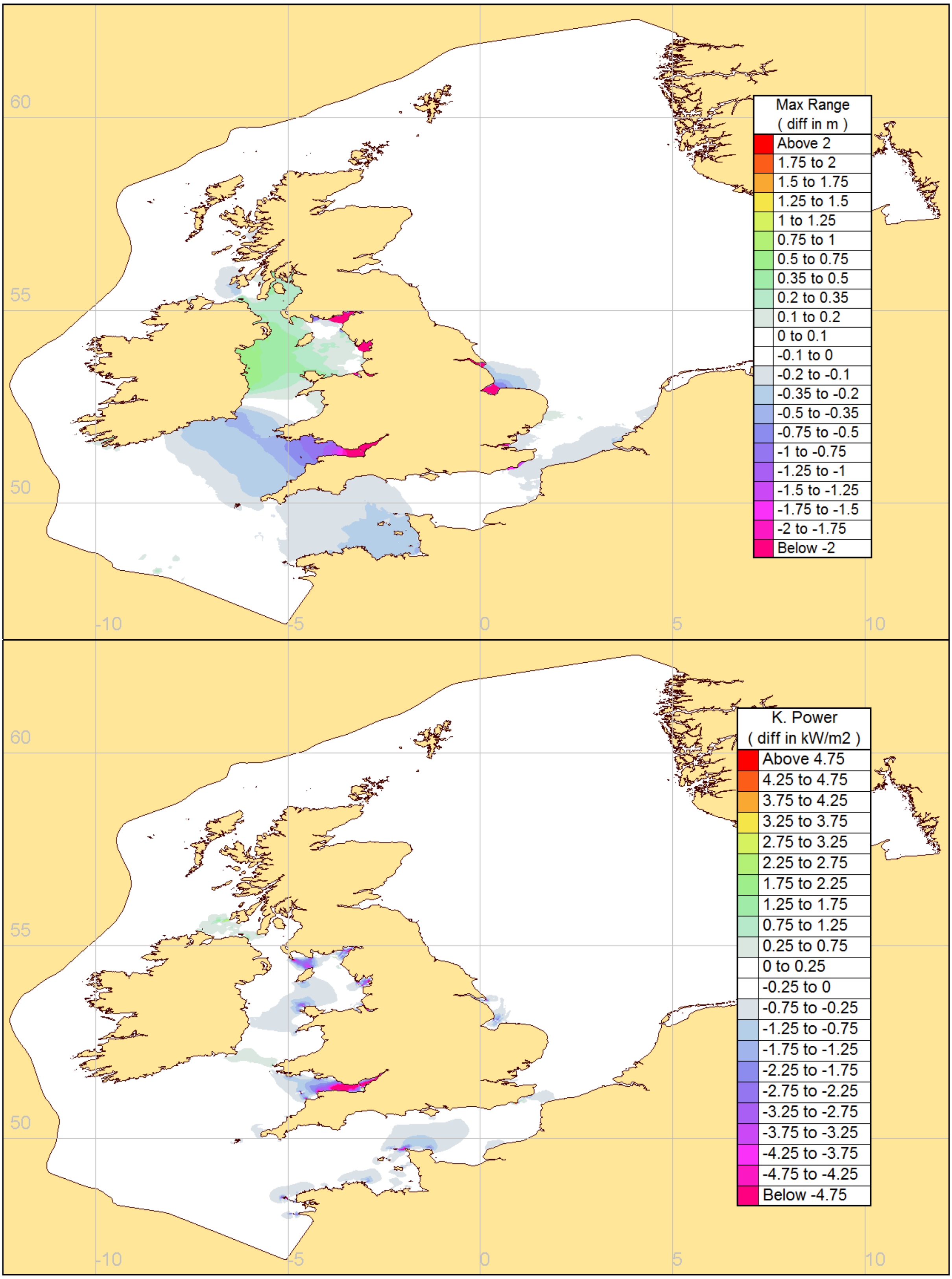

Figure 32 Outcome of the CSM scenario modelling, Scenario 26

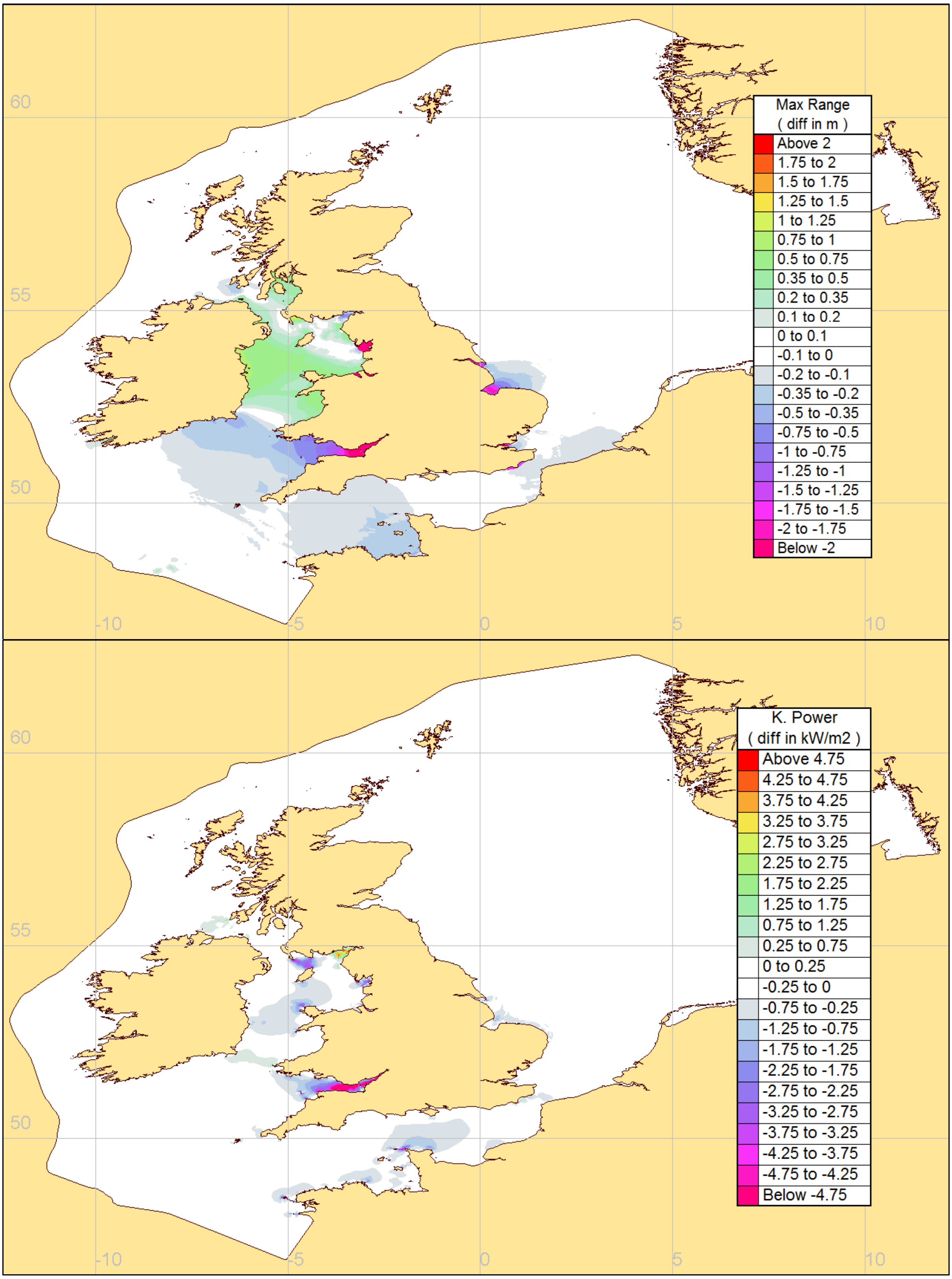

Figure 33 Outcome of the CSM scenario modelling, Scenario 27

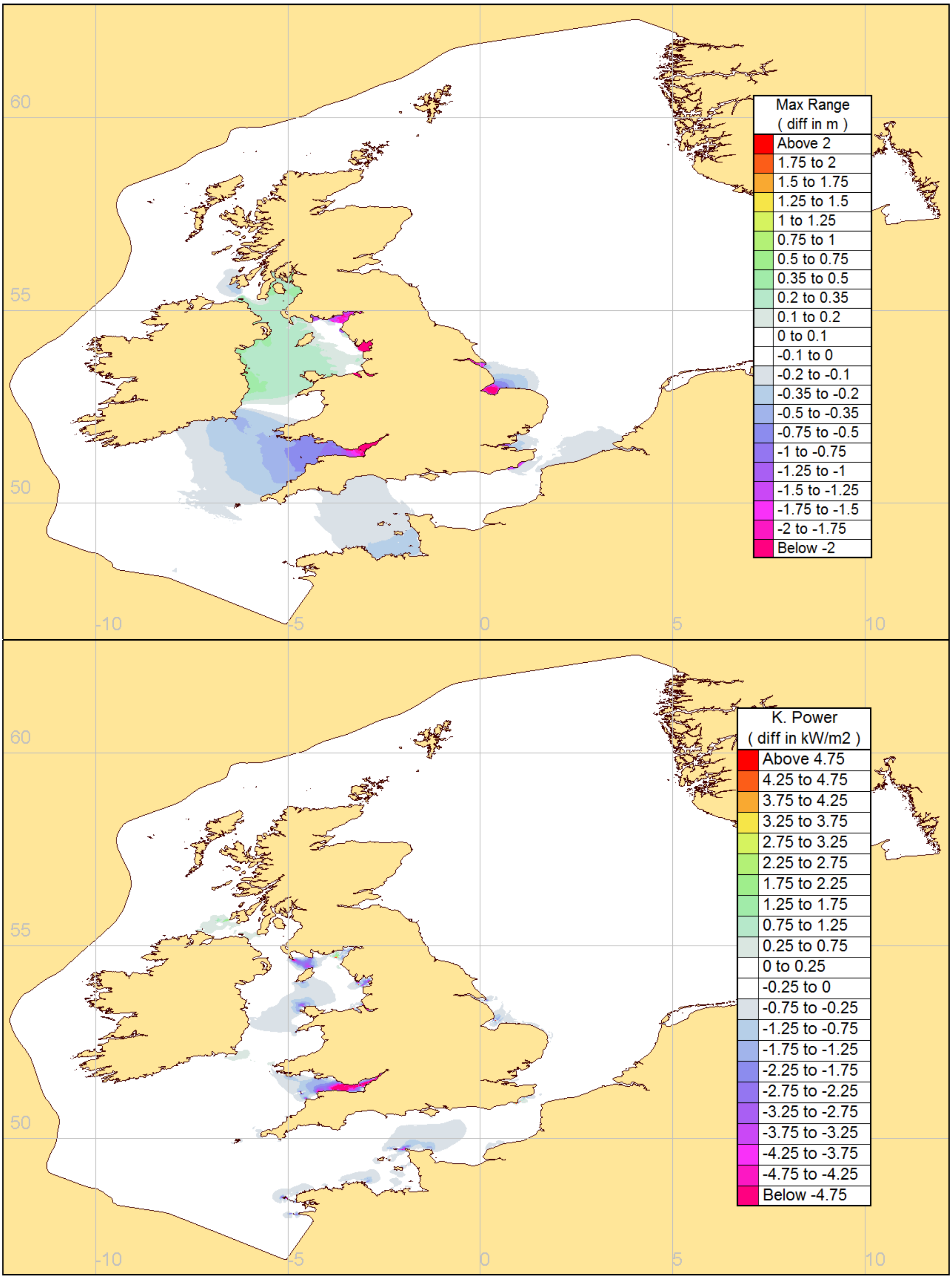

Figure 34 Outcome of the CSM scenario modelling, Scenario 28

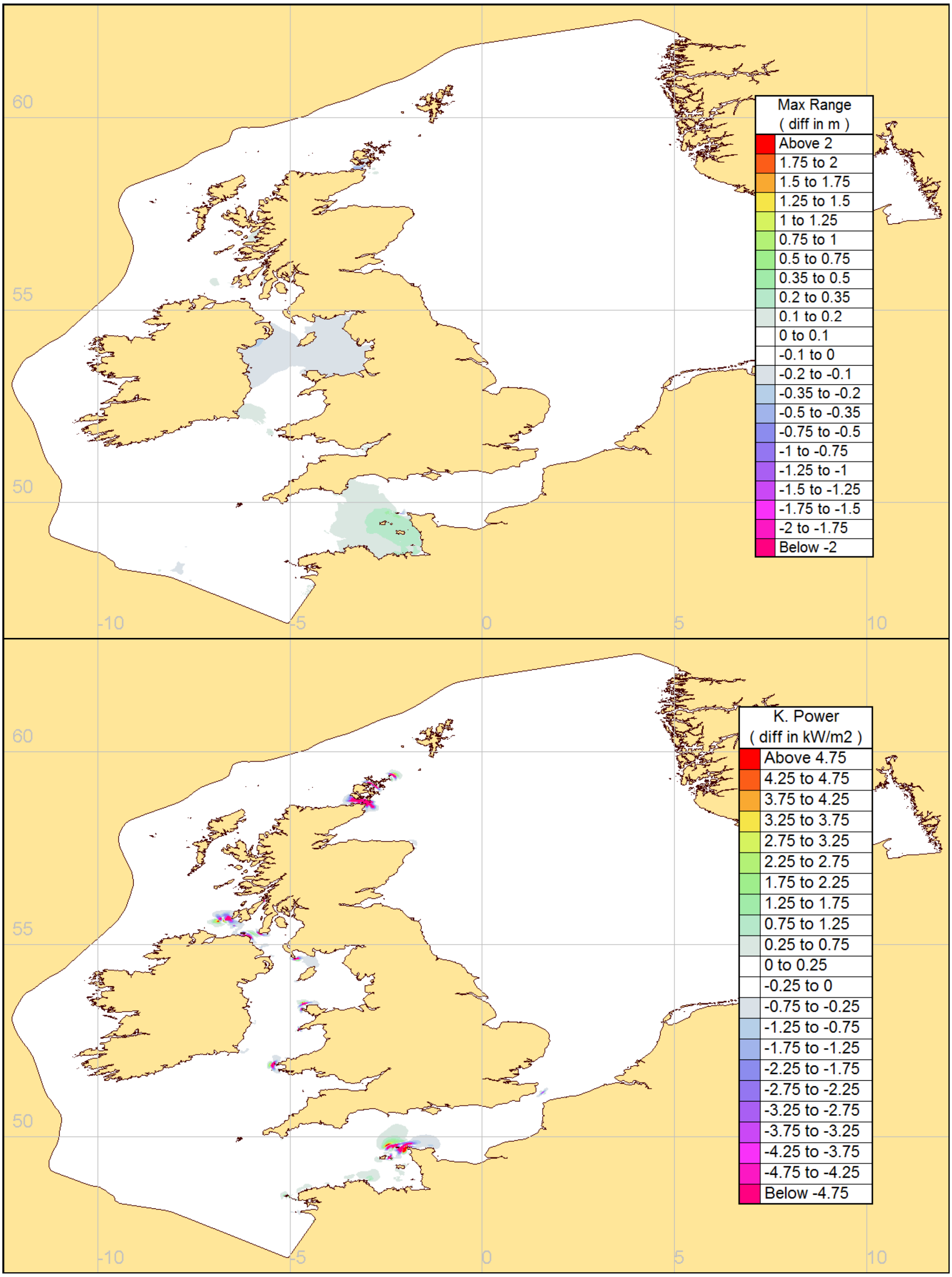

Figure 35 Outcome of the CSM scenario modelling, Scenario 29

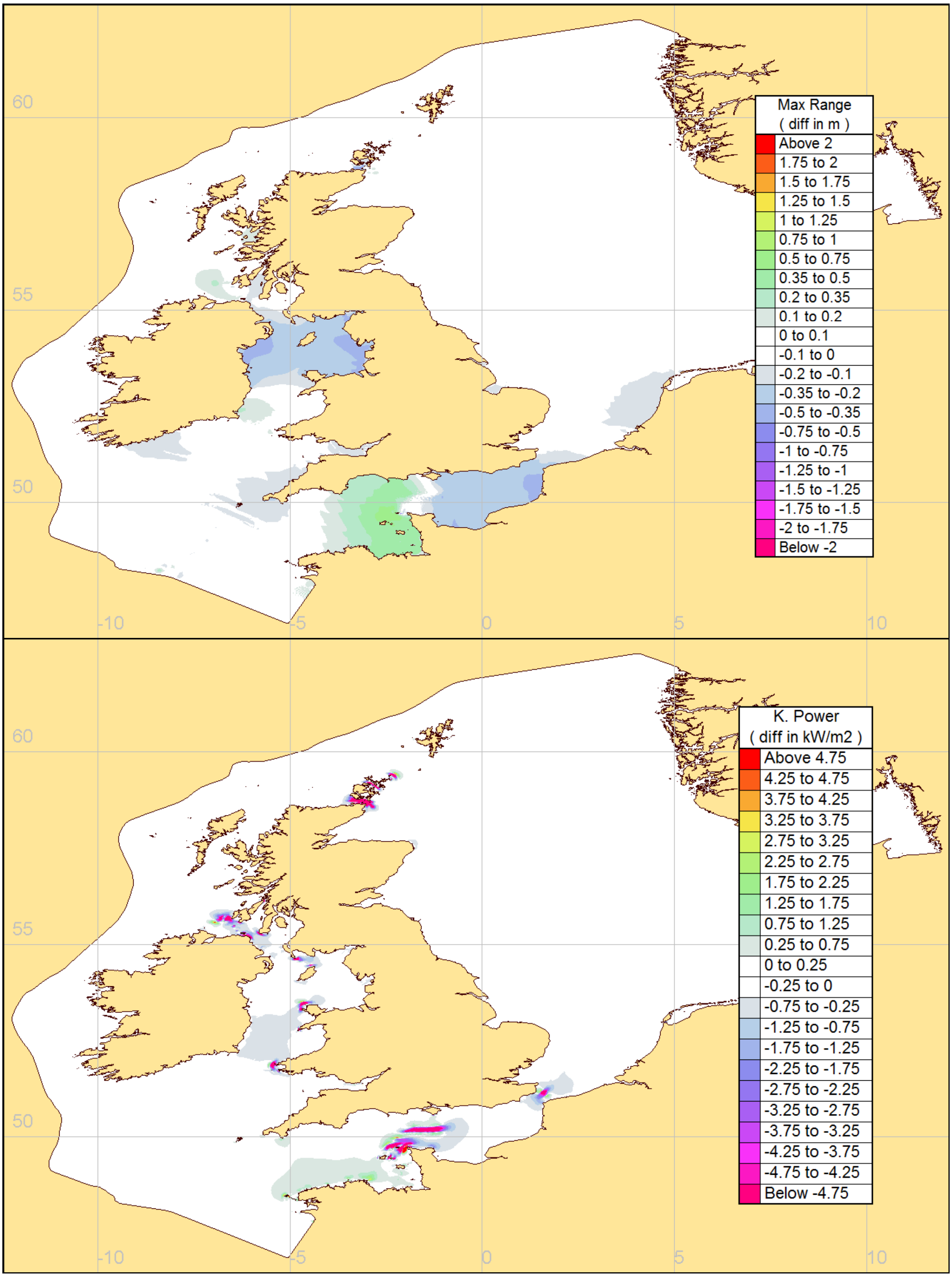

Figure 36 Outcome of the CSM scenario modelling, Scenario 30

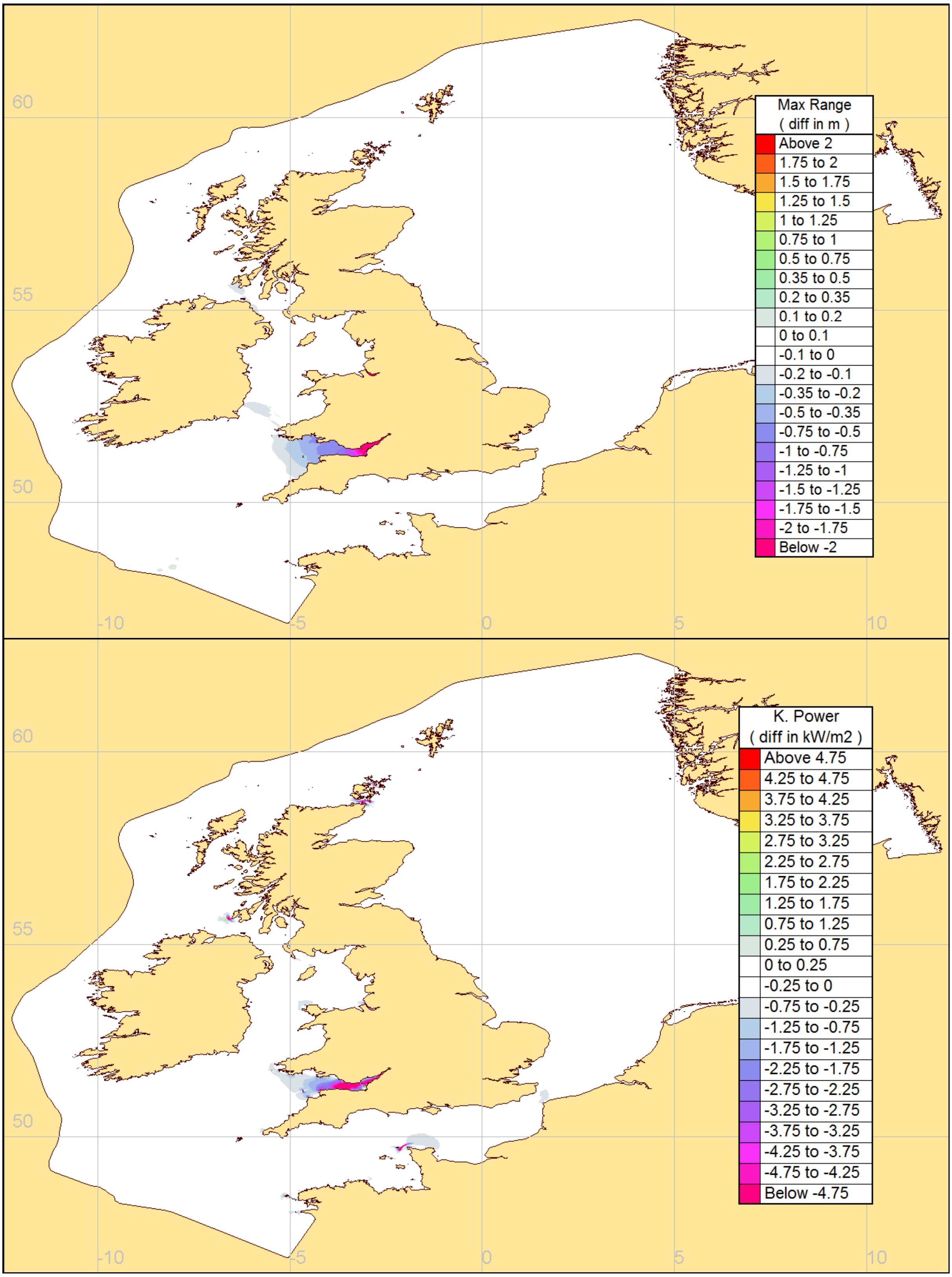

Figure 37 Outcome of the CSM scenario modelling, Scenario 6b (5Dx20D)

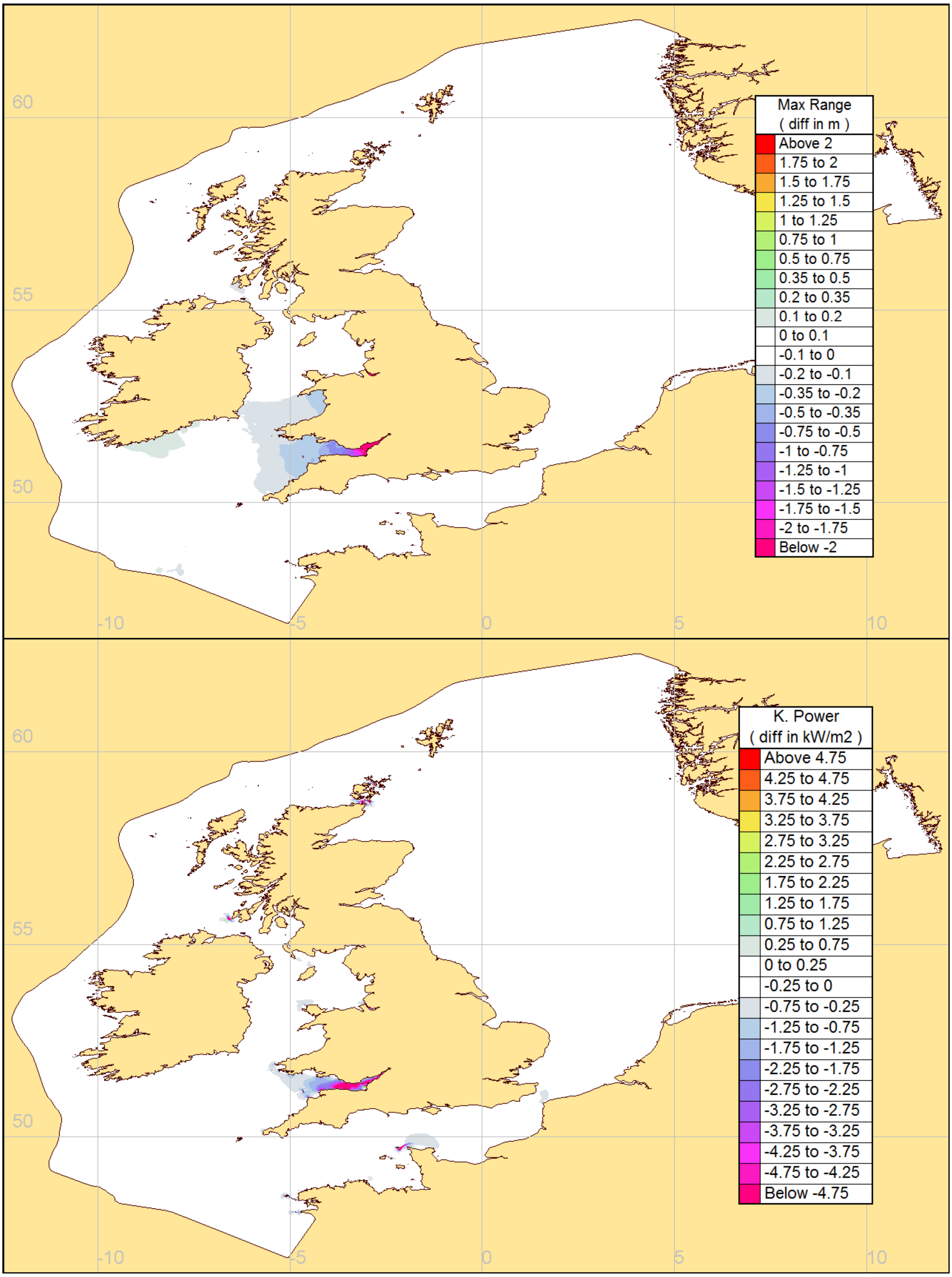

Figure 38 Outcome of the CSM scenario modelling, Scenario 23 (5Dx30D)

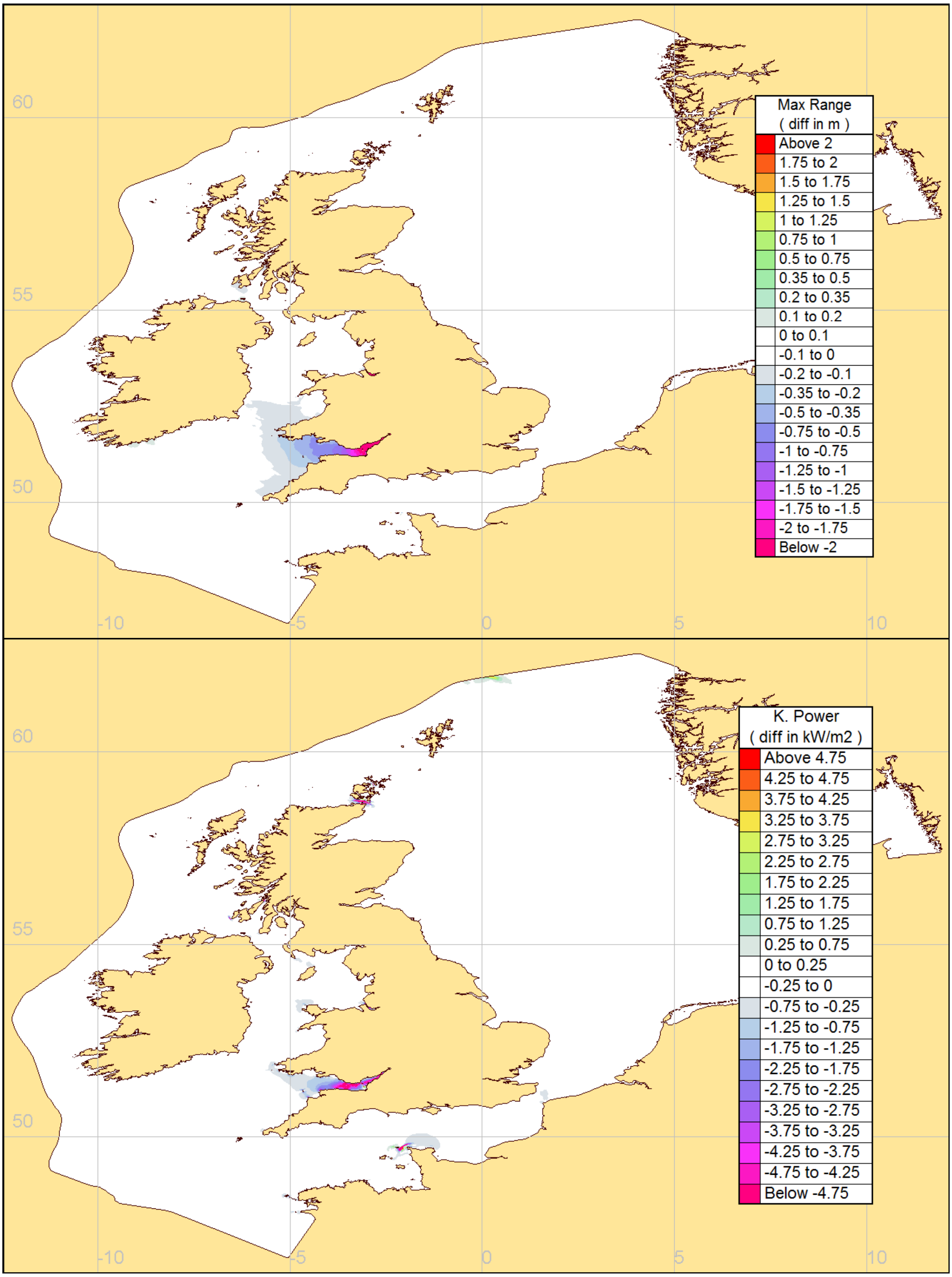

Figure 39 Outcome of the CSM scenario modelling, Scenario 6 (low tide)

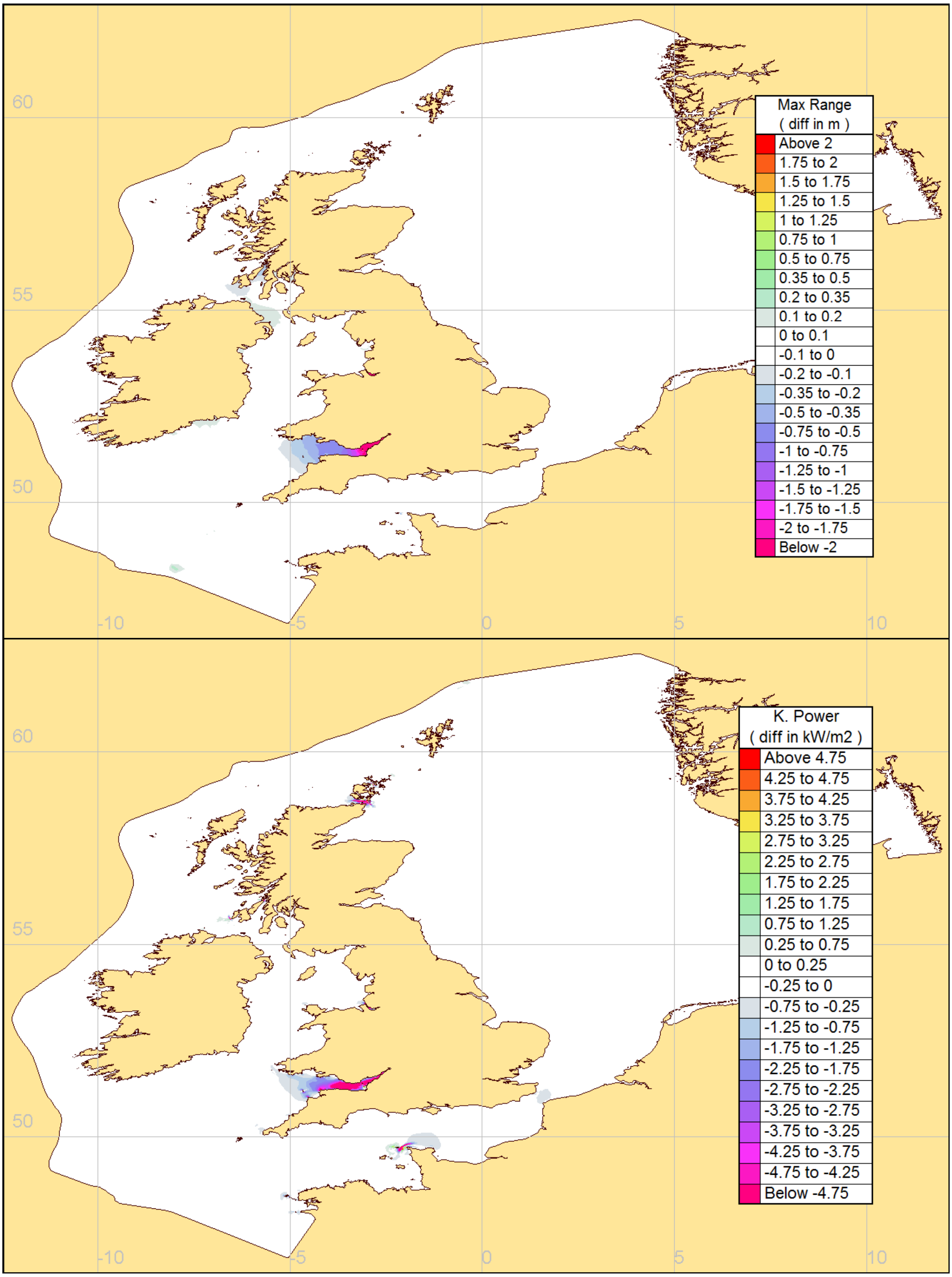

Figure 40 Outcome of the CSM scenario modelling, Scenario 6 (high tide)

Figure 41 Tidal Range and Tidal Current sites

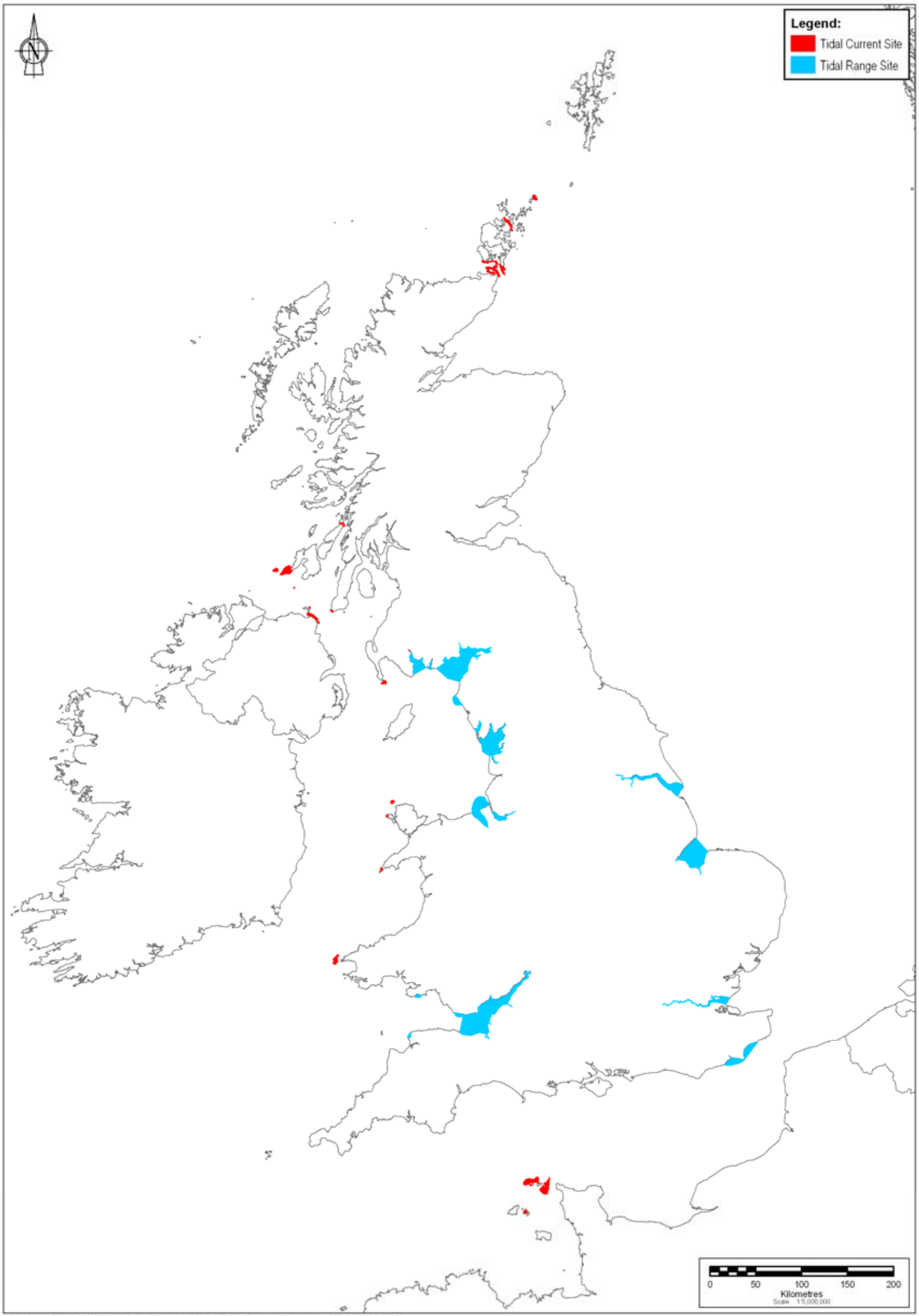

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Figure 42 Environmental Constraints (exclusion areas)

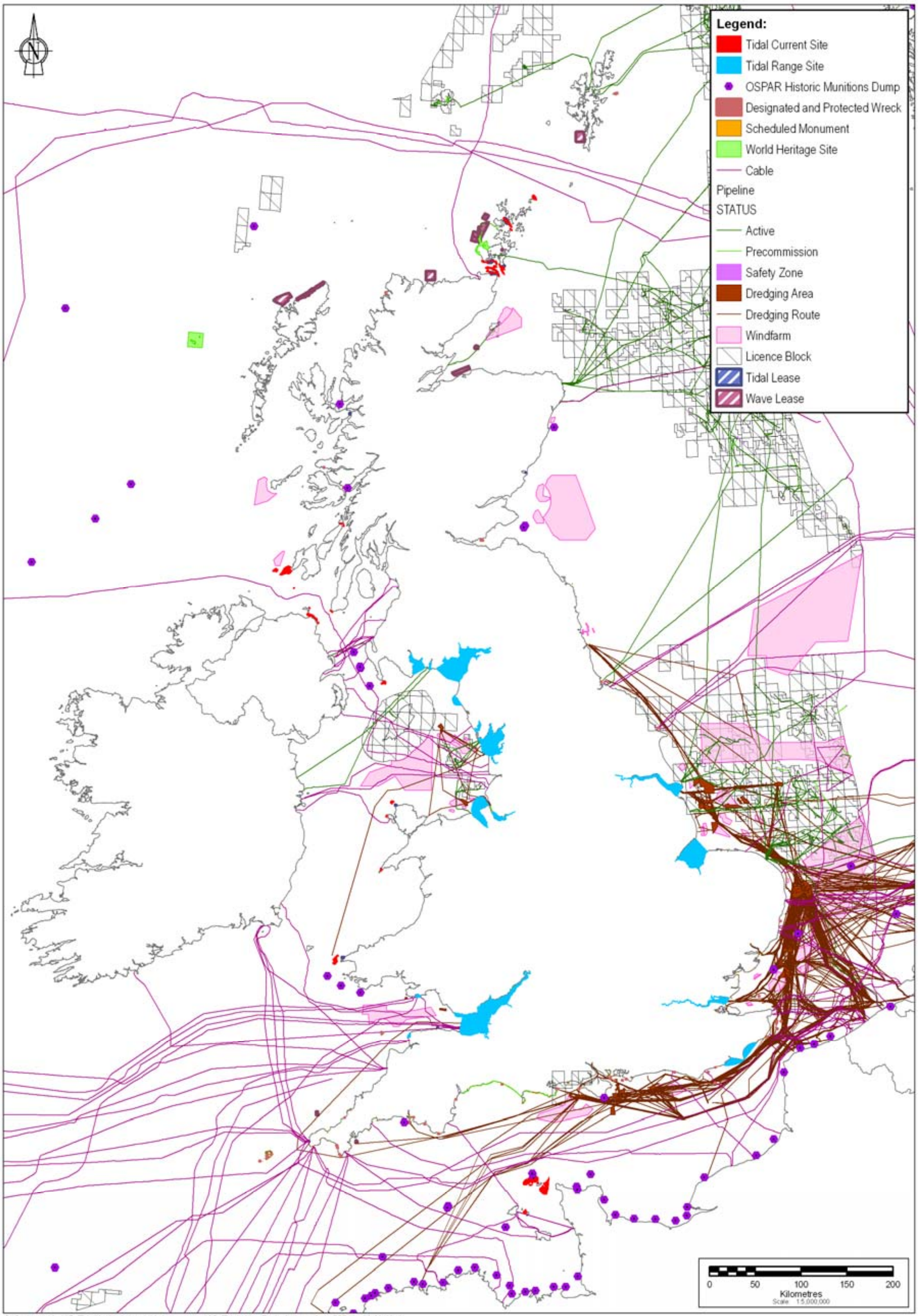

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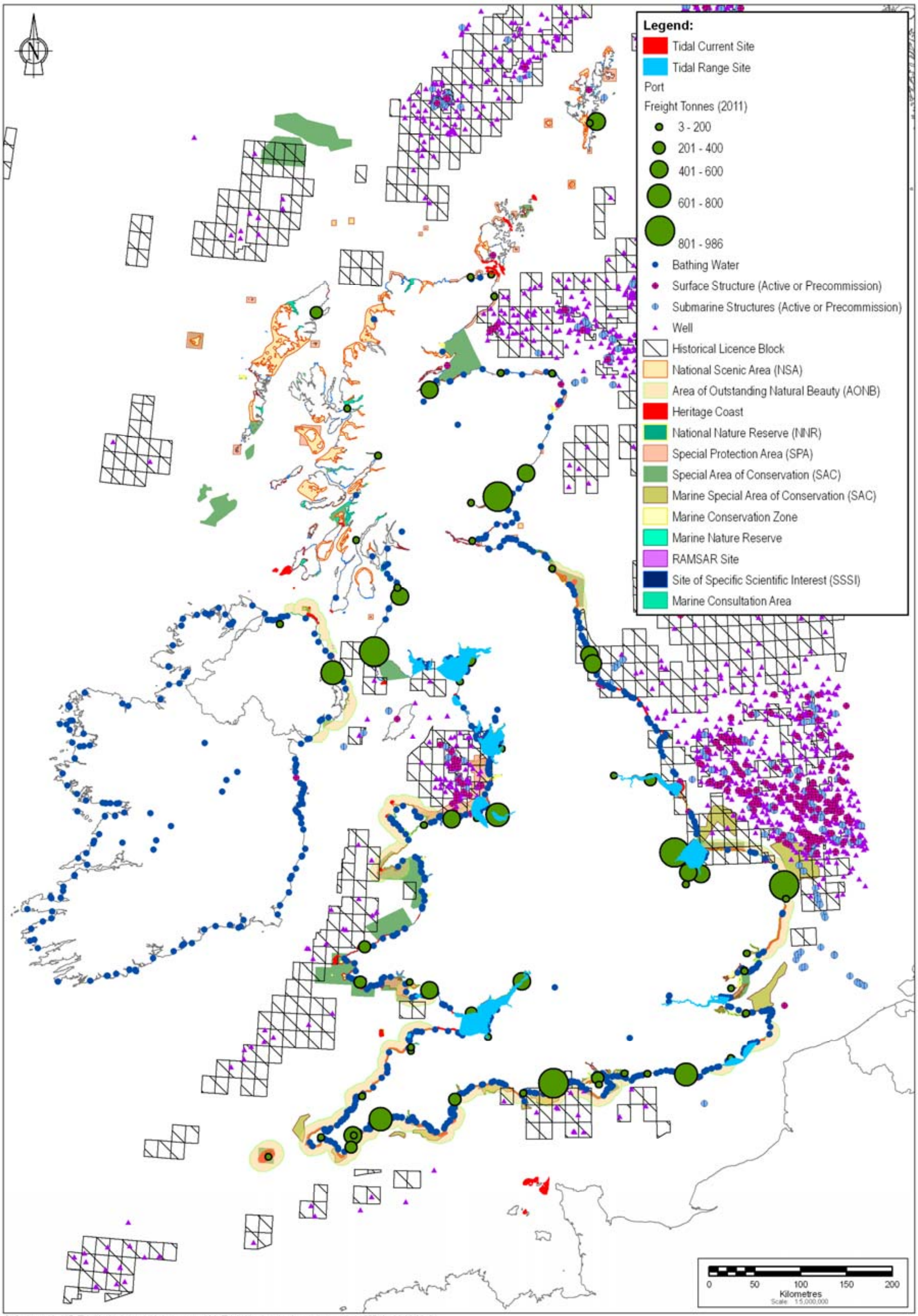
Figure 43 Environmental Constraints (high constraint areas)



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GLOSSARY

0D model – zero-dimensional / flat estuary model. A 0D model uses only two water levels (sea level and basin level). Sea level is a user defined input and, as such, the effect of barrage operations on sea levels is not represented. The basin level is calculated assuming that the water level upstream of the impoundment line is uniform.

1-d model – one-dimensional model. A 1-d model represents water levels in an estuary using a series of cross-sections. Hence water levels can vary moving upstream or downstream from the impoundment line but levels are uniform across the estuary. This means that the effect of a barrage/lagoon on downstream sea levels is represented to some extent.

2D model – two-dimensional model. A 2D model uses a mesh or grid to represent the sea and coastline. Water levels can vary both parallel and perpendicular to the coastline. As such, a 2D model represents the constriction and expansion as water flows into and out of the basin, through the turbine and sluice caissons.

ADP – Acoustic Doppler Profiler.

AEP – Annual Energy Production.

Anthropogenic – resulting from the influence of human beings

Barrage – an impoundment line across an estuary comprising embankment, turbines and usually sluices. Electricity is generated by creating a water level differential across the barrage between the impounded basin and the open sea. Barrages and (coastal) lagoons are similar.

Basin – the impounded area, usually landside, within the barrage/lagoon alignment.

Capacity Factor – generated output divided by the maximum possible generated output (in a given time period, usually 1 year).

Cavitation – the formation and immediate implosion of cavities in water as it passes through turbines. Cavitation can cause significant damage to turbines and is prevented by providing adequate submergence (installing the turbines deep enough below low tide level).

CCSM – Coarse Continental Shelf Model.

CD - Chart Datum. This is the datum used to show levels on Admiralty charts and usually corresponds to lowest astronomical tide level.

CoE – Cost of Energy.

Cp – Device coefficient of performance, i.e. mechanical efficiency at which the device extracts energy from the incoming flow.

DCSM – Detailed Continental Shelf Model.

Dual mode generation – power generation on both the ebb and flood tides.

Ebb tide – the seaward flow of water as the tide level falls.

Embankment – an artificial bank used to intercept and prevent the passage of water, forcing it through the turbine and sluice caissons whilst they are open.

Energy yield – the amount of energy generated by a scheme, usually quoted as an annual total in watt hours.

Flood tide – the landward flow of water as the tide level rises.

Free-wheeling – when turbines are not generating power but the turbine passage is kept open, which aids filling and emptying of the basin.

Generator capacity – maximum power output from each turbine unit, which usually includes an allowance for generator losses applied to the raw turbine power output.

GW – gigawatt, unit of power equal to one billion (10^9) watts.

GWh – gigawatt hours, unit of energy equal to one billion (10^9) watt hours. For constant power, energy in watt hours is the product of power (in watts) and time (in hours).

HAA – Horizontal Axis Axial flow turbine.

HAC – Horizontal Axis Cross flow turbine.

HC – Hydraulic current system.

Head – the hydraulic head, which is equal to the elevation plus velocity head (v2/2g), where v is velocity and g is gravitational acceleration. Head is often used meaning the total head difference (energy loss) across the barrage/lagoon structure.

Headloss – loss of energy experienced by the water flow as it moves through a constriction. Headlosses will occur as water passes through turbines and sluice gates channels or where bed levels are shallow.

Hill chart – turbine performance chart relating head, flow and efficiency, usually shown in non-dimensional form.

Impoundment length – the total length of the barrage/lagoon alignment including embankments, turbine and sluice caissons.

Installed capacity – the total peak power output of the turbine generators (equal to number of turbines multiplied by unit generator capacity).

Intertidal area – seabed of estuary or coastline exposed at low tide but submerged at high tide.

Lagoon (coastal) – similar to a barrage except that the impoundment line can be connected to any coastline rather than specifically across an estuary. A lagoon, therefore, will usually require a longer embankment than a barrage to give the same impounded area.

Lagoon (offshore) – an impoundment that is not connected to the coastline. An offshore lagoon must, therefore, be enclosed on all sides by an artificial embankment.

LWS – Low Water Spring

MAE – Mean Absolute Error

MHWS – Mean High Water Springs
The height of Mean High Water Springs is the average, throughout a year, of the heights of two successive high waters during those periods of 24 hours (approximately once a fortnight) when the range of the tide is greatest.

MLWS – Mean Low Water Springs
The height of Mean Low Water Springs is the average, throughout a year, of the heights of two successive low waters during the same periods.

MSL – Mean Sea Level.

MW – megawatt, equal to one million (10^6) watts.

MWh – megawatt hours, unit of energy equal to one million (10^6) watt hours.

N-RMSE – Normalised Root Mean Square Error, obtained by normalising the RMSE using the higher of the maximum tidal range at the location and 1 m.

Outages – times when turbines are unavailable for power generation. This may be due to routine maintenance or malfunction of some or all of the turbines.

PD – Power Density.

PF – Pentland Firth

PFOW – Pentland Firth and Orkney Waters

Pmax – The maximum total mean power harvested across the tidal cycle considered for a specified tidal system.

Practical Resource – The energy (which is a proportion of the technical resource) that can be harvested after consideration of external constraints (e.g. grid accessibility, competing uses such as MOD, shipping lanes, etc.). This level of assessment fundamentally requires detailed project design and investigation on a case-by-case basis. The practical resource is hence a proportion of the technical resource.

Qmax – The mean of the local maximum volume fluxes (m^3/s) for a particular tidal system over the tidal cycle considered.

Rated head – the lowest head difference across the turbines for which the power output is equal to the generator capacity.

Rectilinear – (Oxford dictionary definition) contained by, consisting of, or moving in a straight line or lines

RES – resonant (basin) system.

RMSE – Root Mean Square Error

Runner – the rotating part of a turbine. Energy is transferred from the water flowing through the turbine by the force on the turbine blades spinning the runner and driving the turbine generator.

SNR – Signal to Noise Ratio. This is a measure of the relevance of the tidal constituents extracted by harmonic analysis of a water level or velocity record. It is generally considered that constituents with a Signal to Noise Ratio lower than 2 should be discarded.

SoI – The sites of interest, which group both tidal current energy schemes and to tidal range energy schemes.

The tidal current sites are: (a) Around the Orkney Islands: north of the North Ronaldsay Firth and the North Ronaldsay Firth itself, the Westray Firth and the deeps and shallows of the Pentland Firth; (b) Within the North Channel: west and south of Islay and the Mull of Oa, Rathlin Island, the Mull of Kintyre and the Mull of Galloway; (c) In the Irish Sea: west of Carmel Head and west of Ramsey Island; (d) In the Bristol Channel: Minehead; (e) On the south coast of England: south of the Isle of Wight; (f) Around Alderney: east and west of Casquets and the Race of Alderney; and (g) Around Jersey: north-east and south of Jersey and south of Minquiers.
The tidal range sites are: (a) In the Irish Sea: Wigtown Bay, the outer and inner the Solway Firth, the Cumbria Lagoon south of St Bees, the Duddon Estuary, Morecambe Bay, the Dee Estuary and around the Wirral and the Mersey Estuaries; (b) In the Bristol Channel: Oxwich Bay, Morte Bay, the outer and inner Severn Estuary, the Cardiff-Weston alignment, Bridgewater Bay, south of Rhoose and south-west of Aberthaw; (c) Around Dover: Dymchurch Bay and Rye Bay; (d) In the Thames Estuary, the inner and outer Thames Estuary; and (e) On the east coast of England: the Wash and the inner and outer Humber Estuary.

TEC – Tidal Energy Converter, a device which captures energy from tidal currents.

Technical Resource – The energy that can be harvested from tidal currents using envisaged technology options and restrictions (including project economics) without undue impact on the underlying tidal hydrodynamic environment. The technical resource is hence a proportion of the theoretical resource.

Theoretical Resource – Maximum energy that can be harvested from tidal currents in the region of interest without consideration of technical, economic or environmental constraints.

Tidal Current – where Tidal Stream is referred to in the Scope of Works it is replaced with Tidal Current within the Tidal Resource Modelling reporting. This is due to a general acceptance that there are three hydraulic mechanisms which, combined, accurately define the hydraulics. Tidal Stream is one of the three hydraulic mechanisms, therefore to complete the Tidal Resource Modelling credibly and accurately, Tidal Current will be used and referred to.

Total Resource – Total energy that exists within a defined tidal system.

TS – Tidal streaming.

TW **-** terawatt, equal to one trillion (1012) watts.

TWh – terawatt hours, unit of energy equal to one trillion (1012) watt hours.

Vmnp (m/s) – Mean neap peak velocity as defined by the Admiralty charts for a particular site, 5 m below the surface.

Vmsp (m/s) – Mean spring peak velocity as defined by the Admiralty charts for a particular site, 5 m below surface.

Vrated (m/s) – Rated velocity of tidal stream device. Rated velocity is the velocity at which the device reaches maximum (rated) output.